Anesthesia Student Survival Guide

A Case-Based Approach

Jesse M. Ehrenfeld
Richard D. Urman
B. Scott Segal *Editors*

Third Edition

Springer

Anesthesia Student Survival Guide

Jesse M. Ehrenfeld
Richard D. Urman • B. Scott Segal
Editors

Anesthesia Student Survival Guide

A Case-Based Approach

Third Edition

Springer

Editors
Jesse M. Ehrenfeld
Department of Anesthesiology
Medical College of Wisconsin
Milwaukee, WI, USA

B. Scott Segal
Department of Anesthesiology
Wake Forest University School of Medicine
Winston Salem, NC, USA

Richard D. Urman
Department of Anesthesiology
Perioperative and Pain Medicine
Brigham & Women's Hospital
Harvard Medical School
Boston, MA, USA

ISBN 978-3-030-98674-2 ISBN 978-3-030-98675-9 (eBook)
https://doi.org/10.1007/978-3-030-98675-9

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword to the Third Edition

As an anesthesiologist and Harvard medical student educator, I have met few people more dedicated to the art of teaching and the experience of learning than Drs. Ehrenfeld, Urman, and Segal. Now I have the privilege of introducing the third edition of their exciting new textbook of anesthesiology written especially for medical students. *Anesthesia Student Survival Guide: A Case-Based Approach* is a wonderful synthesis of the broad scope and key concepts of anesthesiology. The book is presented in an easy format for a medical student to learn and absorb during the typically brief 1–4-week exposure to the specialty.

Students come to their anesthesia rotation with a basic science foundation and little to no familiarity with the types of clinical challenges facing the anesthesiologist. They typically have even less exposure to the thinking and behaviors required to successfully meet those challenges. Drs. Ehrenfeld, Urman, and Segal have created a textbook which not only delivers concise and logical anesthesiology content but also demonstrates the connection between the student's basic knowledge of anatomy, physiology, pharmacology, and the clinical art and science of anesthesiology. The educational format enables students to move up the taxonomy of learning behaviors by helping them synthesize and apply what they learn to sample cases.

The book begins with a historic overview and introduction of the anesthesiology specialty. In addition, the introduction instructs students on how to practically get the most out of their anesthesia rotation. The pharmacologic principles on intravenous and inhala-

tional anesthetic agents, local anesthetics, muscle relaxants, and sedatives are presented in the next five chapters. The all-important preoperative patient evaluation, airway evaluation, and monitoring are covered in the following three chapters.

Pharmacology is then put together with the patient history and physiology to help the student understand the choice of anesthetic techniques, fluid management, common anesthetic problems, and subspecialty management. Postoperative PACU and ICU care with an emphasis on pain and organ system derangement are reviewed. Lastly, the book discusses the complex and contemporary topics of professionalism, teamwork, quality assurance, and ethics in anesthesia in a clear and forthright manner.

Drs. Ehrenfeld, Urman, and Segal clarify and solidify perioperative concepts with their use of a case-based study tool at the end of each chapter. The cases are practical and help to contextualize anesthesia principles. As a medical student educator, I know that case studies are indeed one of the best strategies to help students transition from the classroom to the clinical environment. These cases are illustrative, thought provoking, and a stimulus for further discussion that will help students gain the most from their exposure to anesthesia practice.

The topics are judiciously chosen and are widely applicable to patient care both within and outside the operating room. It will help all students develop the necessary skills to become better perioperative caregivers. This third reiteration of the book is a valuable guide for all students, whether or not they become anesthesiologists, because they will come away with an appreciation of how anesthesiologists apply their understanding of human physiology and pharmacology to provide safe and effective medical care to patients.

Boston, MA, USA Jennifer M. McSweeney, MD

Preface

We are excited to introduce the new and updated third edition of *Anesthesia Student Survival Guide: A Case-Based Approach.* As with the prior editions, our goal was to provide a concise, easy-to-use, and up-to-date introduction to the practice of anesthesiology.

This book is unique in many ways and is primarily intended for students during their anesthesia rotation, although junior residents may also find it useful. The book covers both basic and advanced topics and includes case studies designed to help apply theoretical knowledge to real patient situations. In order to get the most out of the book, when reading a particular section, we suggest you first read the case associated with the section, followed by the chapter, and then try to answer the questions in the case on your own *before* reading our sample answer. This will help you focus your reading and retain as much of the key information as possible because each case will provide a context in which the material is presented.

As educators, we are indebted to generations of students at our respective institutions – Medical College of Wisconsin, Harvard Medical School, and Wake Forest School of Medicine – who inspired us to write this practical "survival" guide, and we are thankful for the support and expertise of our contributors.

We would also like to thank Dr. Joseph Garfield for his outstanding editorial contributions to the previous editions, and Mr. Judd Harly Taback and Dr. Zina Matlyuk for their tireless support, encouragement, and guidance. Finally, a special thanks to our families.

As you discover the exciting world of anesthesiology, we hope that you find our updated edition of the *Anesthesia Student Survival Guide : A Case-Based Approach* an essential tool!

Milwaukee, WI, USA — Jesse M. Ehrenfeld
Boston, MA, USA — Richard D. Urman
Winston-Salem, NC, USA — B. Scott Segal

Prior Edition Contributors

We would like to thank the authors who contributed to the first two editions of *Anesthesia Student Survival Guide: A Case-Based Approach*

Basem Abdelmalak
Jerome M. Adams
Joshua H. Atkins
Rana Badr
Sheila Ryan Barnett
Shawn T. Beaman
Tarun Bhalla
Ruma Bose
Elifce O. Cosar
Francis X. Dillon
D. John Doyle
Patrick J. Forte
Amit Gupta
Emily M. Hayden
Mark A. Hoeft
Stephen M. Howell
Adam Kingeter
Payal Kohli
David C. Lai
Alvaro A. Macias
Matthew D. McEvoy
Brian C. McLean

David G. Metro
R. Dean Nava Jr
Beverly J. Newhouse
Arti Ori
Anthony R. Plunkett
Stephen D. Pratt
Amanda J. Rhee
Thomas M. Romanelli
Mario Serafini
Timothy J. Shiveley
Linda Shore-Lesserson
Roy G. Soto
Jenna L. Walters
Andrea Westman
John W. Wolfe

Contents

Part V Systems Physiology and Anesthetic Subspecialties

Contributors

Basem Abdelmalak Anesthesia Institute, Cleveland Clinic, Cleveland, OH, USA

Meredith A. Albrecht Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

Joshua H. Atkins, MD, PhD Department of Anesthesiology and Critical Care, Perelman School of Medicine at the University of Pennsylvania, University of Pennsylvania Health System, Philadelphia, PA, USA

Department of Anesthesiology and Critical Care, University of Pennsylvania School of Medicine, University of Pennsylvania Health System, Philadelphia, PA, USA

Diana Ayubcha Department of Anesthesiology and Critical Care, University of Pennsylvania, Philadelphia, PA, USA

Tarun Bhalla Department of Anesthesia and Pain Medicine, Akron Children's Hospital, Akron, OH, USA

Sarah Jane Bost Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA

R. Dean Nava Jr Department of Anesthesiology, Northwestern Memorial Hospital, Northwestern University, Chicago, IL, USA

Naucika DeSouza Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA

D. John Doyle Anesthesia Institute, Cleveland Clinic, Cleveland, OH, USA

Angela F. Edwards Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA

Jesse M. Ehrenfeld Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

Herodotos Ellinas Department of Pediatric Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

Stacy L. Fairbanks Department of Anesthesiology, Froedtert & Medical College of Wisconsin, Milwaukee, WI, USA

Laura S. González Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

Thomas J. Hatzidais Department of Anesthesiology and Critical Care, University of Pennsylvania, Philadelphia, PA, USA

Emily M. Hayden Division of Medical Simulation, Department of Emergency Medicine, Massachusetts General Hospital, Boston, MA, USA

Olga Kaslow Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

Seiha T. Kim Department of Anesthesiology, Wake Forest University School of Medicine, Winston Salem, NC, USA

Adam Kingeter Department of Anesthesiology, Vanderbilt University Medical Center, Nashville, TN, USA

Department of Anesthesiology, Vanderbilt University Medical Center, Nashville, TN, USA

Vesela Kovacheva Department of Anesthesiology, Perioperative and Pain Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA

Evelyn Lee Northeast Ohio Medical University, Rootstown, OH, USA

Alvaro Andres Macias University of California San Diego, San Diego, CA, USA

Hemanckur Makker Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

Bryan Marchant Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA

Matthew D. McEvoy Department of Anesthesiology, Vanderbilt University Medical Center, Nashville, TN, USA

Department of Anesthesiology, Vanderbilt University Medical Center, Nashville, TN, USA

Justin Merkow Department of Anesthesia, University of Colorado Hospital, Aurora, CO, USA

Rebecca D. Minehart Harvard Medical School, Boston, MA, USA

Department of Anesthesia, Critical Care and Pain Medicine, Massachusetts General Hospital, Boston, MA, USA

Britlyn D. Orgill Harvard Medical School, Boston, MA, USA

Department of Anesthesia, Critical Care and Pain Medicine, Massachusetts General Hospital, Boston, MA, USA

Carolyn Pinkerton Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

Daniel Presutti Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA

Stephen Raithel Department of Anesthesiology, Perioperative and Pain Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA

Raymond C. Roy Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA

Roger L. Royster Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA

Jacob Schreiner Medical College of Wisconsin, Milwaukee, WI, USA

B. Scott Segal Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA

Eric R. Sloan Department of Anesthesiology, Rush Medical College, Chicago, IL, USA

Joshua A. Spiro Department of Anesthesiology and Critical Care, University of Pennsylvania, Philadelphia, PA, USA

Christina M. Spofford, MD, PHD, FASA Department of Anesthesiology, Marshfield Medical Center, Beaver Dam, WI, USA

Andrea J. Strathman Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA

Ashley L. Talbott, MD Department of Anesthesiology, Wake Forest University School of Medicine, Winston Salem, NC, USA

Rozalin Thapa Medical College of Wisconsin, Milwaukee, WI, USA

Reade E. Tillman Department of Anesthesiology, Duke University, Durham, NC, USA

Ryan J. Traudt, MD Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

Justin R. Traunero Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA

Center for Experiential and Applied Learning, Wake Forest University School of Medicine, Winston-Salem, NC, USA

Mark S. Weiss Department of Anesthesiology and Critical Care, University of Pennsylvania, Philadelphia, PA, USA

John W. Wolfe Indiana University School of Medicine, Indianapolis, IN, USA

Dongdong Yao Department of Anesthesiology, Perioperative and Pain Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA

Part I

Introduction to Anesthesiology

How to Be a "Star" Student, Career Options, and the Match

1

Reade E. Tillman and Stacy L. Fairbanks

For maximum impact, it is recommended that Case Study 1.1 be reviewed before reading this chapter.

Introduction

If your favorite place in the *world* is the operating room, be a surgeon. If your favorite place in the *hospital* is the operating room, be an anesthesiologist. For many, the practice of anesthesiology is the perfect blend of science, medical management, procedural skills, variety, and fun. Where else can you care for critically ill patients, listen to music, socialize with surgeons, and wear your pajamas all at the same time?

R. E. Tillman (✉)
Department of Anesthesiology, Duke University, Durham, NC, USA
e-mail: reade.tillman@duke.edu

S. L. Fairbanks
Department of Anesthesiology, Froedtert & Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: sfairbanks@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_1

This chapter will outline:

- suggested preparation and goal setting for your medical school anesthesia rotation
- career options within anesthesiology
- the future of anesthesiology as a specialty
- the Match
- a run-through of a typical case
- guidance for approaching preoperative evaluation

How to Be a "Star" Student

Your road to being an anesthesiologist starts as early as medical school rotations. Even if you don't have an interest in any other specialty, much of what you learn in your core clerkships will be applicable and important foundational knowledge for anesthesiology. Although anesthesia rotations may be shorter (e.g. two weeks) or elective only, that makes it all the more important to structure your rotation for high yield, both in learning and exposure to the specialty [6]. Many programs are moving away from the "show up and we'll stick you somewhere" method of teaching; start by identifying the educational objectives set by the clerkship director. Here are a few tips for standing out and making the most of your rotation:

1. **Come with flexibility and a positive attitude.**
   Anesthesia is a team game; the kind of cases and how involved you can be might vary day to day, so come in with an open mind and eagerness to learn. Adaptability is an essential skill for an anesthesiologist, and it will serve you well to hone this early on [7]. *It is not expected that you are a pro at placing IVs or know all there is to know about volatile anesthetics, but enthusiasm will go a long way.*
2. **Read about fundamental pharmacology/physiology principles (see suggested reading topics [**Table 1.1**]).**
   In most cases, there will be time for intraoperative teaching so it is helpful to have some foundational knowledge about

Table 1.1 Suggested reading topics

Review airway anatomy and various intubating techniques/tools (e.g. ETT, LMA, bougie, fiberoptic, videoscope) (Chap. 9)
Review principles of preoperative assessment (Chap. 8)
Review basic respiratory and cardiac physiology (Chap. 18)
Review autonomic nervous system pharmacology (Chap. 3)
Review cholinergic and anticholinergic pharmacology (Chaps. 4 and 7)
Review opiate pharmacology (Chap. 4)
Review local anesthetic pharmacology (Chap. 6)
List commonly used medications in each of the following classes: (Chaps. 4, 5, 6, and 7)
Sedative/Hypnotics
Volatile agents
Antiemetics
Neuromuscular blockade and reversal
Local anesthetics
Opioids
Adrenergics (agonist and antagonist)
Non-opioid analgesics

Adapted from original content, courtesy of J. Ehrenfeld

some topics to build on. Focus on quality of material, not quantity – this will be a unique opportunity to see physiology in action (e.g. phenylephrine raising the blood pressure by increasing systemic vascular resistance) so it can help solidify the knowledge of those topics that you learned from your basic science courses and core rotations.

3. **Identify specific learning goals (see some examples [**Table 1.2**]).**

   Take ownership of your rotation. What do YOU want to get out of it? What topics interest you? What questions have come up during your reading? Come each day with at least 1–2 topics you would like to discuss. At the beginning of the rotation, list specific and achievable goals for yourself (think SMART goals) and discuss them with your attending/resident/CRNA.

4. **Know and advocate for your patients.**

   As able, take time to read about the patients that you will be caring for the night before their surgery. Familiarize yourself

Table 1.2 Examples of specific learning goals

Practice mask ventilation on >50% of your patients
Attempt laryngoscopy and endotracheal intubation in 3–5 of your patients
Place/attempt 3–5 PIVs in your patients
Observe at least 1 epidural, 1 spinal, and 1 peripheral block[a]
Spend 1 day in pain clinic or with a pain service[a]
Spend 1 day on an OB anesthesia team[a]

Adapted from original content, courtesy of J. Ehrenfeld
[a]These may be opportunities only offered on sub-specialty or advanced rotations (usually during 4th year)

with their medical conditions, allergies, medications, etc. There may be times when that information is crucial to patient safety, such as avoiding medication errors. Many patients feel very nervous before surgery, so even seemingly insignificant actions (e.g. holding their hand as they go off to sleep) can have a big impact.

5. **Take all the learning opportunities, big and small.**

   You may get the opportunity to practice procedures like intubations, arterial lines, or IVs during your rotation; when you do, take a deep breath and just do your best. Those skills take time to develop, so even an unsuccessful attempt is a useful experience. There will be other opportunities to help, like attaching the patient's monitors, drawing up medications, or spiking IV fluid bags. Willingness to help with these smaller tasks will go a long way (see tip #1), and these are very relevant skills for an anesthesia residency and career.

6. **Develop healthy habits for stress management**

   At this stage in your training, it is likely that you already have been under high levels of stress; the academic rigor, clinical expectations, and emotional toll of medical education can manifest itself in physical, mental, relational, and academic decline. Excessive stress is associated with poorer academic outcomes and increased burnout [19].

   Moreover, studies show an average of 1 in 4 medical students will experience depression, and 1 in 10 medical students will experience suicidal ideation [17]. *During residency, rates of depression are between 20.9–43.2%, and show a 0.5%*

increase per calendar year [12, 18]. *Anesthesiologists in particular are found to have the highest risk of death by suicide of any medical specialty* [3, 16]. *Though these data are sobering, it underscores the importance of building healthy coping habits from the very beginning of training. Integrating practices of adequate sleep* [4], *physical exercise, mental health care including counseling or medication, meditation or yoga* [11], *maintaining hobbies outside of medicine, and meaningful relationships with family and friends will pay dividends later. Although it may seem nearly impossible, developing these habits early in your medical training will serve as the foundation for career longevity and success.*

If you or someone you know is struggling with depression, substance abuse, or thoughts of suicide, ***you are not alone.*** *We've provided a list of resources at the end of this chapter that can help, and in an emergency, you can always call the National Suicide Prevention Lifeline by dialing 988 or visiting https://988lifeline.org.*

7. ***Set a personal standard of professionalism***

It is easy to anchor on academic performance as an objective measure of competence; however, studies show that professionalism violations are one of the top reasons for lack of success in medical school or residency. It is especially difficult to remediate professionalism, unlike most academic or clinical skills [2, 15]. *Qualities like accountability, altruism, ethical behavior and personal well-being are critically important in an anesthesiologist* [20]. *Clearly, it is not just a matter of how much you know, but also how you conduct yourself. Furthermore, unprofessional behavior in medical school has been linked to disciplinary actions by state medical boards later in one's career* [13]. *Start now by developing a high standard for yourself in regards to professional conduct – in how you interact with patients, on medical teams, and even on social media.*

8. **Find a mentor (or a few)**

Arguably the single most important step in setting yourself up for success in anesthesiology is choosing a good mentor. Although a physician who is an anesthesiologist would be able

to give you the most specific information and advice, it is also useful to have mentors in other disciplines for support and encouragement in surviving medical school, taking boards, balancing your own health and family life, choosing a specialty and residency, and more [8, 9]. *Lean on those who have walked the path ahead of you; don't be afraid to ask for help and specifically ask, "Will you be my mentor?" Most faculty members choose to remain in academic medicine because they are passionate about education and mentorship. A successful mentor-mentee relationship requires shared expectations and realistic time commitment.*

Career Options

As an anesthesiologist, you will have a variety of career options to choose from. Some physicians choose to stay in academic medicine – focusing on research, teaching, or advancing clinical practice. Others choose to go into private practice – most often working for a private group that contracts with a hospital, or more frequently becoming direct hospital-paid employees or employees of a larger multispecialty or national group.

Within the specialty, individuals may opt to complete advanced training or fellowships after residency in a variety of accredited [1] or non-accredited sub-specialties, including but not limited to:

- critical care
- acute or chronic pain medicine
- regional anesthesia
- sleep medicine
- adult cardiothoracic anesthesia
- obstetric anesthesia
- pediatric anesthesia
- palliative care/hospice
- neuroanesthesia
- clinical informatics
- perioperative medicine
- global health

Some anesthesiologists obtain other advanced degrees, such as MBA, MPH, or JD and work in the overlap of those sectors with medicine; there are endless opportunities for policy and advocacy, hospital leadership, global health efforts and even serving in the military as an anesthesiologist. Many individuals choose to engage in research training – either during or after their residency. Currently, the American Board of Anesthesiology will allow some residents to enter into the "clinical scientist" pathway – which provides for a 6-month research experience during the final (CA-3) year of residency [5].

The location, size, and type of practice you choose will ultimately affect your practice model. In some states and regions, there is an increased reliance on physician extenders including Anesthesiologist Assistants (AAs) and Certified Registered Nurse Anesthetists (CRNAs). These members of the care team function as advanced practice providers (APPs) under the supervision of a physician as a response to the high demand for anesthesia. Nurse anesthetist/AA supervision in the "anesthesia care team model" is a safe, effective, and efficient way to provide care [10]. That being said, there are a number of variations on the theme, with physician-only practices still popular, and supervision ratios varying widely from 2:1 to 4:1, depending on the setting.

CRNAs are registered nurses who have completed masters-level training in nurse anesthesia following nursing work in a critical care environment. AAs have also completed masters-level training in anesthesia, with an undergraduate degree typically in pre-med or a similar science major. Not all states support AA practice, and there are fewer training programs for AAs than for CRNAs. However, this number increases annually and the role of AA's will likely become more prominent within the specialty in coming years.

Ultimately, the numerous and diverse possible paths available within the specialty mean that most anesthesiologists can build a happy, successful, satisfying career that centers around their interests, skills, and priorities. The future of the specialty continues to be bright.

The Future of the Medical Specialty of Anesthesiology

Along with the rest of healthcare, the specialty of anesthesiology is undergoing some dramatic changes; some common questions often asked by medical students include: Will the medical specialty of anesthesiology continue to exist, particularly given the growing use of CRNAs and AAs? What is the role of the physician-led, care team model? How will technology, including artificial intelligence and closed loop anesthesia control systems, affect the practice of anesthesia? While the way in which anesthesia is practiced today may not be the way it is practiced a decade from now, there will always be a need for well-trained, qualified anesthesiologists. The growth of the perioperative surgical home model, along with the increasing demand for physicians who can design and create systems that can efficiently deliver high-quality and cost-effective care, will drive this demand [14].

The SARS-CoV-2 (COVID19) pandemic of 2020 shone the spotlight on anesthesiologists as frontline workers in a global distaster, both as the principal airway management specialists as well as experts in caring for critically ill patients. This brought with increasing occupational hazards, but it also exemplified how the role of a physician anesthesiologist is ever-changing but never replaceable. As you contemplate entering the field of anesthesiology, keep an open mind. You very well may be the person that helps define what the field looks like for the next generation of anesthesiologists!

The Match

As a specialty, anesthesia has had its ups and downs in popularity, and is now considered a very highly sought-after field. Many seek out the challenge of solving complex physiologic problems in real time, the ability to work in the operating room environment, or the satisfaction of placing endotracheal tubes, invasive monitors, and/or advanced nerve blocks. In addition, the flexible schedule and ability to balance clinical practice with other interests (e.g. teaching, research) are other appealing features of the practice of anes-

thesiology. The Match is currently very competitive, with hundreds of applicants applying for, on average, a dozen positions at popular programs. Figure 1.1 outlines typical milestones for a medical student interested in pursuing anesthesia.

As with most specialties, applicants must use the ERAS system, whether applying for PGY1 or PGY2 positions. All programs formed as of 2008 must have an integrated internship called a "Clinical Base Year" (predominately medicine, surgery, and critical care) instead of the traditional preliminary medicine or surgery internship, and chances are that all programs will move in this direction eventually. Couples matching is supported, and there is no early match system.

Residency interview selection comes from a comprehensive evaluation of personal statement, Dean's letters, class ranking, honor society selection, grades, and letters of recommendation as well as considerations such as geography and medical school reputation. While in the past some programs adhered to strict USMLE Step 1 score cutoffs, programs are moving away from this in light of USMLE reporting Step 1 exams as pass/fail. Therefore, receiving a passing score the first time Step 1 is taken is vital in order to remain a competitive candidate in the match. With that in mind, most programs can only interview ~10 candidates per position

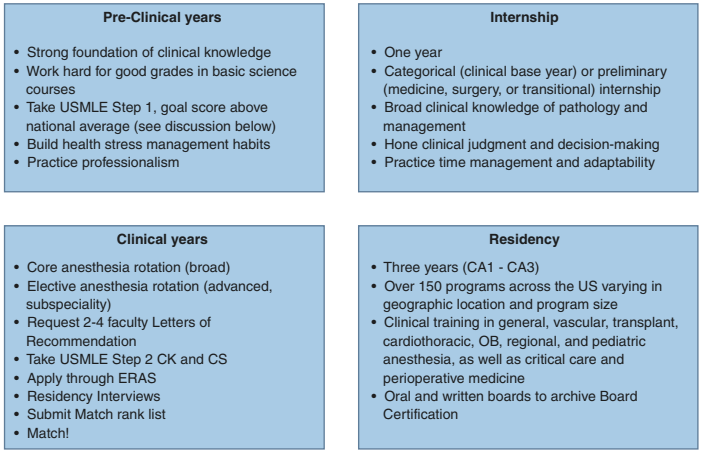


Fig. 1.1 Key milestones on the road to a career in anesthesiology

available, so a well-rounded application will stand out compared with an application with only one area of excellence. The National Resident Matching Program (NRMP) *Charting the Outcomes* data, available on their website, can give some general data on applicant demographics, including average Step 1 scores. Lean on your school's advisors as you build your application, and make it an accurate reflection of who you are, what you have done, and what you will bring to a residency program and anesthesiology as a whole.

Programs may sometimes give priority to applicants they know, whether they are students from their own hospital system or visiting students who have rotated with them. Away rotations aren't considered essential, like they are in other specialties, but may be a good idea if you are set on getting into one particular program or have less-than-impressive test scores. Having personal experience in a department can be a great way to gain an advantage over competing candidates and get to know the program much better than you can from one interview day.

A Typical General Anesthesia Case

Although the anesthesiologist needs to consider various patient and procedure factors when administering anesthesia care for a patient, there is a general workflow in the pre-op holding area, in the operating room, and in the recovery room (PACU) during a typical general anesthetic. Figure 1.2 outlines the phases of a typical general anesthetic case.

Now, let us discuss the flow of a routine general anesthetic:

Josh is a 33-year-old man with cholecystitis who needs his gallbladder removed.

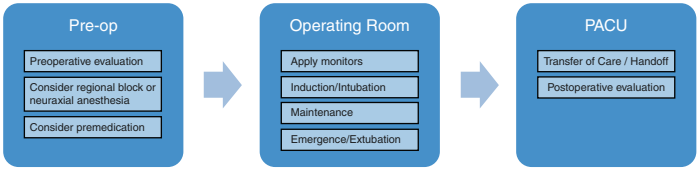


Fig. 1.2 Phases of a typical general anesthesia cases. (Adapted from original content, courtesy of J. Ehrenfeld)

Preoperative Evaluation

Josh has a history of hypothyroidism, but takes his medications and recent thyroid studies are normal. He has no drug allergies, has a good mouth opening, excellent neck extension/flexion, and good dentition. He had an appendectomy 10 years ago, and reports no problems other than postoperative nausea.

Unlike the standard internal medicine history and physical, a preoperative evaluation for anesthesia is much more focused, with specific attention being paid to the airway and to organ systems that are at a potential risk for anesthetic complications. The type of operation and the type of anesthetic will also help us focus our evaluation. Prior problems with anesthesia are noted, and physical exam should focus on the heart, lungs, and airway. See Fig. 1.3 for a sample preoperative template and guide to anesthetic plan.

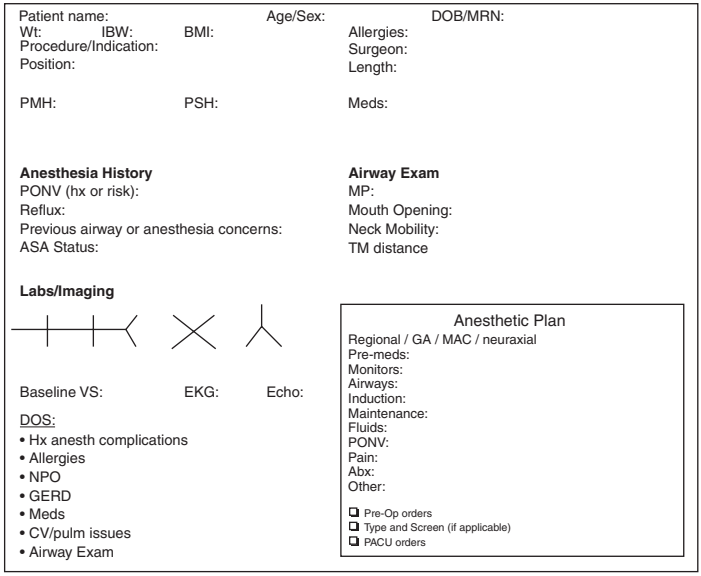


Fig. 1.3 Example of a preoperative assessment template. IBW ideal body weight, PONV post-operative nausea and vomiting, ASA American Society of Anesthesiologist classification, MP Mallampati score, TM thyromental, VS vital signs, DOS day of surgery, GA general anesthesia, MAC monitored anesthesia care, Abx antibiotics

Preoperative Medication

Josh seems relaxed, but his palms are sweaty and his resting heart rate is 90 bpm. Administering 2 mg of midazolam has calmed him right down, and he jokingly asks if he can have it for his kids as he giggles his way into the OR.

Although many patients may try to hide it, anxiety about surgery (as well as pain, prognosis, and being unconscious and naked in front of strangers) is quite common, and understandably so. We frequently sedate patients with midazolam (a benzodiazepine) and/or fentanyl (an opioid) prior to travel to the OR, with the goal of achieving anxiolysis and amnesia, while maintaining normal breathing and airway protective reflexes. Other medications that can be given in preop include oral pain medications (e.g. Tylenol or Celebrex) for multimodal analgesia, or anti-emetics like a scopolamine patch. Regional or neuraxial anesthesia may also be employed where applicable.

Monitoring

Given Josh's good health, you decide to attach him to the standard intraoperative monitors: continuous ECG (3 or 5 lead), noninvasive BP cuff, continuous pulse oximetry, and capnography.

The monitors listed above are the four standard required intraoperative monitoring for general, regional, or sedation anesthesia cases. Additional monitors may include bispectral index (BIS), temperature, invasive blood pressure (e.g. arterial line), central venous pressure monitor, pulmonary artery pressure monitor, TEE (transesophageal echocardiography), and processed EEG (electroencephalography) monitoring, all at the discretion of the provider and guided by the patient's health status and type of procedure.

Induction and Intubation

Josh has a normal-appearing airway, is otherwise healthy, and his operation requires approximately 1 h of paralysis to ensure appropriate abdominal relaxation for pneumoperitoneum (CO_2 insufflation of the abdomen). We will perform a typical induction using propofol (2 mg/kg) and rocuronium (0.6 mg/kg) and intubate him using a Macintosh 3 blade and a 7.5-mm cuffed endotracheal tube. We will confirm tube placement by visualizing chest rise, "misting of the tube," checking for end-tidal (exhaled) CO_2, and listening for bilateral breath sounds.

Following preoxygenation, general anesthesia is induced with a variety of hypnotic and paralytic medications. Propofol is the most widely used induction agent today, with rapid and predictable loss of consciousness in about 20 s, amnesia, and depression of airway reflexes. Other agents include thiopental (a barbiturate), ketamine, which is reserved for those needing a sympathetic boost (e.g. trauma patients), and etomidate, which has minimal cardiac depressant properties and is typically reserved for patients with heart failure or shock. Paralytics come in two flavors: depolarizing and nondepolarizing – with succinylcholine being the only available example of the former. Succinylcholine produces the most rapid paralysis (45 s), but can be associated with hyperkalemia, malignant hyperthermia, and myalgias. The nondepolarizers are slower and longer acting, but are the most predominantly used agents (vecuronium, rocuronium, cisatracurium, and less frequently pancuronium), with each agent having its own unique advantages and disadvantages.

Intubation is performed following preoxygenation, loss of consciousness, and onset of paralysis using a rigid laryngoscope and a plastic endotracheal tube. The actual mechanics of intubation are much better taught on actual patients, and will not be discussed here. In brief, the more intubations you do, the better you get, and the tube will make it into either the right hole (trachea), or the wrong hole (esophagus). The key to success is rapidly determining which it is, and correcting a mistake quickly. A number of alternate airway techniques are available, including awake

fiberoptic techniques, laryngeal masks, indirect visualization devices such as the Glidescope & McGrath video laryngoscopes, and blind techniques such as the Light Wand (see airway chapter for further details).

Maintenance

Now that the intubation is over, we will attach any additional monitors and start the maintenance phase of Josh's anesthesia. We will use isoflurane (1.1% exhaled concentration), fentanyl (1–2 mcg/kg every 20 min as needed, titrated to heart rate and blood pressure), and rocuronium (5–10 mg every 30 min as determined by peripheral nerve monitoring). Given his risk factors for postoperative nausea and vomiting (PONV), we will give him a dose of dexamethasone (4 mg) at the start of the case and ondansetron (4 mg) at the end.

Maintenance of general anesthesia is usually achieved with inhalation of potent volatile agents such as sevoflurane, isoflurane, or desflurane (each with their unique potential advantages and disadvantages). Many anesthetic agents have a summative effective, which promotes the concept of balanced anesthesia - giving drugs from multiple classes decreases the total dose of any one agent required, thereby reducing the chance of side effects. Therefore, in addition to volatile agents, we frequently add nitrous oxide, opioids, IV hypnotics, and paralytics to the mix. If desired, inhaled anesthetics can be avoided completely using a total IV anesthetic (TIVA) technique which is technically more difficult to perform, but can be used to great advantage in certain patients (e.g. patients with risk of malignant hyperthermia) or severe PONV.

Emergence

The case is nearing its end, and it is time to start thinking about emergence. Josh has had an uneventful procedure, is breathing on his own with excellent spontaneous minute ventilation and oxy-

genation, and is hemodynamically stable. He received neostigmine and glycopyrrolate to fully reverse his paralysis, and incremental doses of morphine are titrated to respiratory rate (the goal is the rate in the 10–20 breath per minute range) to achieve a smooth, pain-free wake-up.

There are several well-established extubation criteria: a patient must be hemodynamically stable, be oxygenating and ventilating well, be relatively normothermic, and have return of neuromuscular function. Most importantly, the patient must be able to protect his/her own airway… you've probably seen anesthesiologists asking patients to "open your eyes!" at the end of the case…no, there's no oculo-airway reflex, but we assume that once a patient is awake enough to follow simple commands, that patient is also awake enough to protect his/her airway.

Volatile agents are rapidly exhaled once inspired vapor is turned off, and most intravenous agents have a short enough half-life to ensure rapid awakening. Paralytics usually are actively reversed with cholinesterase inhibitors (increasing acetylcholine available to compete with the paralytics) in tandem with antimuscarinics to counteract unwanted side effects, or sugammadex, a cyclodextrin that selectively reverses rocuronium and vecuronium. Again, antiemetics are frequently given at this point, as are pain medications.

Post Anesthesia Care Unit (PACU) Management

Josh has done well, but upon arrival to the PACU, he begins to complain of pain and nausea despite your best intraoperative efforts. You prescribe doses of promethazine (for nausea) and hydromorphone (for pain), and he ends up meeting discharge criteria in 30 min… another successful anesthetic!

Anesthetic management does not end as soon as the tube comes out! The recovery period can be marked with challenges big and small, and as always, being properly prepared and expecting the unexpected can improve patient safety and satisfaction. Pain, nausea, and shivering are probably the most common complaints (in that order), but other frequently encountered problems include delirium, airway obstruction, bronchospasm, hyperten-

sion, hypotension, tachycardia, postsurgical bleeding, and oliguria. Furthermore, some patients cannot be extubated in the OR, and PACU care, therefore, can include many aspects of intraoperative and Intensive Care Unit (ICU) care.

Chapter Summary

Enjoy your time during your anesthesia rotation! Make sure to come to the clerkship with a good attitude, adaptability, your own goals and objectives in mind. You will likely enjoy doing procedures, but do not worry if you miss some – these skills all take practice, and even an unsuccessful attempt is useful in the learning process. Take the opportunity to also pick the brains of those that you are working with to optimize your time. If you find that anesthesia is not the specialty for you, just direct your efforts to those aspects of anesthesia that most overlap with your career choice and pique your interest: obstetric, pediatric, cardiac anesthesia, regional, pain, etc. Anesthesiologists are experts in physiology, pharmacology, clinical monitoring, and, above all, safety; they have to establish patient rapport rapidly, allay fear, and educate their diverse patients. To make the most of your time on your anesthesia rotation(s), remember to read ahead, ask plenty of questions, and have fun!

Case Study

You are preparing to provide general anesthesia for a 40-year-old woman undergoing an abdominal hysterectomy. She is otherwise healthy. She had two uncomplicated vaginal deliveries in the past, both with uncomplicated epidural labor analgesia. She had uneventful general anesthesia for a laparoscopic tubal ligation 4 years ago. Your attending is willing to let you perform as much of the anesthetic as you are able to describe in detail.

You go into the OR first thing in the morning to prepare the room for your case.

You will do safety checks on the anesthesia machine and make sure your oxygen tank is full. You will draw up all the medications and prime your IV infusions (if any) that you will need for the case. You will set out and organize your airway equipment (planned and emergency backup). You will ensure your monitors are set up and ready to go.

Upon meeting the patient in the pre-op area and reviewing the history and physical, you find no important new information. What steps will you take to prepare the patient for surgery prior to any interventions?

You will greet the patient and her family and answer any questions they may have about the procedure and planned anesthetic. You should review the remainder of the chart, paying special attention to any laboratory studies that may have returned since her pre-op clinic visit, including the hemoglobin and whether she has a sample in the blood bank. You will verify that surgical and anesthetic consent forms have been signed before giving her any preoperative medications. You will check the admission vital signs.

You have engaged the patient and checked all the paperwork and you are ready to begin preparing the patient for surgery. What are the next steps?

You will start an IV, probably a single 18 or 20 G cannula. Some anesthesiologists use a skin wheal of 1% lidocaine at the entry site before placing the IV. You will begin an infusion of IV fluid, typically lactated Ringer's solution. If the patient is anxious, you may consider anxiolysis or light sedation prior to surgery. Not all patients require this and asking the patient whether she would like it or not can help you decide. If desired, midazolam, 1–2 mg with or without fentanyl, 50–100 μg, is a reasonable choice. It is prudent to place a pulse oximeter and to consider supplemental oxygen by mask or nasal cannula, especially if you are leaving the bedside.

You have brought the patient into the OR. Describe the steps you will take prior to induction of anesthesia.

You will help the patient move over to the operating table and position the patient comfortably, making certain her gown is not tied at the neck or in back, and that all pressure points are well-padded. You will apply standard monitors (discussed in Chap. 11), including 3- or 5-lead EKG, pulse oximeter, and noninvasive blood pressure cuff, and verify that all are working properly with a baseline reading. You will then preoxygenate the patient (more precisely, "denitrogenate") by having her breathe 100% oxygen by facemask for several minutes to replace the room air in her lungs (and more specifically functional residual capacity or FRC) with oxygen. With your attending present and the rest of the surgical team (surgeon, circulating nurse, scrub nurse or technician) ready, you can induce anesthesia.

How will you induce anesthesia?

Intravenous induction is most common in adults. A short acting hypnotic, typically propofol, is given to induce unconsciousness. Next, you will ensure that you can ventilate the patient by mask by giving a few breaths and observing chest movement, exhaled carbon dioxide, and noting a reasonable tidal volume on the ventilation monitor. A neuromuscular blocking drug is then given to facilitate endotracheal intubation. Succinylcholine is rapid-acting and reliable, though some anesthesiologists prefer the nondepolarizing type (rocuronium or vecuronium), which can take slightly longer to reach peak effect but may have fewer side effects. After about a minute (succinylcholine) or 2–3 min (nondepolarizers), you will intubate the trachea. A laryngoscope is inserted, carefully avoiding trauma to the lips, tongue, and teeth. The vocal cords are visualized and a cuffed endotracheal tube, usually 7.0 or 7.5 mm internal diameter is inserted until the cuff is below the cords. The cuff is inflated, the tube is connected to the anesthesia machine circuit, and positive pressure breaths are given by hand. You will look for adequate chest rise, misting in the tube, and end-tidal CO_2. Auscultation of bilateral breath

sounds verifies appropriate depth of the tube, which is then secured with tape. The patient can then be ventilated mechanically by activating the ventilator on the anesthesia machine.

Following induction, what else will you do prior to the beginning of the surgical procedure?

You will tape the patient's eyes closed to prevent corneal injury. You will reposition the patient for surgery, if necessary, and check pressure points again. You may add additional monitors (peripheral nerve stimulator to monitor neuromuscular blockade, esophageal temperature probe, processed EEG or consciousness monitor [e.g., BIS]). Often, you will employ a convective air-warming device to help maintain normothermia. Prophylactic antibiotics are best given less than 60 min before incision, so you will start these now if you have not given already. In some operations, a nasogastric or orogastric tube may be useful (but probably not in this case). In others, you might want a second IV or arterial line, a fluid warmer, or a blood administration set. Since you do not expect large fluid shifts or blood loss, you will forego these for now. You will participate in a "safety pause," "time-out," or a more extensive "surgical safety checklist" with the other members of the OR team. You will also begin your maintenance anesthetics.

How will you maintain anesthesia?

There are numerous ways to maintain a general anesthetic, which will be discussed in future chapters. A common one is the "balanced technique" which combines a volatile anesthetic with or without nitrous oxide, an opioid, and a nondepolarizing neuromuscular blocking drug. A reasonable combination would be sevoflurane, fentanyl, and vecuronium. Sevoflurane is rapidly eliminated after discontinuation, so nitrous oxide is not necessary to reduce the amount of sevoflurane given as it might be for a more slowly eliminated drug like isoflurane (see Chap. 5).

What other adjunctive drugs might you give in addition to anesthetics?

A healthy young woman such as our patient is at reasonably high-risk of postoperative nausea and vomiting (PONV). Prophylactic antiemetics are often given, and a reasonable combination would be dexamethasone and ondansetron. You may be asked to give other drugs to facilitate the operation, for example, methylene blue to check for integrity of the urinary bladder. You will also consider longer-acting opioids (for example, morphine or hydromorphone) before the end of the procedure to provide longer-lasting analgesia in the postoperative period.

The operation has gone well and is ending. How will you conclude the anesthetic?

As the surgical stimulation lessens during closure, you will lighten the anesthetic. After the fascia is closed, you can reverse neuromuscular blockade with sugammadex or a cholinesterase inhibitor (e.g., neostigmine) and an antimuscarinic (e.g., glycopyrrolate). You can prepare for emergence by suctioning the patient's mouth, untaping the eyes, and turning off the volatile agent and increasing fresh gas flow of oxygen to help wash out residual anesthetic in the circuit. If the room is cool, you will increase the temperature; if the patient's gown is soiled, it may be changed. Once the surgical instrument and sponge counts are completed, the wound is closed, and the dressing is in place, you can wake up the patient. You will watch for return of spontaneous respiration, switching off the ventilator and allowing the patient to breathe on her own when she is ready. You will ask the patient to open her eyes and to follow a simple command (e.g. "Squeeze my fingers"). Once you are satisfied that she is awake, breathing adequately, and strong enough to protect her airway, you will extubate her by deflating the cuff and removing the endotracheal tube. You will observe spontaneous respiration via a mask for a few moments, and then place a simple oxygen mask or nasal cannula. After

disconnecting the monitors and moving the patient along with their IV lines, urinary catheter, and any other attached items to a stretcher, you are ready for transport to the post anesthesia care unit (PACU; "recovery room.")

What will you do on arrival to the PACU?

Depending on the local procedures at your hospital, you may assist the PACU nurses in getting the patient "settled" by reestablishing hemodynamic monitoring, verifying adequate pain control and absence of nausea, and checking for stable vital signs. You will give a brief report of the procedure and your anesthetic course, fluid totals, analgesics and antiemetics to the PACU nurse. You will ensure that orders are present for maintaining analgesia, and rescue orders for breakthrough pain or nausea.

Congratulations on completing your first anesthetic!

Acknowledgements The authors would like to thank Dr. Jesse Ehrenfeld and Dr. Roy Soto for their contribution to the development of this chapter.

Recommended Anesthesiology Educational Resources

1. Society for Education in Anesthesia (SEA). https://www.seahq.org/page/Student
2. Anesthesia and Critical Care Reviews And Commentary (ACCRAC) podcast, which is available on almost any podcast platform or at http://accrac.com/
3. Open Anesthesia. https://www.openanesthesia.org/
4. Stanford CA1 Tutorial. http://ether.stanford.edu/ca1_new/
5. Medical Student Anesthesia Primer. http://www.anesthesia-education.com/primer.doc

Support and Resources for Those Experiencing Depression, Substance Abuse, or Thoughts of Suicide

1. National Suicide Prevention Lifeline. Call 988 or visit https://988lifeline.org/about/

2. Substance Abuse and Mental Health Service Administration. Call 1-800-662-4357 or visit https://www.samhsa.gov/find-help/national-helpline
3. American College of Physicians: Resource on Physician Suicide and Depression. https://www.acponline.org/practice-resources/physician-well-being-and-professional-fulfillment/physician-suicide-and-depression-resources
4. Compilation of podcasts and videos by the Council of Residency Directors in Emergency Medicine. https://www.cordem.org/resources/professional-development/wellness%2D%2Dresilience%2D%2D-resources-page2/NPSA/podcasts%2D%2Dvideos/

Suggested Educational Resources

1. Accreditation Council for Graduate Medical Education (2020) Anesthesiology subspecialties. https://www.acgme.org/Specialties/Overview/pfcatid/6/Anesthesiology. Accessed 27 Aug 2020
2. Ainsworth MA, Szauter KM (2006) Medical student professionalism: are we measuring the right behaviors? A comparison of professional lapses by students and physicians. Acad Med 81:S83–S86
3. Alexander BH, Checkoway H, Nagahama SI, Domino KB (2000) Cause-specific mortality risks of anesthesiologists. J Am Soc Anesthesiol 93:922–930
4. Almojali AI et al (2017) The prevalence and association of stress with sleep quality among medical students. J Epidemiol Glob Health 7:169–174
5. American Board of Anesthesiology (2020) Alternate entry path. https://theaba.org/alternate%20entry%20pathway.html. Accessed 27 Aug 2020
6. Curry SE (2018) Teaching medical students clinical anesthesia. Anesth Analg 126:1688–1690
7. Curry SE (2018) ASA guide to anesthesiology for medical students – Chapter 3: choosing a career in anesthesiology, pp 7–8. https://www.asahq.org/education-and-career/asa-medical-student-component/guide-to-a-career-in-anesthesiology. Accessed 27 Aug 2020
8. Dalgaty F, Guthrie G, Walker H, Stirling K (2017) The value of mentorship in medical education. Clin Teach 14:124–128
9. Flexman AM, Gelb AW (2011) Mentorship in anesthesia. Curr Opin Anaesthesiol 24:676–681
10. Harter RL (2018) ASA guide to anesthesiology for medical students – Chapter 4: practicing in the Anesthesia Care Team (ACT), pp 7–8. https://

www.asahq.org/education-and-career/asa-medical-student-component/guide-to-a-career-in-anesthesiology. Accessed 27 Aug 2020
11. Hegde SV et al (2018) Knowledge, attitude, and practice of yoga in medical students: assessment of anthropometry and lifestyle factors. Int J Yoga Ther 28:9–14
12. Mata DA et al (2015) Prevalence of depression and depressive symptoms among resident physicians: a systematic review and meta-analysis. JAMA 314:2373–2383
13. Papadakis MA, Hodgson CS, Teherani A, Kohatsu ND (2004) Unprofessional behavior in medical school is associated with subsequent disciplinary action by state medical board. J Med Regul 79:244
14. Prielipp RC, Cohen NH (2016) The future of anesthesiology: implications of the changing healthcare environment. Curr Opin Anaesthesiol 29:198–205
15. Reamy BV, Harman JH (2006) Residents in trouble: an in-depth assessment of the 25-year experience of a single family medicine residency. Fam Med-Kansas City 38:252–257
16. Rose GL, Brown RE Jr (2010) The impaired anesthesiologist: not just about drugs and alcohol anymore. J Clin Anesth 22:379–384
17. Rotenstein LS et al (2016) Prevalence of depression, depressive symptoms, and suicidal ideation among medical students. JAMA 316:2214–2236
18. Schwenk TL (2016) Resident depression: the tip of a graduate medical education iceberg. JAMA 314:2357–2358
19. Stewart SM, Lam TH, Betson CL, Wong CM, Wong AMP (1999) A prospective analysis of stress and academic performance in the first two years of medical school. Med Educ 33:24–250
20. Tetzlaff JE (2009) Professionalism in anesthesiology: "What is it" or "I'll know it when I see it". J Am Soc Anesthesiol 110:700–702

History of Anesthesia and Introduction to the Specialty

2

Raymond C. Roy

Introduction

Let us go then, you and I,
When the evening is spread out against the sky
Like a patient etherized upon a table;

Although the above quotation is actually a 1915 invitation by the poet T. S. Eliot ("The Love Song of J. Alfred Prufrock") to join him on the dark introspective journey, I want you to consider it an twenty-first century invitation to explore the now much brighter world of anesthesiology as a specialty of medicine. Part of the joy of an anesthesia rotation is acquiring practical clinical skills, such as airway assessment, laryngoscopy and endotracheal intubation, venous and arterial cannulation, spinal and epidural needle placement, and peripheral nerve blocks. Acquisition of these skills, plus a bit of knowledge related to the pharmacology of anesthetic agents, set you up to be a good technician. But it is a mistake to think that being facile at performance of these tasks is all that it takes to be a good anesthesiologist. The need

R. C. Roy (✉)
Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA
e-mail: rroy@wakehealth.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_2

to adapt anesthetic administration to different kinds of surgery and patients with varying comorbidities, to understand the variable responses to specific drugs and drug dosing, and to avoid need-to-rescue events make anesthesiology an intellectually challenging subspecialty of medicine. Another complexity is the number of patients anesthesiologists manage at any given time. They may seem to be responsible for only one patient when they actually administer anesthesia. But for each operating room (OR) anesthesiologists are responsible for three patients simultaneously: a patient in the holding room who requires assessment for adequacy of preparation for anesthesia and surgery; the patient in the operating room; and a patient in the recovery room (post anesthesia care unit or PACU). If they are directing anesthesia in four different ORs, they are responsible for as many as 12 patients at the same time.

One way to assess the current breadth and depth of anesthesiology is to look at the areas where there are Executive Section Editors listed in the international journal *Anesthesia & Analgesia* – Regional Anesthesia (includes ultrasound for needle placement and drug injection), Pain and Analgesic Mechanisms (basic and translational research), Acute Pain Management, Chronic Pain Management, Global Health, Healthcare Economics (includes OR management), Neuroscience and Neuroanesthesia (Includes electroencephalography), Cardiovascular Physiology and Outcomes, Cardiovascular and Thoracic Anesthesia (includes transthoracic and transesophageal echocardiography and extracorporeal membrane oxygenation), Critical Care and Resuscitation (includes central venous and pulmonary artery catheterization), Respiration and Sleep Medicine, Ambulatory Anesthesia, Pediatric Anesthesia, Obstetrical Anesthesia, Geriatric Anesthesia, Trauma, Airway Management, Anesthesia Mechanisms (basic and translational research), Transfusion, Hemostasis and Thrombosis, Perioperative Medicine, Simulation and Computing, Anesthesia Pharmacology (drugs administered by anesthesia providers), Clinical Pharmacology (non-anesthetic drugs which patients are taking), and Patient Safety.

The First Anesthetic Agents

The first general anesthetic agent, ether (also referred to as diethyl ether or sulphuric ether), had its beginnings as a party drug during socially acceptable ether frolics that took place in the drawing rooms of early nineteenth century homes with men and women formally dressed for the event. During these events participants would occasionally fall and bruise themselves, but recover with localized pain but no recollection of the injury. The first person to receive an ether anesthetic for a surgical procedure was James Venable, a participant in an ether frolic in the home of Crawford W. Long, M.D., in Georgia. Because of this prior experience, Mr. Venable was amenable to inhaling ether to have a tumor removed from his neck on March 30, 1842. Ether was poured onto the corner of a towel for inhalation. Because of religious and cultural perceptions that experiencing pain was actually a good thing during surgery and childbirth, Dr. Long may have worried about reporting his experience and delayed doing so until 1849. Or he might have read about the administration of ether in Boston four years later and wanted to receive the credit for being first. Or he was in private practice and not at a hospital which trained physicians and had a strong culture to publish. The popularly celebrated Doctor's Day in the United States occurs every March 30th, the anniversary of the first ether anesthetic.

The first successful public demonstration of ether anesthesia for surgery took place in Boston in the surgical amphitheater of Massachusetts General Hospital on October 16, 1846 (Fig. 2.1). William Thomas Green Morton, a dentist, administered ether using a vaporizer-inhaler, essentially a glass flask containing a sponge soaked in liquid ether. The flask had two openings, one from which the patient, a 20-year-old named Edward Gilbert Abbott, inhaled room air with ether vapor from the flask and the other into which air was entrained into the flask. Once the patient was asleep, the flask was removed and the surgeon, John Collins Warren, M.D., professor of surgery at Harvard Medical School, excised a congenital vascular malformation from Mr. Abbott's neck. During the initial part of the surgery, the patient did not

Fig. 2.1 "Ether day, 1846" in the "Ether Dome". Pictured are Gilbert Abbott (the patient), John Collins Warren, M.D. (the surgeon), William T. G. Morton (the anesthetist) and Henry J. Bigelow, M.D. (the junior surgeon). Note the absence of absence of operating room attire, the presence of spectators, and the sitting position of the patient. (Painting by Warren and Lucia Prosperi. Photograph by Andrew Ryan. Reproduced with permission from Massachusetts General Hospital, Archives and Special Collections)

move, and this impressed Dr. Warren and one of the observers Henry Jacob Bigelow, M.D. Because the patient was not given additional ether to inhale during the surgery, he "began to move his limbs, cry out, and utter extraordinary expressions" at the end of the surgery. This concerned Dr. Warren, but he was relieved when the patient stated he felt no pain, just a scraping sensation.

Because surgeons at that time preferred natural lighting, the operating arena where this event took place was situated on the top floor with strategically placed windows to maximize the sunlight. Elective surgeries were scheduled mid-day also to take advantage of the best sunlight. The "Ether Dome", as this arena is now called, served as a functioning site for over 8000 surgeries from 1821 until 1867. But this means that for the first 25 years the

patients received no anesthesia for hernia repairs, amputations, cutaneous excisions, etc. Typically the patient would be held down by several attendants and the surgeon with an assistant would operate as quickly as possible while the patient writhed and screamed. There were no local anesthetic agents and there were no hollow needles through which to inject them. From October 16, 1846 to April 1, 1848, 154 operations under anesthesia were performed at MGH, 146 under ether and 8 under chloroform anesthesia. However, it was not Dr. Warren, but his successor as professor of surgery, Dr. Bigelow, who studied and published his clinical experience with general anesthesia and was the force behind its adoption.

Urban legend has it that Dr. Warren was so impressed by the initial lack of response to incision that he said, *"Gentlemen! This is no humbug."* It is unlikely that Dr. Warren actually said this. The now iconic statement was probably artistic license on the part of Morton's biographer Nathan P. Rice, M.D., to differentiate Morton's successful administration of ether as a general anesthetic from an unsuccessful attempt to induce general anesthesia for a dental extraction with nitrous oxide by Horace Wells in January 1845. When Well's patient groaned at the start of the procedure, the observers felt the patient was not anesthetized and cried out "humbug," a very popular word for hoax in the mid-1800s. Recall that Scrooge said "Bah! Humbug!" in *A Christmas Carol* by Charles Dickens published in 1843. Unappreciated by the observers was the fact while Well's patient did cry out, he felt no pain and had no recall when his tooth was extracted.

Horace Wells had previously administered nitrous oxide successfully on multiple occasions as an analgesic for painless dental extractions. Like ether, nitrous oxide also started out as an entertainment drug when traveling showmen would charge admission for public administrations. Because inhalation would produce giggling, euphoria, dizziness, and silly or uninhibited behavior in the participants, it acquired the nickname "laughing gas." During one of these demonstrations witnessed by Wells, participants fell but did not complain of pain. Interestingly Sir Humphrey Davy made a similar observation in animals and wrote in an 1800 publication "as nitrous oxide … appears capable of destroying physical pain,

it may probably be used to advantage during surgical operations." But his observation was never followed up by those who read his article. Nitrous oxide is less potent than ether. It has a faster onset time to peak effect, but also has a faster recovery time. It must be administered continuously in high (hypoxic) concentrations if it is to serve as the sole agent for general anesthesia. Today it is used as an inhaled analgesic at lower concentrations in dentistry and other procedures or it is combined with more potent inhaled agents, such as isoflurane or sevoflurane, to reduce the amount of these agents necessary to maintain anesthesia.

A third anesthetic gas, chloroform, introduced in 1847 by Dr. James Young Simpson, a Scottish obstetrician, deserves mention. It was more pleasant to inhale than ether, more potent and non-flammable. The first anesthetic death, which occurred on January 28, 1848, was associated with the administration of chloroform. Hannah Greener, a healthy 15-year-old girl who previously had undergone an uneventful ether anesthetic for removal of a toenail, died during administration of chloroform for a second toenail extraction. The cause of death was hotly debated. Was it a cardiac arrest triggered by the chloroform administration, or aspiration, or poor resuscitation technique? Dr. John Y. Snow, an early iconic figure in the history of anesthesia and the father of Epidemiology (remember the London cholera epidemic of 1854 and the Broad Street pump), felt the problem was that chloroform administered at high concentrations too quickly triggered cardiac arrhythmias and cardiac arrest. He became a strong advocate of more controlled administration of chloroform, and for that matter all anesthetic agents, with calibrated vaporizers rather than open drop onto a cloth. Snow and Queen Victoria helped popularize analgesia for childbirth when Snow administered chloroform to her when she gave birth to the last two of her nine children in 1853 and 1857. Interestingly during the American Civil War, chloroform was the predominant agent in the South and ether in the North. Chloroform remained a popular anesthetic agent for its first 50 years but eventually fell out of favor primarily because it triggered too many adverse cardiac events. Ether persisted for another 50 years.

When general anesthesia is administered by ether or chloroform, the patient has to breathe spontaneously, because respiratory frequency and volume were signs of the depth of anesthesia and because there were no endotracheal tubes and mechanical ventilators to control ventilation. The anesthetist had only three choices with regard to administering anesthesia – increase the concentration of the inhaled agent, keep the concentration the same, or reduce/withdraw the agent. During the induction of general anesthesia with ether it was not unusual for the patient to experience an "excitement phase", the intensity of which depended in part on the skill of the anesthetist, before a surgical plane was established. The patient did not remember the excitement phase but still required attendants to hold him still.

Intravenous anesthesia initially emerged as a way to administer anesthesia for cranial and head and neck surgery. Prior to the intravenous approach, ether or chloroform was administered after performing a tracheostomy, first reported in 1871 by Dr. Friedrich Trendelenburg, or after inserting a flexible brass oro-tracheal tube, first reported in 1878 by Dr. William MacEwan. Intravenous anesthesia required a hollow needle and syringe. Dr. Alexander Wood gets the credit for this invention (1853) and Dr. Charles Hunter for the term "hypodermic". Both used their needles and syringes to inject morphine "under the skin". Wood felt that the morphine had to be injected in the region where the pain was, i.e., a local effect, while Hunter discovered it could be injected anywhere, i.e., a systemic effect. In the early 1900s, intravenous cannulation was considered a surgical procedure called a cutdown. The first widely successful intravenous agent was actually ether dissolved in normal saline. The first intravenous injection of dissolved non-gaseous anesthetic agents, barbiturates, occurred in the 1930s. Pentothal (brand name for sodium thiopental) was commonly used to induce, or initiate, an intubating and surgical plane of anesthesia, and inhaled agents, or continuous infusion of intravenous agents, were used to maintain the depth required for surgery. Because of its association with lethal injections for capital punishment, Pentothal is no longer used in the United States, Canada, or Europe.

What Is Anesthesia?

I have applied two terms to the state of consciousness that Wells and Morton were trying to induce – general anesthesia and sleep. But general anesthesia is not equivalent to sleep. You will awaken from a sound sleep with any surgical incision. "Going to sleep" is commonly (mis)used by both laymen and anesthesia providers talking to patients. General anesthesia was not a term in common usage in 1846. Most reports used insensibility or etherization instead. Although the word anesthesia appears in the Hippocratic Collection (460-380 BCE), it referred to a disease state in which there is a neurologic loss of sensation. Oliver Wendell Holmes, Sr., M.D., suggested its use to describe the effects of ether in a letter to Morton dated November 21, 1846. Morton initially seemed to ignore this suggestion but then Holmes' letter was subsequently published by Edward Warren, a publicity agent for Morton, in a pamphlet marketing ether as Letheon in late May or early June 1847. A second big push for its use came when term anesthesia was used by the Scottish obstetrician James Young Simpson, M.D., when he published reports on the use of ether and chloroform for labor and delivery in November/December 1847.

The modern definition of anesthesia has expanded to include local anesthesia and field blocks, regional anesthesia associated with nerve blocks, neuraxial anesthesia using spinal and epidural needles/catheters to administer local anesthetics, intravenous sedation and analgesia (what anesthesia providers refer to as Monitored Anesthesia Care), and general anesthesia. The modern definition of general anesthesia requires six criteria to be satisfied: (1) loss of consciousness; (2) loss of recall (amnesia); (3) immobility (neuromuscular blockade or muscle relaxation); (4) hemodynamic and respiratory stability; (5) analgesia (preventing movement in response to nociceptive stimuli); and (6) reversibility. The mechanism and sites of action by which a single inhaled gas produces general anesthesia are still not well-established. We can now administer intravenous drugs that act at well-established receptor sites specific to each one of the six

criteria. For example, it is common for an anesthetist to administer intravenously propofol to produce loss of consciousness, midazolam to provide amnesia, rocuronium to provide neuromuscular blockade, ephedrine to raise the blood pressure, fentanyl to provide analgesia, and neostigmine or sugammadex to reverse the neuromuscular blockade.

Who Administers Anesthesia?

The person who actually administers an anesthetic is referred to as an anesthetist. In modern medicine the anesthetist may be an anesthesiologist, a certified registered nurse anesthetist (CRNA), or an anesthesia assistant (AA), who is a physician assistant specializing in anesthesia. An anesthesiologist is a physician who may either administer anesthesia personally or may direct or supervise its administration by a CRNA or AA. Currently most anesthesiologists serve as the head of anesthesia care teams that include CRNAs or AAs rather than directly administer sedation or general anesthesia to a patient. However, guidelines of care for safety and reimbursement require the anesthesiologist to be physically present for the most dangerous times of an anesthetic – induction and intubation and extubation and recovery – and immediately available to address need-to-rescue events.

Modern Anesthesia Machinery

Today's anesthesiologist uses an anesthesia work station that contains a delivery system for gases, including oxygen, air, nitrous oxide, and sometimes helium; two or three calibrated vaporizers to deliver potent inhaled agents; anesthesia monitors, including an electrocardiograph, an automated blood pressure device, pulse oximetry, oxygen gas detectors in breathing circuits, a capnograph, anesthesia gas analyzers, and thermometers; a ventilator to control ventilation with monitors of ventilatory parameters and circuit disconnects; and an anesthesia information system that collects and

records vital signs, generates an anesthesia record, and via telemetry, sends this information to other observation sites. It contains many alerts and alarms to warn the anesthetist of hypoxia, hypertension, bradycardia, tachycardia, disconnects in the breathing circuit, hypercarbia and high inspiratory pressure. Laryngoscopy and endotracheal intubation in patients with complicated airways are facilitated by imaging with video laryngoscopes and fiberoptic bronchoscopes. Ultrasound is used to facilitate insertion of central venous and pulmonary artery catheters via the internal jugular vein and to locate precisely the site for injection of local anesthetic agents to block a peripheral nerve. Monitors of neuromuscular blockade guide dosing of muscle relaxants.

Conclusion

I have been an academic anesthesiologist for more than forty years. Every day was intellectually stimulating and emotionally satisfying but sometimes very challenging. Not every anesthetic went as envisioned the night before. I have seen the introduction of many new drugs and many new instruments and devices that have eased the administration of anesthesia, increased patient safety, and provided information for clinical studies and quality improvement. Anesthesia is safer now than it was at the beginning of my career. I do not want a return to the "good old days". They were good only because of the camaraderie and excitement of a medical specialty on the move. I believe you will find it is still on the move.

Case Study

The time is now and you are observing the administration of anesthesia to patient with a non-toxic goiter who undergoing a thyroidectomy. An intravenous line is in place, anesthetic agents have been administered, and the surgeon is operating. Now stop and pretend you are observing the

same operation in 1909, the year Dr. Emil Theodor Kocher received the Nobel Prize for Medicine in part for developing a safe technique for surgical excision of the thyroid gland.

What attire would the anesthetist wear in the operating room?

It is unlikely the anesthetist would be wearing mask or gloves and around a fifty percent chance that he or she would be wearing street clothes.

How much anesthesia training would the anesthetist have had?

Very likely, the most junior person on the surgical team would administer the anesthesia. It might even be his first anesthetic. In some situations, it could have been a nurse. In spite of the fact that anesthesia was consider so simple to administer in those years that the most junior person was assigned to handle the task, anesthesia was critical to allow a surgeon to take his time to dissect, control bleeding, and perform complex surgery. Without the invention of anesthesia, the development of a safe thyroid surgical technique could not have occurred and Dr. Kocher would not have earned his Nobel Prize. No early anesthetist received the Nobel Prize for the invention of anesthesia in part because its discovery occurred well before Nobel Prizes were first awarded in 1901.

Would an intravenous cannula be present?

The patient is unlikely to have an intravenous infusion. If he did, it would have been a cut down performed by the surgeon. There were no intravenous anesthetic agents, antibiotics, or blood available to give.

Which anesthetic agents would be used? How will the airway be managed? Would oxygen be administered?

Prior to the surgery the patient may have received an injection of morphine and scopolamine via a hypodermic needle and syringe. It is also possible that the surgeon may have considered providing local anesthesia for surgery by

injecting procaine, first synthesized in 1905 by Alfred Einhorn and the only local anesthetic available until the 1940s. More likely the patient would receive general anesthesia with either open drop ether or chloroform. Open drop means that ether or chloroform was poured onto gauze in a wire mesh mask (Fig. 2.2), which would then be placed over the patient's mouth and nose. Anesthesia would be induced with the patient breathing room air spontaneously through the anesthesia-saturated gauze mask. No oxygen would be administered. Throughout the surgery an important job for the anesthetist was to maintain a patent airway. To do so, he may have had to perform a continuous jaw thrust maneuver. Laryngoscopes and endotracheal tubes would not be commonly used for another three decades.

How will the patient be monitored?

The anesthetist would palpate a pulse and the strength of that pulse would be the primary indication of an adequate blood pressure. Although systolic blood pressure measurement was possible in the late 1800s, adaptations to sphygmomanometers making possible their routine use in the operating room did not occur until after World War I. Oxygenation would be assessed by looking at the color of arterial blood in the surgical field. Ventilation would be assessed by observing evidence of diaphragmatic movement in the chest or abdomen, listening for upper airway sounds of partial obstruction, or feeling air movement through the mask. There would be no electrocardiogram. Dr. Willem Einthoven would receive his Nobel Prize for discovery of the mechanism of the electrocardiogram in 1924.

Will there be an anesthetic record?

By 1909 a record of the pulse rate and respiratory rate would be made and subjective observations related to changes in the patient's condition during the surgery would be handwritten.

Fig. 2.2 Ether mask and bottles. (Photo J. Ehrenfeld, M.D.)

Suggested Further Reading

1. Adams LW, Aschenbrenner CA, Houle TT, Roy RC (2016) Uncovering the history of operating room attire through photographs. Anesthesiology 124(1):19–24
2. Buslov A, Carroll M, Desai MS (2018) Frozen in time: a history of the synthesis of nitrous oxide and how the process remained unchanged for over 2 centuries. Anesth Analg 127(1):65–70
3. Hansson N, Fangerau H, Tuffs A, Polianski IJ (2016) No silver medal for Nobel Prize contenders. Why anesthesia pioneers were nominated for but denied the award. Anesthesiology 25(1):34–38
4. Haridas RP (2016) "Gentlemen! This is no humbug" Did John Collins Warren, M.D., proclaim these words on October 16, 1846, at Massachusetts General Hospital, Boston? Anesthesiology 124(3):553–560
5. Hendrickx JFA, De Wolf AM (2018) The anesthesia workstation: quo vadis? Anesth Analg 127(3):671–675

6. Knight PR III, Bacon DR (2002) An unexplained death: Hannah Greener and chloroform. Anesthesiology 96(5):1250–1253
7. Lugli AK, Yost CS, Kindler CH (2009) Anaesthetic mechanisms: update on the challenge of unravelling the mystery of anaesthesia. Eur J Anaesthesiol 26(10):807–820
8. Roberts M, Jagdish S (2016) A history of intravenous anesthesia in war (1656–1988). J Anesth Hist 2(1):13–21
9. Shephard DAE (2009) Why was there a four-decade delay before anesthesia was introduced in 1846? Bull Anesth Hist 27(2):33–38
10. Simpao AF, Rehman MA (2018) Anesthesia information management systems. Anesth Analg 127(1):90–94

Part II

Pharmacology

Pharmacology Principles

3

John W. Wolfe and Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xviii are reviewed before reading this chapter.

Key Learning Objectives

- Understand the basic principles of pharmacokinetics such as drug absorption, distribution, metabolism, and excretion.
- Learn the basic principles of pharmacodynamics such as drug potency, efficacy, and therapeutic index.
- Discuss the concept of context-sensitive half-time.

J. W. Wolfe (✉)
Indiana University School of Medicine, Indianapolis, IN, USA
e-mail: jwolfe@iupui.edu

J. M. Ehrenfeld
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_3

Basic Pharmacologic Principles

An understanding of pharmacologic principles is important for effective anesthetic management. These principles are commonly divided into two groups:

1. ***Pharmacokinetics*** describes the fate of drugs once they have been administered to a patient. This process can generally be divided into three phases:
   (a) drug administration
   (b) drug distribution into the body
   (c) drug metabolism and excretion
2. ***Pharmacodynamics*** describes the actions that a drug has on the body. This mainly consists of drug actions in which cellular receptors are enhanced or antagonized and includes the relationship between drug concentration and effects.

Pharmacokinetics

Absorption

The first step in drug delivery is absorption of the drug into the systemic circulation. A drug's bioavailability is the fraction of the dose administered that reaches the plasma in an active form. Major factors affecting the bioavailability include:

- ***Route of administration***: Most anesthetic drugs are administered via intravenous or inhaled routes, providing rapid and reliable blood concentrations of drug and high bioavailability. Other routes for administration include intramuscular or subcutaneous injection, oral or rectal administration, transcutaneous absorption (i.e., a fentanyl patch), and transmucosal absorption (i.e., sublingual nitroglycerin, nasal midazolam).
- ***First pass metabolism***: Drugs administered via the gastrointestinal tract pass through the portal venous system prior to entry into the systemic circulation. As a result, drugs that are exten-

sively metabolized by the liver must be administered in larger doses via the oral route versus the IV route in order to achieve similar blood concentrations.

- ***Ionization***: The pH of the environment at the site of absorption (i.e., acidic conditions in the stomach) may affect the efficiency of drug absorption. In general, the nonionized fraction of a drug crosses the gastric mucosa more easily. Drugs that are weak acids, such as barbiturates, exist in a nonionized state at low pH and cross the gastric mucosa relatively easily. The opposite is true for drugs that are weak bases, such as opioids.

Distribution

Once the drug has entered the systemic circulation, it is distributed to various sites in the body, including the target organs. Factors affecting distribution include:

- ***Free fraction and protein binding*** : Many drugs exist in the plasma in an equilibrium of free drug and drug bound to various plasma proteins. In many cases, the drug is more than 90% protein-bound (midazolam, propofol, bupivacaine, etc.). The portion of the drug that is protein bound is therapeutically inactive, and the free, unbound fraction is active. In cases where plasma protein levels are decreased, the free fraction of the drug (and the therapeutic effect of a given dose) is increased. Some conditions, such as hepatic or renal disease, can decrease the affinity of plasma proteins for drugs, again increasing the free fraction of the drug.
- ***Volume of distribution (Vd)***: The volume of distribution is defined as the total dose of drug given divided by the plasma concentration of drug. Drugs which are highly hydrophilic or protein-bound and stay in the plasma have a V_d close to the plasma volume. Those that are highly lipid-soluble will redistribute from the plasma to adipose tissue, leading to a low plasma concentration and a high apparent volume of distribution.

- ***Redistribution***: This phenomenon describes a rapid fluctuation of drug concentration in highly perfused tissues that is most commonly seen with very lipid-soluble drugs (e.g., thiopental). It consists of the following stages:
  - After injection, the free fraction of the drug rapidly enters highly perfused tissues such as the brain and the heart, and more slowly enters into less perfused tissues such as adipose tissue.
  - As plasma drug levels drop because of continued entry of the drug into adipose tissue, the drug distributes back from the highly perfused tissues into the plasma. This typically terminates its therapeutic effect.
  - The drug then continues to distribute into adipose tissue, where it is stored.
- ***Storage***: If doses of highly lipid soluble drugs such as thiopental are given repeatedly, the storage sites in adipose tissue may become saturated. The termination of the drug's therapeutic effect then becomes dependent on metabolism and excretion, which are typically much slower than redistribution.

Metabolism and Excretion

Drug effects are terminated by metabolism and excretion. Factors affecting this process include:

- ***Mechanisms of metabolism***: Most anesthetic drug metabolism and excretion occurs at the liver, kidneys, and lungs. The major mechanisms can be summarized as below:
  - *Hepatic*: The liver eliminates drugs primarily by metabolizing them to inactive or less active compounds. The end products of hepatic metabolism are typically polar, water-soluble compounds that are suitable for renal excretion. Some drugs and drug metabolites are also excreted into the biliary system.

  - *Renal*: The kidneys primarily eliminate drugs by excretion of water-soluble drugs or drug metabolites into the urine. Some direct drug metabolism also occurs in the kidneys.
  - *Pulmonary*: The lungs are the primary site of elimination of inhalational anesthetics, which are absorbed from the plasma and exhaled.
- ***Zero-order pharmacokinetics***: A few drugs are eliminated via processes that obey zero-order kinetics, in which the drug is metabolized at a fixed rate, regardless of its concentration (see Fig. 3.1).
- ***First-order pharmacokinetics***: Most drugs are metabolized via processes that obey first-order kinetics, meaning that the rate of drug metabolism is proportional to the concentration of the drug (see Fig. 3.1). The rate of elimination is usually described in terms of the drug's half time, which is the time in which metabolism and excretion reduce the plasma concentra-

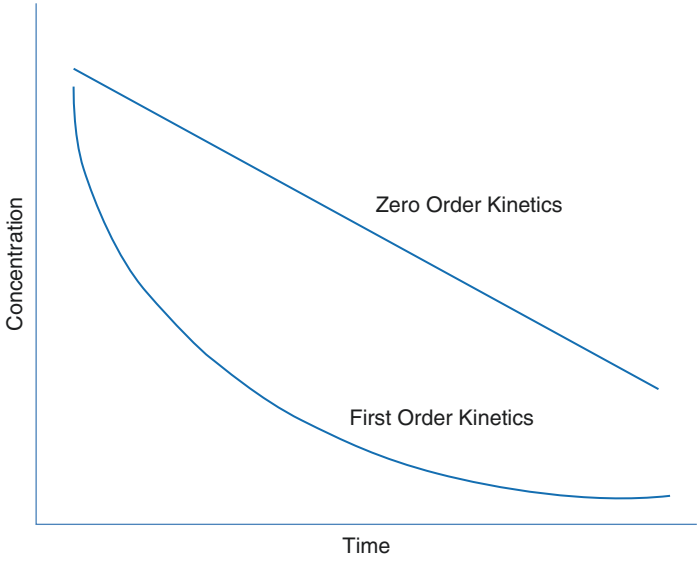


Fig. 3.1 Zero vs. first order kinetics. (Image Courtesy J. Ehrenfeld)

Table 3.1 Drug remaining at multiples of the half-time

Number of half-times	Percent of drug remaining	Percent of drug removed
0	100	0
1	50	50
2	25	75
3	12.5	87.5
4	6.2	93.8
5	3.1	96.9

tion of the drug to 50% of its starting value. As further time progresses, the process continues as detailed in Table 3.1. Note that after 5 half-times have passed, 96.9% of the drug has been eliminated, and for practical purposes, the drug has been fully eliminated.

- ***Clearance***: The clearance of a drug is defined as the theoretical volume of blood that is completely cleared of drug per unit time. It is analogous to the creatinine clearance rate of the kidneys. Different pathways of clearance for a drug (i.e., renal and hepatic) are additive, and a decrease in a major pathway of clearance will prolong the effect of drugs that use that pathway for elimination (e.g., administration of a drug that is mainly cleared by the kidneys to a patient with impaired renal function will result in a relatively long duration of action).
- ***Context-sensitive half-time***: As discussed above, some drugs are eliminated from the plasma by redistribution to adipose tissue. As the adipose tissue acquires more drug, the diffusion gradient from plasma to tissue decreases, and the rate of redistribution decreases. This leads to the phenomenon of context-sensitive half-times, in which the time to 50% reduction in drug concentration increases with increasing total doses of the drug or duration of infusion. Drugs that are highly redistributed but metabolized relatively slowly, such as thiopental, are affected more than drugs with rapid metabolism, such as propofol. The context sensitive half-times as a function of duration of drug infusion are shown for a few anesthetic drugs in Fig. 3.2.

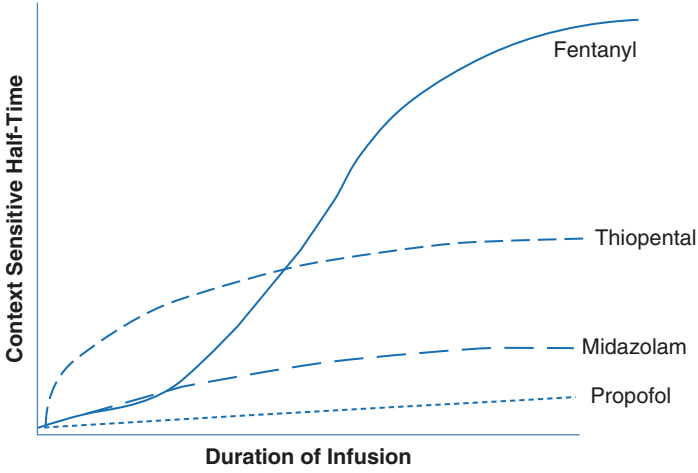


Fig. 3.2 Context sensitive half times as a function of duration of infusion. (Image Courtesy J. Ehrenfeld)

Pharmacodynamics

Factors relating to the actions that a drug has on the body include:

- ***Potency***: A drug's potency refers to the dose of the drug required to achieve a therapeutic effect. A smaller dose of a more potent drug will achieve the same effect as a larger dose of a less potent drug (see Fig. 3.3).
- ***Efficacy***: A drug's efficacy refers to the maximum effect achievable with the drug. Once a drug's maximum effect has been reached, giving more will not result in increased effects (see Fig. 3.3).
- ***Toxicity***: Drug toxicity occurs when undesirable side-effects of its administration occur.
- ***Therapeutic index***: The therapeutic index of a drug is the ratio of the dose producing a toxic effect to that producing a therapeutic effect. A drug with a high therapeutic index requires a much higher dose to do harm than to achieve a desired effect, giving a relatively high margin of safety.

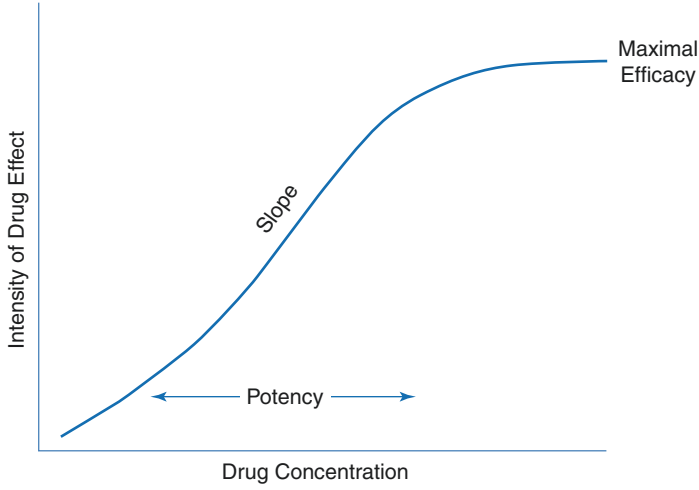


Fig. 3.3 Drug dose response relationship. (Image Courtesy J. Ehrenfeld)

- ***Actions on receptor systems***: Most drugs used in anesthesia exert their effects by binding to and modulating cellular receptor systems. In general, these effects can be categorized as being agonistic (enhancing the receptor system) or antagonistic (decreasing the receptor system). Some drugs are partial agonists, meaning that they have a relatively low efficacy and cannot produce a maximal effect on a receptor system, even at very high doses.
- ***Competitive vs. noncompetitive antagonism***: Competitive antagonists bind reversibly to cellular receptors, but do not activate them. The antagonist molecules compete with agonist molecules for access to the receptors. The effect of a competitive antagonist can be overcome by administering a high dose of an agonist. Noncompetitive antagonists bind to sites on the receptor molecule that are separate from the agonist binding site, decreasing the receptor's affinity for agonist molecules or preventing the receptor from responding to the presence of an agonist. Because they bind to a separate site on the receptor, noncompetitive antagonists cannot be overcome by increased doses of agonist.

- ***Stereospecificity***: Many drugs are supplied as a mixture of enantiomers (left/right stereoisomers). The levo- and dextro-variants of the drug may have different pharmacologic properties, and based on this, some drugs are supplied as pure levo- or dextro- formulations (e.g., levobupivacaine, ropivacaine).
- ***Additive and synergistic responses***: Drugs with similar physiologic effects may interact with additive effects (i.e. Drug A plus Drug B gives the sum of their expected effects). In some cases, the interactions are synergistic, meaning that the combined effect is larger than would be expected from the additive effects of the drugs given.
- ***Tolerance and physiological dependence***: Repeated administration of a drug can result in changes in its target receptor system as the body adjusts to the presence of the drug. Tolerance occurs when progressively larger doses of drug are required to produce the same physiologic effect. Physiological dependence occurs when a subject's receptor systems have adjusted to the presence of a drug, and withdrawal symptoms occur when it is stopped (e.g., with opioids or benzodiazepines). Physiological dependence is distinct from addiction, which is characterized by psychological craving for a substance and its pursuit despite actual or potential negative consequences.

Case Study

You are finished with a radical cystectomy with creation of an ileal pouch neobladder on an otherwise healthy, 80 kg, 60-year-old man with bladder cancer. The operation began 6 h ago and the patient has not yet emerged from general anesthesia. The case was uneventful, and you believe the problem to be pharmacologic. The patient received 4 mg of midazolam in divided doses during the preoperative period to facilitate placement of an arterial line. Anesthesia was induced with thiopental and succinylcholine. You maintained anesthesia with isoflurane, nitrous oxide, vecuronium,

and fentanyl. Hydromorphone was given during the last hour of the case. You administered ondansetron during closure as antiemetic prophylaxis. You gave neostigmine and glycopyrrolate a few minutes ago for reversal of neuromuscular blockade. The isoflurane vaporizer is turned off and the patient is being ventilated with 100% oxygen.

Which classes of drugs are most likely to be responsible for his delayed emergence? Which are less likely?

The patient received a short acting **benzodiazepine** and a single dose of a **barbiturate** induction agent with a short biologic action many hours ago. Although the terminal elimination of both drugs takes many hours, it is unlikely that either is responsible for delayed emergence from anesthesia. He received a **depolarizing neuromuscular blocking agent** during induction. Under ordinary circumstances, this drug (succinylcholine) would have lasted only 3–5 min and would therefore be an unlikely cause of delayed awakening. If the patient had a genetic deficiency in pseudocholinesterase, he would not have been able to metabolize succinylcholine, and this would have vastly prolonged its effect. Most anesthesiologists would not have administered vecuronium, the longer-acting **nondepolarizing neuromuscular blocking drug**, if the patient had not shown signs of recovery from succinylcholine. Nitrous oxide, an **inhalation anesthetic**, is very rapidly eliminated after discontinuing its administration, making it an unlikely cause. The **anticholinesterase** neostigmine, the **anticholinergic** glycopyrrolate, and the **serotonin antagonist (antiemetic)** ondansetron do not cause sedation and are not causes of delayed emergence. This leaves the inhalation agent isoflurane, the **opioids** fentanyl and hydromorphone, and the **neuromuscular blocking agent** vecuronium as possible causes.

Among the most likely possible causes, do you suspect a pharmacokinetic problem? A pharmacodynamic problem?

Sensitivity to inhalation anesthetics does not vary markedly between otherwise healthy individuals who are not at

the extremes of age. Therefore, if isoflurane is responsible for this patient's slow emergence, it is likely due to a pharmacokinetic problem. Long periods of inhalation anesthesia can slow emergence more than proportionately, because of the shape of the elimination curve. Opioid sensitivity varies significantly between individuals, and even if given based on body weight, unexpectedly intense effects may be observed. In addition, some opioids, such as fentanyl, have significantly increased context-sensitive half lives after long infusions or multiple administrations and may have sedating effects for longer than anticipated. In addition, the relatively long duration opioid hydromorphone was given recently, also suggesting a kinetic problem. Vecuronium is metabolized hepatically, and in the absence of liver disease, prolonged elimination (pharmacokinetic effect) is unlikely. However, if the effect of neostigmine is incomplete, either due to insufficient dose or time elapsed since administration, vecuronium may still be active. This would represent a combination of a pharmacodynamic effect of vecuronium and possibly a pharmacokinetic effect of neostigmine, which takes several minutes to produce its full effect.

How could you narrow the differential diagnosis using history, physical examination, clinical monitors, or pharmacologic probes?

The presence of isoflurane should be detected by an agent monitor, which measures the concentration of inhaled anesthetics in the expired gas. Generally, patients should awaken when the end-tidal concentration falls to less than 0.1–0.2 MAC, which would be about 0.1–0.2% for isoflurane. The presence of opioids may lower this value for "MAC awake." The peripheral nerve stimulator can diagnose residual neuromuscular blockade. Four strong twitches on train-of-four stimulation, or more accurately, sustained (>5 s) tetanus in response to 50–100 Hz stimulation, rules out residual vecuronium action. Alternatively, an additional dose of neostigmine (up to 5 mg total) can be given to

ensure full antagonism. However, nerve stimulation is more reliable. A processed EEG monitor (e.g., BIS) can differentiate a sedated patient from a paralyzed but "awake" patient. Opioid effects are more difficult to diagnose. The history of dose and timing of administration may be helpful. For example, one should check to see if a large dose of opioids was recently given, or if a prolonged fentanyl infusion was only recently discontinued. The presence of pinpoint pupils is a sign of mu-opioid agonism, but pupillary signs are considered only partially reliable under general anesthesia. However, if isoflurane has been eliminated and neuromuscular blockade has been reversed, then the physical sign may be helpful. Slow respiratory rate may also indicate excessive opioid effect. In some cases, careful titration of naloxone, an opioid antagonist, can be used to reverse opioids. Care must be taken not to be overzealous with this drug. Sudden reversal of deep narcosis can lead to hypertension and pain. Moreover, due to naloxone's short duration of action, vigilance for return of opioid effects in the PACU is essential.

If you conclude that isoflurane is responsible for the patient's delayed awakening, how will you proceed?

Isoflurane must be eliminated by exhalation. You can raise the fresh gas flow of 100% oxygen to 10 L/min or more to ensure that the patient does not rebreathe any isoflurane. Modest hyperventilation, or at least avoidance of hypoventilation with the use of controlled ventilation or careful attention to end-tidal CO_2 during hand ventilation, may increase the rate of elimination. However, care must be taken not to hyperventilate to the point of cerebral vasoconstriction, which may counteract any enhanced elimination by reducing egress of drug from the brain. Beyond these maneuvers, only time will terminate the action of isoflurane. In some cases, postoperative ventilation in the PACU may be necessary.

Suggested Further Reading

1. Bryant B, Knights K, Salerno E (2007) Pharmacology for health professionals. Mosby, Sydney
2. Murphy J (2005) Clinical pharmacokinetics, 3rd edn. American Society of Health-System Pharmacists, Bethesda

Pharmacology of Intravenous Anesthetic Agents

4

John W. Wolfe and Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xviii are reviewed before reading this chapter.

Key Learning Objectives

- Learn the relative advantages of each of the commonly used intravenous induction agents (propofol, etomidate, ketamine, thiopental).
- Discuss the pharmacokinetic properties of each of the commonly used intravenous opioids (fentanyl, morphine, hydromorphone, remifentanil).
- Understand the differences between depolarizing and nondepolarizing neuromuscular blockers.
- Understand the pharmacology of reversal of neuromuscular blockade.

J. W. Wolfe (✉)
Indiana University School of Medicine, Indianapolis, IN, USA
e-mail: jwolfe@iupui.edu

J. M. Ehrenfeld
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_4

Ideal anesthetic agents are typically easy to administer (even in patients who are noncooperative), act quickly, and have limited durations of action and side effects. Inhalational and intravenously administered drugs tend to share these characteristics, in contrast to oral, intramuscular, and subcutaneous agents. It is for this reason that inhalational and IV drugs are used most frequently during general anesthesia.

General anesthesia is the process of rendering a patient unconscious for the purpose of performing a surgical operation or other procedure. It should facilitate airway management, including endotracheal intubation, if necessary. A general anesthetic will ensure that the patient is unconscious and amnestic throughout the procedure, optimize surgical conditions, maintain hemodynamic stability, and will not negatively impact the patient's intraoperative course or recovery. There is no one drug that can accomplish all these things in every patient, so multiple drugs are typically utilized in concert. This concept is known as "balanced anesthesia." The anesthesiologist strives to maximize the positive actions of various drugs, while minimizing negative side effects.

Neuraxial (spinal and epidural) anesthesia and peripheral nerve blockade are anesthetic techniques requiring drug delivery to very precise locations along the body's neural transmission pathways. Local anesthetic drugs are primarily used for these techniques. A full description of both neuraxial blockade and peripheral nerve blockade appears in subsequent chapters.

The intravenous route is the primary means of delivery for most drugs during a typical anesthetic case, owing to the ease of administration and rapidity of transit to the drugs' sites of action. We will consider several of the most commonly used intravenous drugs according to their pharmacological classes and their clinical application. The **five most commonly used** classes of drugs for a typical anesthetic are benzodiazepines, opioids, induction agents, neuromuscular blockers (NMBs), and sympathomimetics.

Benzodiazepines

The benzodiazepines utilized in anesthesia include midazolam, diazepam, and lorazepam, all of which exert their sedative and hypnotic effects by enhancing transmission of the inhibitory neurotransmitter GABA. The most commonly used perioperative benzodiazepine is midazolam, which has an elimination half-life of 3 h. With a typical sedative IV dose of 1–2 mg, the clinical effect typically lasts for 20–30 min owing to redistribution. Benzodiazepines are used for sedation, anxiolysis, and amnesia. A beneficial side effect of these drugs is their anticonvulsant activity, which can help raise the seizure threshold in susceptible patients (e.g., patients receiving nerve blocks who may be at risk for local anesthetic neurotoxicity). Benzodiazepines do not provide analgesia and can be very long-acting when used in large doses. This is why benzodiazepines are usually used jointly with other agents during the course of an anesthetic. A new drug called remimazolam possesses the properties of both midazolam (a benzodiazepine) and remifentanil (an opioid) and has been used for premedication, procedural sedation and as part of total intravenous anesthesia.

Some patients, particularly children, are so anxious that the anesthesiologist deems it prudent to administer a benzodiazepine for anxiolysis prior to entering the operating room. Midazolam (0.25–0.5 mg/kg orally in children) can be administered in these situations. It is important to remember that loss of balance, upper airway obstruction, and respiratory depression can occur after administration of benzodiazepines (particularly when combined with opioids). Patients given a benzodiazepine preoperatively should not be allowed to ambulate without assistance, and should always be monitored.

Intraoperatively, benzodiazepines can be used for sedation in instances where the patient does not receive a general anesthetic (often referred to as monitored anesthesia care, or MAC), or to provide sedation and/or amnesia as part of a balanced anesthetic technique. The amnestic properties of benzodiazepines are particularly useful in patients with poor hemodynamic status, who may not tolerate a high enough dose of inhaled anesthetic agent to ensure complete unconsciousness.

If a patient becomes oversedated, or exhibits delayed emergence from general anesthesia, and benzodiazepines are suspected to be the offending agent, flumazenil can be administered. Flumazenil is a pharmacologic antagonist which acts at the benzodiazepine receptor and effectively reverses the sedation from benzodiazepines. The drug is titrated in boluses of 0.1 mg every 5 min in adults. Because flumazenil only lasts about an hour and produces incomplete reversal of respiratory depression, resedation can occur after administration (especially when used with diazepam, which has a half-life of approximately 20 h).

Opioids

Commonly used opioids include morphine, hydromorphone, fentanyl and its derivatives, and meperidine. These drugs provide sedation and analgesia, but do not provide reliable amnesia. They act on receptors in the brain (periaqueductal gray area) and spinal cord (substantia gelatinosa) via the mu (μ), kappa (κ), and delta (δ) receptors by mimicking endogenous endorphins. Opioid receptor activation is considered to lead to neurotransmitter inhibition via inhibition of acetylcholine and substance P release. Table 4.1 shows opioid receptor subtypes and effects.

IV opioids are the primary means by which pain is controlled for surgical patients. While short-acting opioids such as fentanyl and its derivatives are used mainly for pain control intraoperatively, longer-acting opioids such as morphine or hydromorphone are usually used for postoperative pain control. In addition to

Table 4.1 Opioid receptor subtypes & effects

	μ/δ	κ
Analgesia	Supraspinal/spinal	Spinal
Respiratory rate	↓↓	↓
GI motility	↓	
Sedation	↑↑	↑
Dependence	↑↑	↑
Other effects	Euphoria	Dysphoria

Table 4.2 Dose, time to peak effect, and duration of analgesia for commonly used perioperative opioids

Opioid	Dose[a] (mg)	Peak (min)	Duration (h)
Morphine	10	20–30	3–4
Meperidine	80	5–7	2–3
Hydromorphone	1.5	15–30	2–3
Fentanyl	0.1	3–5	0.5–1
Sufentanil	0.01	3–5	0.5–1
Alfentanil	0.75	1.5–2	0.2–0.3
Remifentanil	0.1	1.5–2	0.1–0.2

[a]Approximately equianalgesic dosages

varying durations of action, opioids vary in their degree of binding to different opioid receptors and their consequent side effect profiles. Table 4.2 shows the relative dose, time to peak effect, and duration of action for the most commonly used IV opioids.

Fentanyl is a rapid-acting synthetic opioid which is about 100 times more potent than morphine. It is often given (dose 50–150 mcg for a 70 kg adult) during the induction of anesthesia to blunt the sympathetic response to laryngoscopy and intubation. It can cause apparent chest wall rigidity in high doses (1000 mcg), which in rare cases may impair or prevent adequate ventilation.

Sufentanil and **Alfentanil** are both analogues of fentanyl. When compared with sufentanil and fentanyl, alfentanil is an ultra short-acting opioid (5–10 min), about 25% as potent as fentanyl, but has significantly faster onset than fentanyl (1–2 min). Sufentanil is approximately 5–10 times more potent than fentanyl. Both opioids may be used for induction and maintenance of anesthesia.

Morphine is the least lipid-soluble opioid and the most likely agent to accumulate in the presence of renal failure. It can cause bradycardia and histamine release in some patients. Morphine has a slower peak onset (30 min) when compared with fentanyl. Morphine is typically administered in incremental doses of 1–5 mg, with a total dose of 5–15 mg typically administered for adult patients.

Hydromorphone is another long-acting opioid that is typically administered at the end of surgery to provide post-operative analgesia. It is more potent and more lipid-soluble than morphine. Hydromorphone is typically administered in incremental doses of 0.2–0.5 mg, with a total dose of 1–2 mg typically administered for adult patients.

Meperidine is structurally similar to atropine (may increase heart rate) and is metabolized to an active agent, normeperidine. It has useful antishivering properties and may be used postoperatively for this effect. It can accumulate in patients with renal failure leading to oversedation and/or seizures, and can cause release of histamine. It should be avoided in patients taking type A monoamine oxidase inhibitors, as it may lead to hyperthermia, seizures, and even death. There is a well-known case involving the death of a patient named Libby Zion who received meperidine, although she had been taking phenelzine (Nardil), a type A MAO inhibitor. This error was found to result from overworked resident physicians who overlooked this drug interaction, and this finding ultimately led to the 80-h workweek limitation for residents.

Remifentanil has a potency similar to fentanyl, but is much shorter-acting (context sensitive half-time is about 4 min). It is broken down by nonspecific plasma esterases, and does not accumulate in patients after prolonged infusion, or in patients with renal or hepatic failure. It is almost always used as a continuous infusion, but can also be given as a bolus to facilitate intubation or nerve blocks.

Figure 4.1 shows how the context-sensitive half-time is a function of the length of time that the agent is administered. For opioids that exhibit accumulation (i.e., fentanyl), the context-sensitive half-time increases markedly with long durations of administration. Opioids which are enzymatically degraded as fast as they are administered (i.e., remifentanil) do not show this effect.

Opioids can be used alone for sedation cases but have several dose-dependent adverse side effects and are not reliable for producing amnesia. Consequently, opioids are more commonly used in combination with other agents for MAC cases or as part of a balanced general anesthetic.

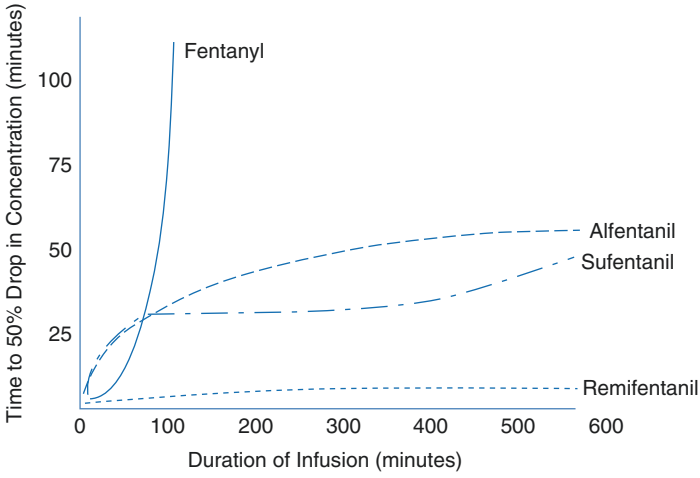


Fig. 4.1 Context-sensitive half time for opioid infusions. (Image Courtesy J. Ehrenfeld)

The major adverse side effect of opioids is respiratory depression. This is due to both a decrease in the hypoxic drive to breathe, and an increase in the apneic threshold (the CO_2 level above which patients are stimulated to breathe). If a patient is nonresponsive and/or hypoventilating from opioid overdose, this effect can be reversed with naloxone (0.04–0.4 mg every 2 min) which antagonizes mu receptors. Other adverse side effects of opioids include pruritus, bradycardia, arterial and venous vasodilation, nausea and vomiting, urinary retention, miosis, muscle rigidity (mainly with fentanyl), and decreased gastric motility/constipation.

There are also peripheral opioid receptors located in the gastrointestinal tract and other organs. Methylnaltrexone is a peripheral opioid receptor antagonist and a quaternary derivative of naltrexone. Unlike naloxone, methylnaltrexone offers the therapeutic potential to block or reverse the undesired side effects of opioids that are mediated by receptors located in the periphery (e.g., in the gastrointestinal tract), without affecting analgesia or precipitating the opioid withdrawal symptoms that are predominantly mediated by receptors in the central nervous system.

Blunting of the endocrine stress response is a side effect of opioids that can be beneficial, especially during surgery. Because of their ability to decrease the stress response and minimal effects on baseline cardiovascular status, high-dose opioids are favored over other anesthetics in cases where hemodynamic instability is anticipated, or in patients where such changes would not be well tolerated.

Induction Agents

Induction is the process of starting a general anesthetic, or "putting the patient to sleep." An ideal induction agent should be quick in onset, but should also be short-acting in case problems are encountered and the patient has to be awakened, or if the procedure is short in duration. Any IV medication that causes a patient to become unconscious can be considered an induction agent, and both benzodiazepines and opioids have been used in this capacity. However, due to their unpredictable onset time and long durations of action when used in doses high enough for induction, neither class is commonly used alone. Typical induction agents include propofol, thiopental, etomidate, and ketamine. The agent chosen is usually determined by each drug's side effect profile in relation to the patient or the case. Table 4.3 summarizes intravenous drugs and their dosages commonly used in anesthesia practice.

Propofol is the most commonly used induction agent and acts by enhancing transmission at the GABA-A receptor. Because of its rapid onset, titratability and short duration of action, propofol is also frequently utilized as an IV infusion to provide sedation for MAC or sedation cases, or as part of a balanced general anesthetic.

Propofol is a water insoluble agent that can only be administered intravenously. It is prepared as a 1% emulsion with egg lecithin, glycerol, and soybean oil.

Propofol's initial distribution half–life is 2–8 min, and it undergoes rapid hepatic metabolism to water soluble metabolites which are excreted by the kidneys. Remarkably, few pharmacokinetic

Table 4.3 Recommended drug dosages for common IV agents

Benzodiazepines and opioids[a]	Induction agents
Midazolam 1–4 mg	Propofol 2–2.5 mg/kg (induction), 25–200 mcg/kg/min (infusion)
Diazepam 2.5–10 mg	Thiopental 3–5 mg/kg
Lorazepam 1–4 mg	Etomidate 0.2–0.5 mg/kg
Opioids (Bolus)[a]	Ketamine 1–2 mg/kg IV, 3–4 mg/kg IM (induction or bolus),
Morphine 1–5 mg	0.25–2 mg/kg/h (infusion)
Hydromorphone 0.2–0.5 mg	*Neuromuscular blockers*[b]
Fentanyl 25–100 mcg	Succinylcholine 1–2 mg/kg, 20 mg bolus for laryngospasm
Meperidine 25–50 mg	Rocuronium 0.6 mg/kg
	Vecuronium 0.1 mg/kg
	Cisatracurium 0.15 mg/kg
	Pancuronium 0.1 mg/kg

Adult dosages: always start at low end of range and titrate up
[a]Titration ranges for premedication or intraop/post op bolus dosing
[b]Intubating dosages: divide by 3 for ED95, divide by 5 for maintenance bolus dosing

changes are noted in the elimination of propofol for patients with liver or renal disease.

Propofol is a potent cardiovascular and respiratory depressant, and it should only be used by persons qualified and prepared to maintain the patient's airway and hemodynamic stability. Propofol is often avoided in cases where the maintenance of spontaneous ventilation is required, the patient is already hypotensive, or the patient's ability to sustain hemodynamic stability is in question for any reason. Propofol decreases the body's normal response to both hypoxia and hypercarbia, and up to 35% of patients experience apnea after an induction dose. Propofol decreases blood pressure by decreasing cardiac contractility, systemic vascular resistance, and preload. It is generally thought of as having the most profound cardiodepressant effects of all the induction agents.

From a neurologic standpoint, propofol has moderate anticonvulsant activity. It reduces both intracranial pressure and cerebral blood flow. However, due to greater effects on systemic blood pressure, propofol can actually decrease cerebral perfusion pressure when given in large doses. Another advantage of propofol is that it is less likely to lead to post-operative sedation than other induction agents.

In addition to negative side effects of propofol already mentioned, pain on injection is seen in up to 67% of patients. Pain can be lessened by administration of IV lidocaine before injection of propofol. In addition, patients may experience mild muscle twitching and hiccupping. Favorable propofol side effects include antipruritic and antiemetic properties.

Thiopental is a barbiturate that, like propofol, enhances GABA transmission. It is rapid in onset, and has both cardiovascular and respiratory depressant properties. Many favor propofol because of the prolonged cognitive disarray observed in some patients after administration of thiopental. Thiopental is also possibly cerebro-protective, and it is used in many brain surgery cases. Thiopental solution is very alkaline, and can form a precipitate that will occlude IV catheters if mixed with acidic solutions or drugs (such as paralytic agents). Thiopental induces the enzyme ALA synthetase (the rate limiting step in porphyrin synthesis), and is therefore contraindicated in patients with inducible porphyrias. Repeated doses may result in a delayed emergence because of high protein binding and a low hepatic extraction ratio.

Etomidate is an imidazole which increases GABA transmission and has the advantages of minimal cardiac and respiratory depression. Its onset and duration of action are similar to propofol, but etomidate is considered a safer drug to use for patients in a compromised hemodynamic state. Trauma patients, elderly patients, and patients who are severely volume depleted or are on vasopressors are typical candidates for an etomidate induction. After a single bolus, the clinical effect of etomidate is terminated by redistribution and rapid hepatic metabolism. A concern exists regarding transient adrenal suppression after use of etomidate,

due to enzyme inhibition. The drug should therefore be used with caution or in concert with corticosteroid administration in those patients demonstrating adrenal insufficiency. Other side effects include myoclonus, pain on injection, and a high incidence of postoperative nausea and vomiting.

Ketamine is a dissociative anesthetic agent that acts as an NMDA receptor antagonist. Its major drawback is psychomimetic effects such as altered visual perception, dysphoria, and hallucinations. It is the only induction agent that is a cardiovascular stimulant, owing to inhibition of norepinephrine reuptake at sympathetic nerve endings, and has minimal effects on respiratory drive. Of additional benefit is the fact that ketamine is both a potent analgesic and a bronchodilator (it is often administered in the emergency room to patients in status asthmaticus). Ketamine is ideal for many trauma inductions (sedation, analgesia, amnesia, and cardiovascular support), and for use in pediatrics (where perceptual distortions are not as bothersome to the patient as they can be for adults). It is typically avoided in situations where cardiac stimulation could be deleterious (arrhythmias, hypertension), and in cases where the patient is expected to emerge from anesthesia soon after administration (again due to expected deleterious psychological effects and cognitive disarray). Further side effects include increased salivation and intracranial pressure elevations (relative contraindication in patients with intracranial hypertension). Table 4.4 shows the cardiovascular effects of the most commonly used IV induction agents.

Table 4.4 Cardiovascular effects of IV induction agents

Drug	Mean arterial pressure	Systemic vascular resistance	Cardiac output	Contractility	Heart rate	Intracranial pressure
Propofol	↓↓	↓↓	↓↓	↓↓	↓↓	↓
Thiopental	↓		↓	↓	↑	↓
Etomidate	–	–	–	–	–	↓
Ketamine	↑	↑	–	–	↑	↑

Neuromuscular Blocking Agents

Neuromuscular blockers (NMBs) or "paralytics" are frequently utilized during the administration of a general anesthetic. They are used to facilitate intubation and to improve surgical conditions by inducing relaxation of skeletal muscle. There are two major classes of NMBs: depolarizing and nondepolarizing. The classes are differentiated based on their action at the neuromuscular junction. Adequacy of relaxation can be determined by use of a nerve stimulator (see Chap. 11 on equipment). Nerve stimulator testing of a typical blockade with nondepolarizing NMBs demonstrates tetanic fade, posttetanic facilitation, train of four ratio less than 30%, and the ability to be reversed with anticholinesterases or sugammadex. In contrast, a typical depolarizing block does not display these characteristics – unless a Phase II block is present (see section "Depolarizing NMBs" below). The appropriate NMB for a given situation is chosen based on desired onset time, duration, elimination, and side effects.

Depolarizing NMBs

Succinylcholine is the only commercially available depolarizing NMB. Like acetylcholine, it works as an agonist on acetylcholine receptors at the neuromuscular junction. This causes depolarization, and prolonged binding of succinylcholine to the receptor prevents junctional repolarization because the drug is not hydrolyzed by true acetylcholinesterase. It is during this period that the muscle becomes relaxed.

Succinylcholine has the quickest onset (30–45 s) and shortest duration (~5 min) of any available NMB, and it is the drug of choice for "rapid sequence" inductions. Because of its short duration, succinylcholine is used almost exclusively during intubation, and only rarely for maintenance of relaxation during a procedure. Should repeated doses of succinylcholine be administered (4–6 mg/kg in total), phase II blockade may occur leading to a slow recovery. This occurs when prolonged end-plate depolarization leads to conformational changes within the acetylcholine receptor.

Table 4.5 Contraindications to succinylcholine use

Elevated serum potassium levels (>5.5 meq/L)
History of burn injury
History of denervation injury
Known or suspected myopathy
Known or suspected risk for malignant hyperthermia
Known pseudocholinesterase deficiency

Pseudocholinesterase is the enzyme responsible for breaking down succinylcholine. Some people have a partial or total deficiency of this enzyme and can therefore exhibit slightly prolonged (20–30 min for heterozygotes) or significantly prolonged (6–8 h for homozygotes) paralysis when the drug is administered.

One important side effect of succinylcholine is an elevation in serum potassium levels after administration. Because of this effect, succinylcholine must be used with caution in patients with elevated K^+ levels and is usually avoided in patients with burn or denervation injury as these patients have an upregulation of postjunctional acetylcholine receptors and a consequently exaggerated potassium release in response to the drug that may lead to a fatal arrhythmia. Bradycardia, owing to a resemblance to acetylcholine and subsequent action on muscarinic receptors, and malignant hyperthermia (a rare hypermetabolic state that can occur in the skeletal muscle of susceptible individuals) are other side effects of note. Table 4.5 shows contraindications to the use of succinylcholine. Because of its mechanism of action, succinylcholine cannot be "reversed" by acetylcholinesterase inhibitors. In fact, attempting reversal can actually make neuromuscular blockade prolonged and more intense.

Nondepolarizing NMBs

There are several types of nondepolarizing NMBs, with the four in most common use being rocuronium, vecuronium, cisatracurium, and pancuronium (see Table 4.6). They can be subdivided according to their chemical structure into benzylisoquinoliniums (cisatracurium), and aminosteroids (rocuronium, vecuronium,

Table 4.6 Neuromuscular blocking drugs

Drug	Onset	Duration (min)	Mode of elimination	Important notes/side effects
Succinylcholine	30–45 s	5	Plasma cholinesterase	Increased duration in pts. with pseudocholinesterase deficiency
Cisatracurium	2–4 min	30–40	Hoffman degradation	Elimination is organ-independent
Vecuronium	2–4 min	30–40	Liver/renal	Few side effects
Pancuronium	4–6 min	120–180	Liver/renal	Can cause tachycardia & hypertension
Rocuronium	1–2 min	30–40	Liver/renal	May be used for rapid sequence induction if succinylcholine is contraindicated

and pancuronium). Nondepolarizing NMBs exert their effects by competitively antagonizing acetylcholine from binding at the postsynaptic nicotinic receptor in the neuromuscular junction. The result of this competitive antagonism is an inhibition of junctional depolarization.

Onset time and duration of action are as follows: rocuronium < vecuronium < cisatracurium < pancuronium. Because of their longer durations of action as compared to succinylcholine, NMBs are commonly used to maintain muscle relaxation during surgery. NMBs are also used to facilitate intubation, but the time to achieve equivalent and ideal intubating conditions is significantly longer than with succinylcholine.

Most of the commonly used NMBs are metabolized to some degree, but they rely mainly on biliary and renal excretion for termination of action. Cisatracurium is the exception, as it is degraded in the plasma by Hoffman elimination. Cisatracurium is therefore commonly used in patients who have renal or hepatic dysfunction.

Side effects of NMBs are rare, with tachycardia (pancuronium), and hypotension (cisatracurium) being the most frequently encountered. Allergic reactions to anesthetic drugs are rare but are most commonly from NMBs.

Acetylcholinesterase Inhibitors

Reversal of NMBs can be accomplished by the administration of an acetylcholinesterase inhibitor (e.g., neostigmine), which prevents breakdown of acetylcholine at the neuromuscular junction. The subsequent excess of acetylcholine can then out-compete the NMB for junctional binding and allow for muscle depolarization. An anticholinergic, such as glycopyrrolate, must be simultaneously administered to prevent muscarinic overactivity. Aminosteroid NMB's (rocuronium, vecuronium) can also be neutralized with sugammadex.

A **"cholinergic crisis"** may result from an overdose of acetylcholinesterase inhibitors or when the agent is given without a concomitant anticholinergic drug. Symptoms include bradycardia, bronchospasm, vomiting, miosis, and muscle weakness. Many nerve gasses used in warfare are acetylcholinesterase inhibitors that can lead to a severe cholinergic crisis.

Anticholinergics

Atropine and glycopyrrolate are both anticholinergics that are used perioperatively for several purposes. As their name implies, they are used to counteract harmful cholinergic responses that can occur during NMB reversal with anticholinesterase inhibitors, particularly bradycardia and parasympathetic side effects. Both agents are also antisialogues, and they are often used to improve intubating conditions. Neostigmine and glycopyrrolate (slower onset, longer acting) are used in concert for neuromuscular blockade reversal, while edrophonium is paired with atropine (quicker onset, shorter acting). This specific pairing is due to the comparable durations of action of the combinations, as outlined in Table 4.7.

Table 4.7 Reversal of neuromuscular blockade

Neostigmine 50 mcg/kg paired with glycopyrrolate 10 mcg/kg
Edrophonium 500 mcg/kg paired with atropine 20 mcg/kg
Sugammadex 2–4 mg/kg

A **central anticholinergic syndrome** may result from an overdose of atropine (which, unlike glycopyrrolate, crosses the blood brain barrier). Symptoms include delirium, excitation, fever, flushing, and tachycardia. Treatment is with physostigmine (a centrally acting acetylcholinesterase inhibitor) which acts to restore blocked cholinergic activity in the CNS.

Sugammadex is a selective NMB binding agent typically administered at a dose of 2–4 mg/kg. Structurally, it is a gamma cyclodextrin with a lipophilic core region of the right shape to encapsulate and bind aminosteroid NMBs (rocuronium, vecuronium). Compared to reversal with neostigmine/glycopyrrolate, sugammadex reversal is faster and more complete. Sugammadex cannot be used for reversal of blockade with succinylcholine or cisatracurium. Side effects are uncommon but can include bradycardia or allergic reactions. Of note, sugammadex can bind other steroidal substances, such as oral contraceptives. Patients who use oral contraceptives for birth control should be advised to use a second form of birth control for several days after they are given sugammadex.

Case Study

You are asked to provide general anesthesia for an otherwise healthy 30-year-old woman undergoing pelviscopy. She has a history of endometriosis and chronic pelvic pain. Her brother had a near-fatal episode of malignant hyperthermia as a child, and she has been counseled to avoid triggering anesthetics. You decide to manage the case with total intravenous anesthesia, avoiding inhalation anesthetics altogether. You have appropriately removed the vaporizers from your anesthesia machine and flushed it with 100% oxygen according to published recommendations.

Which classes of intravenous agents will you need?

As with any anesthetic, you need to provide all three components of complete anesthesia: hypnosis, analgesia, and muscle relaxation. Although inhalational anesthetics can provide all three of these elements at high doses, no

single intravenous agent can. As you do with balanced anesthesia, you will likely use a combination of drugs that provide primarily one of the three components. You will need a sedative-hypnotic, an opioid analgesic, and a neuromuscular blocking drug.

Which drug will you use to produce and maintain unconsciousness? How will you know you have given enough? Will the dose need to change during the surgery?

The most commonly used drug in this class for total intravenous anesthesia (TIVA) is propofol, due to its short acting properties and relatively rapid elimination after even prolonged administration. Unfortunately, unlike inhalation anesthetics, there is no equivalent of end-tidal concentration to directly monitor effect site concentration. Mathematical models have been developed, however, which closely model this concentration and can be used to control infusion pumps or guide a human operator. In Europe, but not yet in the United States, target controlled infusion pumps exist and can be programmed directly in terms of the desired brain concentration of propofol. When using a manual pump, the dose will indeed be reduced over time in order to maintain such a constant effect site concentration. Monitoring the patient's EEG, as with a BIS or other brain state monitor, can provide information about the patient's depth of anesthesia and can guide dosing of propofol.

Which opioid would be most appropriate for intraoperative use? The case is booked for 2 h. Will you change to a different agent for postoperative analgesia?

As shown in Fig. 4.1, opioids differ markedly in their context-sensitive half times (CSHT; the time required for a 50% decrease in plasma concentration after discontinuing a constant-dose infusion). Therefore, if you are not using a computerized pump that holds a constant effect site concentration by decreasing the infusion rate over time, it would be most appropriate to select a drug with a relatively flat CSHT curve. This would include sufentanil, alfentanil, or remifen-

tanil. The latter, though expensive, is often favored for TIVA because even very high doses are rapidly eliminated after discontinuation. At the end of the case, you should consider administering a longer acting drug such as fentanyl, morphine, or hydromorphone to provide postoperative analgesia. The choice may depend on whether the patient will be staying overnight in the hospital (favoring longer acting drugs) or having outpatient surgery (favoring fentanyl).

Which neuromuscular blocking drug(s) will you choose, if any?

You will avoid succinylcholine because it is a trigger for malignant hyperthermia. In general, you will need to intubate and control ventilation in patients undergoing pelviscopy. Therefore, you will use a short-acting and rapid-onset nondepolarizing neuromuscular blocking drug such as vecuronium, rocuronium, or cisatracurium. Given the duration of the case (2 h), any would be a reasonable choice. Using rocuronium or vecuronium would give you the option of reversing neuromuscular blockade with sugammadex at the end of the case.

At the end of the case, how will you conduct the emergence?

This can be the greatest challenge of a TIVA. Since you cannot monitor the concentration of the drugs in the patient's body, and because there is no well-characterized equivalent of MAC, you must have an understanding of the pharmacokinetics of the drugs in order to allow the patient to awaken promptly at the end of the surgery. You will reverse neuromuscular blockade and discontinue the opioid infusion. If you are using remifentanil, you will consider a small dose of a longer acting drug to provide early postoperative analgesia. Propofol elimination is rapid but not instantaneous; the context-sensitive half time is 11 min for a 1 h infusion plus 4 min per additional hour for propofol, so you will have to carefully monitor the procedure and discontinue it at the appropriate time. Moreover, a 50% decrease in concentra-

tion may or may not be sufficient for the patient to awaken, so more or less time may be required. You can monitor the depth of anesthesia with clinical signs (BP and heart rate, signs of sympathetic activation such as tearing or sweating) and with an EEG monitor such as a BIS. You may also decrease the rate of the propofol infusion somewhat as surgical stimulation decreases during surgical closure to facilitate emergence once the infusion is halted.

Suggested Further Reading

1. Euliano TY, Gravenstein JS (2004) A brief pharmacology related to anesthesia. Essential anesthesia: from science to practice. Cambridge University Press, Cambridge, p 173
2. Kanto JH (1985) Midazolam: the first water-soluble benzodiazepine. Pharmacology, pharmacokinetics and efficacy in insomnia and anesthesia. Pharmacotherapy 5(3):138–155
3. Komatsu R, Turan AM, Orhan-Sungur M, McGuire J, Radke OC, Apfel CC (2007) Remifentanil for general anaesthesia: a systematic review. Anaesthesia 62(12):1266–1280
4. Kopman AF, Eikermann M (2009) Antagonism of non-depolarizing neuromuscular block: current practice. Anaesthesia 64(suppl 1):22–30

Pharmacology of Inhalational Anesthetics

5

John W. Wolfe and Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xix are reviewed before reading this chapter.

Key Learning Objectives

- Learn the pharmacokinetic factors affecting the rate of induction and emergence with inhalational anesthetics.
- Understand the concept of Minimum Alveolar Concentration (MAC).
- Know the key characteristics of the four most commonly used inhalational agents (nitrous oxide, isoflurane, desflurane, sevoflurane).

J. W. Wolfe (✉)
Indiana University School of Medicine, Indianapolis, IN, USA
e-mail: jwolfe@iupui.edu

J. M. Ehrenfeld
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_5

The inhalational anesthetics (nitrous oxide and various volatile halogenated ethers) play a key role in current anesthetic practice. They provide rapid induction of anesthesia, easy titratability during the anesthetic, and rapid emergence at the conclusion of the anesthetic. At clinically relevant doses, the volatile anesthetics provide reliable amnesia, immobility, a modest degree of muscle relaxation, and blunting of the adrenergic response to surgical stimulation.

Pharmacokinetics of Uptake, Distribution and Elimination

Induction

In order to have an effect on the patient, inhalational anesthetics must be:

1. Inspired after having been delivered from the breathing circuit
2. Absorbed from the alveoli into the blood
3. Transported from the lungs to the target tissue
4. Absorbed from the blood into the target tissue (i.e. the brain)

Emergence

The sequence of events from the induction of anesthesia is reversed (i.e. the agent is absorbed from the target tissue into the blood, transported to the lungs, and then expired into the breathing circuit).

A useful analogy for induction and emergence from inhalational anesthetics is to imagine that a reservoir is being filled during induction and emptied during emergence. When the reservoir is empty, the partial pressure of the anesthetic in target tissues is zero, and the patient is awake. When the reservoir is full of drug, the partial pressure of the anesthetic in target tissues is therapeutic, and the patient is anesthetized.

Factors affecting the rapidity of induction and emergence include:

- ***Tissue and blood solubility***: Agents that are more soluble in blood and tissues effectively have a larger reservoir that must be filled before adequate tissue partial pressures are reached to achieve an anesthetic effect. On emergence, the more soluble agents have a larger reservoir of drug that must be emptied. By the same mechanism that induction is slowed (owing to the larger reservoir that has to be filled), emergence with the more soluble agents typically takes longer. For example, all other factors being equal, induction and emergence with isoflurane is slower than with desflurane (See Table 5.1, Physical Characteristics of Inhalational Agents).
- ***Inspired concentration***: A high inspired concentration of the anesthetic speeds induction by providing a large gradient between the partial pressure of the agent in the alveoli and the blood. This concentration gradient increases the arterial concentration of the agent, thereby speeding induction of the anesthetic effect. The reverse of this phenomenon is seen on emergence, when an inspired concentration of zero favors passage of volatile agent out of the blood into the alveoli (see Fig. 5.1).
- ***Fresh gas flow rate***: A higher fresh gas flow rate into the anesthesia machine circuit speeds induction. By more completely

Table 5.1 Physical characteristics of inhalational anesthetics

Agent	Vapor pressure (20 °C)	Blood: gas partition coefficient[a]	Fat: blood partition coefficient	Metabolism	Pungency[b]
N_2O	38,770 mmHg	0.46	2.3	0	None
Desflurane	669 mmHg	0.42	27	0.02%	High
Sevoflurane	157 mmHg	0.65	48	5%	Low
Isoflurane	238 mmHg	1.46	45	0.2%	High

[a]The low blood: gas partition coefficients (i.e., low solubility in blood) of nitrous oxide, desflurane, and sevoflurane speed induction and emergence
[b]Due to their low pungencies, nitrous oxide and sevoflurane are excellent agents for inhalational induction of anesthesia by mask

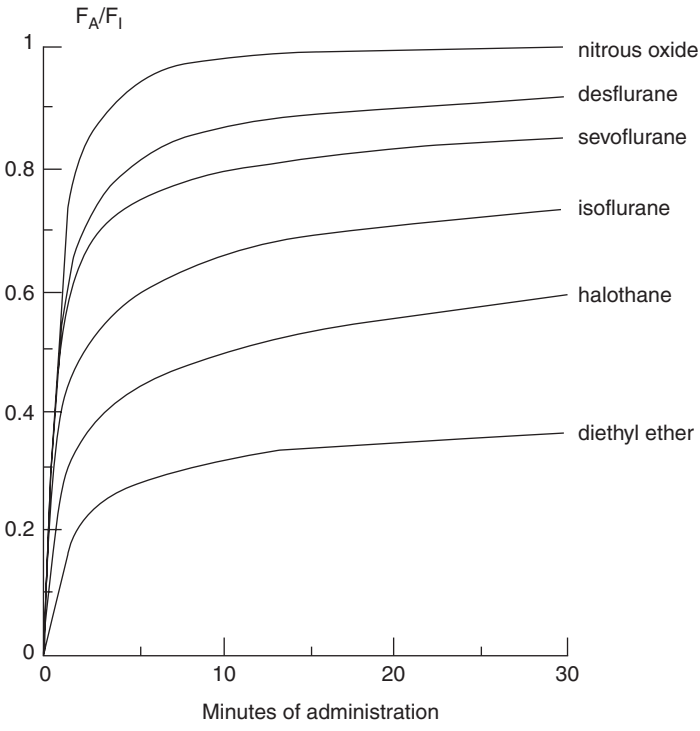


Fig. 5.1 Ratio of concentration of anesthetic in alveolar gas to inspired gas. Graph shows how the ratio between the inspired (FI) and alveolar (FA) concentrations of inhalational anesthetics changes with time of administration. The least soluble drugs approach equilibrium (FA/FI) the fastest. (From *Modern Anesthetics: Handbook of Experimental Pharmacology*, by Helmut Schwilden, Springer 2008. Used with Permission)

and rapidly replacing expired gases (which contain less anesthetic agent), a consistently high inspired concentration is provided. Similarly, a high inflow rate of anesthetic-free fresh gas during emergence quickly flushes the anesthetic agent out of the circuit, enhancing the elimination of inhaled anesthetic from the lungs.

- ***Minute ventilation***: High minute ventilation (respiratory rate x tidal volume) increases the rate of induction and emergence by rapidly providing fresh inhalational agent during induction and

rapidly removing it during emergence. This is clinically relevant during inhalational inductions and during the emergence of most patients. For example, a patient with high minute ventilation (i.e. an infant) will have a faster inhalational induction and emergence than a patient with lower minute ventilation (e.g., an elderly patient). Ventilation has a greater effect on high-solubility agents (such as diethyl ether) and a lesser effect on relatively insoluble agents (such as nitrous oxide). Since most of our commonly used inhalational agents have low to intermediate solubilities, this effect is therefore of a moderate significance.

Theories of Inhalational Anesthetic Action

The mechanism of action of the inhalational anesthetics remains incompletely understood. Anesthetic effects have been demonstrated at the levels of the spinal cord, brain stem, and cerebral cortex.

Theories explaining the mechanism of action of inhalational anesthetics include:

- ***The Meyer-Overton Rule***: It has been observed that the potencies of inhalational agents correlate with their lipid solubilities. Extrapolating from this observation, it has been theorized that inhalational anesthetics act by dissolving at hydrophobic sites, formerly assumed to be in the lipid bilayers of cell membranes, but currently thought to be in the relatively hydrophobic regions of one or more proteins.
- ***GABA enhancement***: Many inhaled anesthetic agents enhance activity of the gamma-aminobutyric acid (GABA) system, which is also enhanced by intravenous anesthetic agents such as benzodiazepines, propofol, and etomidate. It has been observed that the potencies of inhalational agents correlate with their potentiation of the GABA system, leading to the theory that GABA enhancement may be a key element of inhalational anesthetic activity.

- ***Other receptors systems***: Inhalational anesthetic agents have been shown to interact to varying degrees with a wide variety of cellular receptors, including NMDA and acetylcholine receptors.

Depth of Anesthesia and MAC

The minimum alveolar concentration (MAC) is a commonly used method for describing the dose of inhalational anesthetics. MAC, as used by anesthesiologists, is a specialized example of an ED_{50}, where a MAC of 1 is the alveolar concentration of a drug at which movement in response to a surgical incision will be absent in 50% of subjects. By referring to the MAC of a volatile agent being delivered, one can normalize the different potencies of the various agents when comparing them. In addition, MAC values for inhalational agents are additive (a patient receiving 0.5 MAC of one agent and 0.4 MAC of another has a total anesthetic dose of 0.9 MAC), allowing estimation of anesthetic depth in patients receiving more than one agent concurrently (usually a volatile anesthetic and nitrous oxide).

Multiples of the MAC for inhalational anesthetics can be used to describe differing depths of anesthesia, although MAC multiples are not linear because the dose–response curves for different agents do not parallel. Nevertheless, some useful dose levels are:

- 0.3–0.4 MAC is associated with awakening from anesthesia in the absence of other agents (referred to as MAC-awake).
- 1.3 MAC is known to prevent movement in 95% of patients in response to a surgical incision (making 1.3 MAC an inhalational anesthetic analog to an ED_{95} dose used for intravenous agents).
- 1.5 MAC typically blocks the adrenergic response to the surgical stimulus.

Please note that the MAC values cited above are values for healthy adults. Table 5.2 lists MAC values for commonly used inhalational agents.

Table 5.2 Minimum alveolar concentration (MAC) values

Agent	MAC (%)
Desflurane	6.0
Sevoflurane	2.05
Isoflurane	1.15
Halothane	0.75
Nitrous oxide	105

Table 5.3 Factors affecting MAC

Increased MAC	Decreased MAC
Children (from infancy to adolescence)	Premature infants and the elderly
Hypernatremia	Hypothermia
Cocaine or amphetamine intoxication	Pregnancy
Chronic alcohol use	Acute alcohol intoxication
MAO inhibitors	Opiates, benzodiazepines, barbiturates, clonidine, dexmedetomidine
Tricyclic antidepressants	

The MAC value for an inhalational anesthetic may be increased or decreased in individual patients by a variety of factors, as outlined in Table 5.3:

Nitrous Oxide

Nitrous oxide is a colorless, non-pungent gas with a slightly sweet odor and taste. It is the only inorganic chemical in current use as an anesthetic. The vapor pressure of nitrous oxide at room temperature is 745 PSI. Therefore, it exists as a gas at atmospheric pressure and is stored as a compressed liquid. Note that due to its low potency (MAC = 105%). administration of 1 MAC of nitrous oxide at atmospheric pressure is not possible, as this would lead to asphyxia from a lack of oxygen. In practice, the highest MAC of nitrous oxide that can be delivered on most anesthesia machines is 0.67 (corresponding to an inspired concentration of 70%).

- ***Cardiovascular effects***: Nitrous oxide depresses myocardial contractility, but this effect is usually offset by its stimulation of the sympathetic nervous system. Blood pressure and heart rate are generally unchanged by administration of nitrous oxide in the absence of surgical stimulation.
- ***Respiratory effects***: Nitrous oxide causes an increase in respiratory rate and a decrease in tidal volume. These effects are balanced, so that minute ventilation is minimally changed. Hypoxic ventilatory drive is markedly diminished, so that patients may remain apneic despite marked hypoxemia. Nitrous oxide may increase pulmonary vascular resistance and is generally avoided in patients with pulmonary hypertension.
- ***Cerebral effects***: Nitrous oxide increases cerebral blood flow, blood volume, and oxygen consumption. Intracranial pressure is mildly increased.
- ***Diffusion into gas filled spaces***: Nitrous oxide can diffuse from the patient's blood into gas-filled spaces within the patient (bowel gas, pneumothorax, etc.) more rapidly than other gases (e.g. nitrogen) can diffuse out. This is because nitrous oxide is 20 times more soluble in blood than nitrogen. This diffusion continues until the partial pressure of nitrous oxide in the space equals that in the blood. The accumulation of nitrous oxide can lead to expansion of the gas-filled space, causing distention of the bowel or expansion of a pneumothorax.
- ***Methionine synthetase inhibition***: Nitrous oxide oxidizes the cobalt atom in vitamin B12, inactivating vitamin B12-dependent enzymes, such as methionine synthetase. Prolonged exposure to nitrous oxide causes bone marrow depression and neural toxicity similar to that seen with vitamin B12 deficiency. It is unknown whether short perioperative exposures cause clinically important sequelae by this mechanism.
- ***Teratogenicity***: Nitrous oxide has been implicated as a possible teratogen in animal studies and is usually avoided in pregnant patients.
- ***Nausea and vomiting***: Nitrous oxide has been implicated as a possible cause of postoperative nausea and vomiting. This effect is thought to be less prevalent in children.

- ***Diffusion hypoxia***: At the conclusion of an anesthetic, when nitrous oxide is discontinued, it will diffuse out of the blood into alveoli in large volumes over a period of 2–3 min. Because nitrous oxide is usually administered at concentrations around 50% inspired, appreciable quantities of the gas can dissolve in body tissue, often as much as 12–14 L over a long case. At the beginning of emergence, if the patient is allowed to breathe room air, large quantities of nitrous oxide diffuse out through the alveoli, significantly reducing the alveolar PO_2 by a dilutional effect. This can lead to a phenomenon known as diffusion hypoxia, but it may be prevented by administering 100% O_2 for several minutes at the beginning of the emergence phase as nitrous oxide is discontinued.

Concentration Effect

The **concentration effect** explains why higher inspired anesthetic agent concentrations lead to faster rises in arterial concentrations. Because the volume of gas entering the pulmonary capillaries is higher than the amount of nitrogen entering the alveolus, the result is a decrease in alveolar volume. This decrease in alveolar volume leads to a higher fractional concentration of anesthetic agent, somewhat analogous to the creation of a vacuum within the alveolus whereby additional agent enters rapidly in response. This effect is most significant with nitrous oxide.

Second Gas Effect

The **second gas effect** is an extension of the concentration effect and a theoretical concept which may occur when nitrous oxide is combined with an inhalational agent (e.g., isoflurane). Just as we see with the concentration effect, despite its relatively low solubility, large volumes of nitrous oxide may be rapidly absorbed into arterial blood during induction, creating a vacuum of sorts within

the alveoli. This, in turn, leads to an increase in the uptake of the second agent, which enters the alveoli more readily in response to the partial vacuum created by rapid absorption of nitrous oxide.

Volatile Anesthetics (Isoflurane, Sevoflurane, and Desflurane)

The volatile anesthetic agents used in current anesthetic practice share many similar characteristics and side effects:

- ***Cardiovascular effects***: The volatile anesthetics depress myocardial contractility and cause peripheral vasodilation (the various agents differ somewhat in the balance of these two effects). The effect on heart rate is variable. Arterial blood pressure is decreased in a dose-dependent fashion.
- ***Respiratory effects***: Tidal volume is decreased by the volatile anesthetics. Respiratory rate increases slightly or remains stable, leading to decreased minute ventilation. The responses to hypercapnia are blunted (i.e., an anesthetized patient will increase minute ventilation in response to hypercapnia less than an awake patient and will remain apneic at a higher PCO_2 than an awake patient). As with nitrous oxide, hypoxic ventilatory drive is markedly diminished. Volatile anesthetics also produce bronchodilation.
- ***Cerebral effects***: The volatile anesthetics reduce cerebral oxygen consumption. At doses above 1 MAC, cerebral blood flow and consequently intracranial pressure are increased. Hyperventilation reverses the cerebral vasodilation seen with these agents.
- ***Musculoskeletal effects***: The effects of neuromuscular blockers are potentiated by volatile anesthetics.
- ***Obstetric effects***: The volatile anesthetics produce a dose-dependent reduction in uterine smooth muscle contractility.
- ***Renal and hepatic blood flow***: All agents decrease renal blood flow, glomerular filtration rate, and urinary output. They also decrease hepatic blood flow.

- ***Nausea and vomiting***: The volatile anesthetic agents are known to cause postoperative nausea and vomiting.
- ***Malignant hyperthermia***: The volatile anesthetic agents are triggers for malignant hyperthermia *(note: nitrous oxide is* ***not*** *a triggering agent).*
- ***Cardiac preconditioning***: Exposure of cardiac tissue to volatile anesthetics may be protective against the effects of subsequent ischemia and reperfusion.

Specific characteristics of the volatile anesthetics include:

Isoflurane

- *Hepatic effects*: Although total hepatic blood flow is reduced during isoflurane anesthesia, isoflurane may preserve hepatic blood flow to a greater degree than the other inhalational anesthetics.

Sevoflurane

- *Fluoride*: Sevoflurane is metabolized at an overall rate of 5%, which is much higher than the metabolism rates of isoflurane (0.2%) or desflurane (0.02%). Inorganic fluoride is an end-product of sevoflurane metabolism. No association has been demonstrated between this fluoride production and postanesthetic renal dysfunction (such an association was previously made with the volatile anesthetic methoxyflurane, which is also metabolized to inorganic fluoride).
- *Compound A*: Sevoflurane can degrade in the presence of soda lime to produce a known nephrotoxin called Compound A. Higher levels of Compound A are associated with high respiratory gas temperature, low-flow anesthetic techniques, high sevoflurane concentrations, and sevoflurane anesthetics of long duration. Due to concern about Compound A production,

the package insert for sevoflurane recommends that fresh gas flows be maintained at least 1 L/min. Some anesthesiologists avoid sevoflurane in patients with known renal impairment.

Desflurane

- *Cardiovascular effects*: High concentrations and rapid increases in the concentration of desflurane can cause a transient period of sympathetic activation, with tachycardia and hypertension.
- *Vapor Pressure*: Desflurane's high vapor pressure (669 mmHg at 20 °C) is close to atmospheric pressure, so it almost boils at room temperature. As a result, the desflurane vaporizer is constructed differently than the vaporizers for isoflurane and sevoflurane. The desflurane vaporizer heats and pressurizes the anesthetic gas, then delivers a fractional concentration into the fresh gas flow.

Case Study

You are asked to induce anesthesia for an ENT procedure, in which the surgeon wishes to inspect the airway during spontaneous respiration without the presence of an endotracheal tube or laryngeal mask airway. The patient is otherwise healthy and has a normal appearing airway, and you judge that maintaining the airway by mask will be successful. You agree to induce anesthesia by inhalation. The patient has an IV and standard monitors are in place.

Which inhalation agent will you choose?

The ideal agent would have several properties. It would be relatively potent, so that a high multiple of the minimum alveolar concentration (MAC) could be delivered by the vaporizer during induction. It would have low solubility, so that the "tank" needed to be filled before the brain concentration reaches that needed for anesthesia would be small.

Importantly for inhalation induction in an awake patient, it would be pleasant smelling and would not irritate the airway. Of the available drugs in clinical practice today, nitrous oxide and sevoflurane are not pungent and are therefore potentially suitable for inhalational induction. Nitrous oxide is not potent and indeed at 1 atm the MAC exceeds 100%, meaning it is not possible to fully anesthetize a patient with nitrous oxide alone. It is, however, insoluble and thus has a rapid uptake into the brain. Sevoflurane is relatively potent (a commercial vaporizer can deliver approximately 4 MAC inhaled agent) and has low solubility, making it the preferred choice for inhalational induction of anesthesia.

Would a combination of more than one inhaled agent offer any advantage?

Theoretically, adding nitrous oxide will help speed inhalational induction with sevoflurane. This is because of the two-part "second gas effect." First, the rapid uptake of nitrous oxide from the alveoli will concentrate sevoflurane there, effectively increasing the inhaled concentration. Second, this same uptake will entrain more gas from the trachea (which contains sevoflurane in the case of inhalation induction), effectively increasing alveolar flow of this "second" gas. These physiologic effects have been conclusively demonstrated in research studies. However, in practice, their effect on clinical induction is minimal. Indeed, randomized trials comparing inhalation induction with sevoflurane in oxygen vs. in N_2O plus oxygen have demonstrated no difference in the rate of induction.

What are the factors you can control which will speed induction of anesthesia?

After picking a low solubility and non-pungent agent like sevoflurane, you can also speed induction by increasing the inspired concentration and fresh gas flow. The former causes the gradient across the pulmonary capillary (from the alveolus to the pulmonary vein) to be higher, increasing the amount of drug crossing into the bloodstream. The latter

ensures that expired gas, which will contain very little sevoflurane at the beginning of the anesthetic uptake, will not dilute the inspired gas. Although you cannot directly control it during spontaneous respiration, you can ask the patient to breathe deeply, increasing minute ventilation and increasing transfer of drug from the lung to the pulmonary venous blood. With sevoflurane, these factors can be combined to achieve single-breath induction: the patient breathes out to residual volume and then takes a vital capacity breath of high concentration of sevoflurane (6–8%, with very high fresh gas flow set on the machine). The patient holds the breath as long as possible, increasing uptake into the blood from the high alveolar concentration. Many patients will lose consciousness with this first breath, but will also resume spontaneous respiration shortly thereafter.

You have an end-tidal gas monitor to measure exhaled agent. How will you know when you have the patient deeply anesthetized enough to allow the surgeon to perform laryngoscopy?

Once you have achieved induction of anesthesia and the patient is unconscious, you will continue to have the patient breathe sevoflurane at relatively high inspired concentration as the brain completely equilibrates with the alveolar concentration. While the induction is taking place, these two concentrations are not the same (the brain lags about 2 min behind the alveolus). At equilibrium, the alveolar concentration, as estimated by the end tidal concentration, should reflect the vessel-rich group concentration, which includes the brain and spinal cord. These are the structures that need to be anesthetized for the surgery to begin. The concentration should be somewhat higher than 1 MAC, which is the concentration at which 50% of patients will move in response to surgical stimulation. At 1.3 MAC, 95% will not move. For sevoflurane, with an MAC of 1.7–2%, this means you should strive for an end-tidal concentration of about 2.2–2.6%. Since the goal in this case is to maintain sponta-

neous respiration, you will likely not add opioids or neuromuscular blocking drugs to enhance anesthesia. However, since anesthetic delivery will be interrupted during the surgeon's examination of the airway, you will need to have intravenous agents ready should the patient react, and you and the surgeon will have to maintain close communication during this part of the procedure. In some cases, it is possible to use jet ventilation (directing a high pressure jet of gas from the laryngoscope down the airway) with oxygen and sevoflurane.

Suggested Further Reading

1. Campagna JA, Miller KW, Forman SA (2003) Mechanisms of actions of inhaled anesthetics. N Engl J Med 348:2110–2124
2. Eger EI (2005) Uptake and distribution. In: Miller RD (ed) Anesthesia, 6th edn. Churchill Livingstone, New York, pp 131–153
3. Eger EI, Saidman LJ, Brandstater B (1965) Minimum alveolar anesthetic concentration: a standard of anesthetic potency. Anesthesiology 26(6):756–763

Pharmacology of Local Anesthetics

6

John W. Wolfe and Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xix are reviewed before reading this chapter.

Key Learning Objectives

- Understand the basic mechanisms of local anesthetic action and metabolism
- Appreciate the differences in the properties among commonly used local anesthetics
- Learn the signs of local anesthetic toxicity and its treatment

J. W. Wolfe (✉)
Indiana University School of Medicine, Indianapolis, IN, USA
e-mail: jwolfe@iupui.edu

J. M. Ehrenfeld
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_6

History of Local Anesthetics

Cocaine was the first local anesthetic to be discovered after isolation from coca leaves by Albert Niemann in the 1860s. Cocaine was first used clinically in 1884 by Sigmund Freud, who used it to wean a patient from morphine addiction. Freud and Karl Kollar also noticed the anesthetic effects of cocaine, and Kollar later described its utility as a topical ocular anesthetic. Later in 1884, William Halsted published a description of the injection of cocaine into a sensory nerve to provide surgical anesthesia.

Local Anesthetic Mechanism of Action

The cell membrane of a nerve axon contains sodium and potassium channels that control the flow of ions between the extracellular fluid and the interior of the cell. Local anesthetics exert their effects by inhibition of sodium channels.

When nerve cells are at rest, these sodium channels are in a resting, nonconducting state, and the cell has a resting membrane potential of about −70 mV. During membrane depolarization, the sodium channels open briefly, allowing sodium ions to flow into the cell and the transmembrane potential to rise to +35 mV. After a depolarization, the sodium channels are rapidly inactivated and the resting membrane potential is reestablished. This series of events is collectively referred to as the action potential.

Local anesthetics preferentially bind to sodium channels in the open or inactivated state and prevent ion conduction. When local anesthetic molecules have bound to a sufficient number of sodium channels, the membrane is unable to depolarize sufficiently to reach the threshold potential, and generation of an action potential is prevented.

Factors Affecting Local Anesthetic Action

- ***Fiber size and type***: Peripheral nerves contain myelinated A and B fibers and unmyelinated C fibers, as outlined in Table 6.1. In general, smaller nerve fibers of the same type are more readily blocked than larger fibers, yet the smaller unmyelinated fibers are less easily blocked than the larger myelinated ones. The "size principle" leads to the commonly observed phenomenon of *differential conduction blockade*, in which sympathetic fibers are more easily blocked than pain and temperature fibers, which are more easily blocked than motor, pressure, and proprioceptive fibers. Clinically, this phenomenon is seen in patients who may have incomplete blockade of motor fibers and pressure sensations despite sympathectomy and blockade of pain sensations. There is considerable overlap of local anesthetic sensitivity among nerve fiber types.
- ***pH***: Most local anesthetics are weak bases that exist as an equilibrium of a more lipid soluble, neutral form and a less lipid soluble, charged form. The local anesthetics typically have pK_a's greater than 7.4, so less than 50% of the drug exists in the lipid soluble form in normal extracellular fluid. Additionally, commercial preparations of local anesthetics typically have pH's between 6 and 7, further increasing the proportion of the drug in the protonated form. The action of local anesthetics requires that their molecules permeate lipid-rich neural membranes to reach their site of action. Clinical implications of these factors are:
  - Addition of sodium bicarbonate to the local anesthetic solution (typically 1 mL of sodium bicarbonate solution to

Table 6.1 Pain fiber types

Fiber type	Local anesthetic sensitivity	Size	Myelination
A	+	Large	Yes
B	++	Medium	Yes
C	+++	Small	No

10 mL of local anesthetic) increases pH and the fraction of local anesthetic in neutral form, speeding onset of action.
  - Tissues with local acidosis (e.g., infected or ischemic tissues) will be relatively resistant to local anesthetic action.
- ***Use-dependent blockade***: Access to sodium channels is enhanced by repeated membrane depolarization because depolarization increases the time that the channels spend in the open or inactivated forms. Frequent action potentials in the presence of local anesthetic speeds onset of neural blockade.
- ***Epinephrine***: Epinephrine affects local anesthetic action in two ways:
  - Epinephrine-containing local anesthetic solutions are formulated at lower pH's (4–5) than plain local solutions because of epinephrine's instability in alkaline environments. Low pH slows onset of local anesthetic action as described above.
  - Epinephrine causes local vasoconstriction and slows absorption of the local anesthetic from its site of deposition, prolonging local anesthetic action. This effect is prominent with the shorter-acting local anesthetics (e.g., the duration of lidocaine blockade can be increased 50% by addition of epinephrine). The longer-acting local anesthetics (bupivacaine and ropivacaine) are released so slowly from neural tissue that epinephrine does not significantly increase their durations of blockade, but does decrease their peak blood concentrations after injection.

Local Anesthetic Metabolism

The action of local anesthetics is terminated by absorption of the drug from the site of action into the circulation. Following absorption, the drug is metabolized and excreted.

Local anesthetics fall into two structural categories, **amides** and **esters**. A schematic representation of local anesthetic structure is shown in Fig. 6.1.

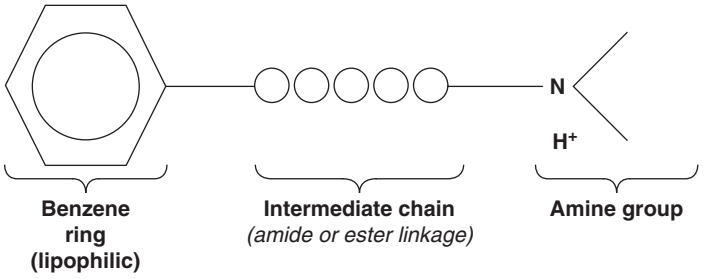


Fig. 6.1 Local anesthetic structure

- **Amides** are metabolized by microsomal enzymes (cytochromes) in the liver
- **Esters** are primarily metabolized by pseudocholinesterase in the plasma (the exception is cocaine, which is partially metabolized by the liver and partially excreted unchanged by the kidneys)

Peak blood levels of local anesthetics are related to the dose administered and the rate of absorption of the drug from its site of action. Injection into a highly vascular area leads to higher blood levels of the drug than placing a similar amount of drug into a less vascular area. The rank order of peak blood concentrations of local anesthetic after administration of the same dose of drug at different sites is shown below:

> intravenous > tracheal > intercostal > caudal > epidural > brachial plexus > sciatic > subcutaneous injection

Epinephrine and other vasoconstrictors slow the rate of absorption.

Strongly protein-bound local anesthetics (e.g., bupivacaine and ropivacaine) tend to be more lipid soluble, more potent, and have longer times to onset, longer durations of action, and slower absorption from neural tissue (Table 6.2).

Table 6.2 Properties of common local anesthetic agents

	Agent	Onset of action	pK_a (36 °C)	Max dose (mg/kg)[a]	Duration of action (h)
Amides	Lidocaine	Rapid	7.8	4.5 (7 with epi)	1–2
	Mepivacaine	Moderate	7.7	5 (7 with epi)	1.5–3
	Prilocaine	Slow	8.0	6 (9 with epi)	1–2
	Ropivacaine	Slow	8.1	2.5 (3 with epi)	4–8
	Bupivacaine	Slow	8.1	2.5 (3 with epi)	4–8
Esters	2-Chloroprocaine	Very Rapid	9.1	9 (15 with epi)	0.5–1
	Procaine	Rapid	8.9	7 (10 with epi)	0.75–1
	Tetracaine	Slow	8.4	1.5(2.5 with epi)	3
	Cocaine	Rapid	8.7	1.5	0.5

[a] Maximum dose for a single subcutaneous injection

Uses of Local Anesthetics in Anesthesia Practice

While local anesthetics can be directly injected into incisions to block pain, anesthesiologists typically use them in ways that target specific nerve structures. Local anesthetics may be used in peripheral nerve blocks, compartment blocks (such as TAP blocks), epidural anesthesia and analgesia, and spinal anesthesia. Lidocaine is often used to numb patients' skin before IV or arterial line placement. Lidocaine is also administered intravenously during induction of anesthesia to blunt the patient's sympathetic response to laryngoscopy and to reduce the pain that can occur during propofol administration. A newer drug, the liposomal bupivacaine, allows for extended release of the local anesthetic and can be used for nerve blocks and wound infiltration.

Local Anesthetic Side Effects and Toxicity

- ***Central nervous system effects***: Dysfunction of the central nervous system is often the first sign of local anesthetic toxicity. Signs and symptoms of local anesthetic toxicity tend to follow a stereotypical sequence. Early symptoms may include lightheadedness, perioral or tongue numbness, or a metallic taste. Higher levels may lead to tinnitus, visual dysfunction, agitation, and anxiety. Central nervous system depression can follow, with unconsciousness, respiratory arrest, and seizure activity. Local anesthetic-induced seizures can be treated with hyperventilation, benzodiazepines, or small doses of thiopental or propofol.
- ***Cardiovascular effects***: If blood concentrations rise high enough, local anesthetics can bind to sodium channels present on myocardial cells. This reduces myocardial automaticity and shortens the refractory period. Cardiac arrhythmias, depressed contractility, and cardiac arrest can ensue. In general, the high-potency agents such as bupivacaine and ropivacaine have greater cardiotoxicity than the lower-potency agents. Successful resuscitation of a patient with local anesthetic-induced cardiotoxicity can require prolonged efforts and may prove to be difficult (or impossible). *Of note, cardiotoxic effects of bupivacaine and ropivacaine have been observed to occur without promontory central nervous system effects.*
- ***Neurotoxicity***:
  - *Lidocaine*: Permanent neurologic injury (cauda equina syndrome) has been associated with infusion of 5% lidocaine through spinal microcatheters. It has rarely been observed after single-dose spinal injections. It is thought that pooling of this concentrated local anesthetic solution around nerve fibers may cause neurotoxic effects.
  - *2-Chloroprocaine*: 2-chloroprocaine was used for spinal anesthesia in the 1950s, and is still commonly used for epidural anesthesia (particularly in obstetrics). In the early

1980s, multiple cases of neurological injury were associated with accidental intrathecal injections of large doses of chloroprocaine. Investigations showed that a likely cause of injury was the low pH and metabisulfite preservative in the solutions used. Plain, preservative-free 2-chloroprocaine in appropriate intrathecal doses appears to be no more neurotoxic than other commonly used spinal anesthetic solutions, and it may carry a reduced risk of TNS (see below).

  - *Transient neurologic symptoms (TNS)*: Patients receiving spinal anesthesia may have transient hypesthesias, paresthesias, and motor weakness in the legs or buttocks. TNS is significantly more common with lidocaine than with bupivacaine or tetracaine (and likely 2-chloroprocaine). TNS symptoms typically resolve within 3 days, but occasionally may persist for as long as 6 months.

- ***Methemoglobinemia***: Larger doses of prilocaine and benzocaine (a common ingredient in local anesthetic sprays) can convert hemoglobin to methemoglobin. Infusion of 1–2 mg/kg of methylene blue reverses this reaction.
- ***Hypersensitivity/Allergy***: While an adverse reaction to a local anesthetic is not uncommon, a true allergy is exceedingly rare. Allergic reactions are most often associated with esters because of sensitivity to their metabolite, para-aminobenzoic acid (PABA). Should this occur, consider switching to an amide anesthetic.

Treatment of Local Anesthetic Toxicity

Infusion of 20% lipid emulsion solution (such as Intralipid) has been reported to be effective in reversing the symptoms of local anesthetic toxicity. The presumed mechanism of action is that the lipid-soluble fraction of the local anesthetic is sequestered in the lipid emulsion and effectively removed from the plasma. The following treatment protocol has been proposed (see www.lipidrescue.org):

- Bolus 1.5 mL/kg of 20% lipid emulsion, then run 0.25 mL/kg/min for 10 min.
- Repeat the bolus dose and double the infusion rate for persistent asystole or hemodynamic instability.
- Avoid vasopressin, beta blockers, and calcium channel blockers.
- Epinephrine should be avoided or given in small doses (less than 1 mcg/kg).

Case Study

A 70 kg, otherwise healthy male patient is undergoing bilateral inguinal herniorrhaphy under local anesthesia administered by the surgeon. You are providing intravenous sedation. The surgeon is planning to infiltrate the skin with lidocaine prior to skin incision. The patient reports a history of an "allergic reaction" to Novocain (procaine) which he received during a dental procedure. Is it safe to administer the planned local anesthetics?

Most dental reactions are not true allergies, but either unpleasant sensations from the intended local anesthetic effect (numb tongue and lips that feel swollen), or tachycardia from absorbed epinephrine. Even if the patient were truly allergic to procaine, it is exceedingly unlikely that he would also be allergic to lidocaine or bupivacaine, which are amide type local anesthetics, whereas procaine is an ester type drug.

The surgeon is planning to use 2% lidocaine with epinephrine for initial infiltration, followed by bupivacaine, 0.5% for longer lasting analgesia. How can she enhance the onset of the block?

Lidocaine with epinephrine is prepared with a very low pH (4–5) in order to stabilize the epinephrine, which is unstable at neutral or basic pH. At this low pH, only a tiny fraction of the lidocaine will be in the uncharged, base form,

which can permeate nerve cell membranes. The addition of bicarbonate (1 mL per 10 mL of local anesthetic solution) will raise the pH and the basic fraction, speeding the onset. Raising the solution pH also has the benefit of significantly reducing the pain of injection.

After infiltration with lidocaine, the surgeon is prepared to infiltrate further with bupivacaine and perform some deep nerve blocks to enhance analgesia. She asks you how much of a 0.5% solution she can safely use. How will you respond?

The limit for a single subcutaneous infiltration of bupivacaine is approximately 2.5 mg/kg. A 0.5% solution of bupivacaine contains 5 mg/mL, so the surgeon can use 175 mg, or 35 mL. This is an estimate based on average rates of absorption, and in practice, actual toxicity often does not occur even at doses higher than this. Conversely, this limit assumes no drug is injected intravascularly.

The surgeon begins infiltration with bupivacaine. After about 15 mL have been injected, the patient complains of lightheadedness, and then his eyes roll back and loses consciousness. The patient develops tonic-clonic movements of his extremities. How will you respond?

Seizures associated with local anesthetic toxicity are treated symptomatically. Tell the surgeon to immediately stop injecting to limit further toxicity. You should administer supplemental oxygen and maintain the airway. If the patient is not breathing, you should administer positive pressure ventilation by mask. Intubation is not always necessary, as seizures associated with local anesthetic are often short lived. A small dose of midazolam (a benzodiazepine) or propofol will help terminate the seizure.

Despite your initial efforts, the patient remains unresponsive. The electrocardiogram shows ventricular tachycardia. You cannot palpate a pulse. How will you proceed?

Your patient has developed a much more severe form of toxicity, cardiovascular compromise. This syndrome is

associated with potent lipophilic anesthetics such as bupivacaine (had the surgeon only been using lidocaine, this complication would have been less likely). Immediate treatment is supportive: call for help, administer chest compressions, obtain a defibrillator, and begin ACLS treatment for ventricular fibrillation. Remember that epinephrine should be avoided or given in small doses in this situation. Have a team member bring a bag of 20% lipid emulsion and start infusing it as early as possible (1.5 mL/kg bolus followed by 0.25 mL/kg/min for 10 min). Repeat the bolus and double the infusion rate if the first doses are not effective. Unfortunately, bupivacaine associated cardiotoxicity is often very difficult to reverse. In extreme cases where all other treatments have failed, emergency cardiopulmonary bypass support has been used to buy time for patients to metabolize the local anesthetic and recover a normal cardiac rhythm.

Suggested Further Reading

1. Cousins MJ, Bridenbaugh PO, Carr DB, Horlocker TT (2008) Neural blockade in clinical anesthesia and pain medicine. Lippincott, Williams, and Wilkins, Philadelphia
2. Evers AS, Maze M, Kharasch (eds) (2011) Anesthetic pharmacology – basic principles and clinical practice. Cambridge University Press, New York
3. Morgan GE, Mikhail MS, Murray MJ (2006) Local anesthetics. In: Clinical anesthesiology. McGraw Hill, New York
4. www.lipidrescue.org

Pharmacology of Adjunct Agents

7

John W. Wolfe and Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xx are reviewed before reading this chapter.

Key Learning Objectives

- Understand the clinical properties and uses of direct and indirect-acting sympathomimetic drugs
- Learn the mechanism of action of antiemetic drugs
- Review the properties of nonsteroidal anti-inflammatory drugs

Sympathomimetics

Sympathomimetics (or vasopressors) are drugs that are used to support the cardiovascular system, particularly the blood pressure. They work by individually or collectively affecting arterial

J. W. Wolfe (✉)
Indiana University School of Medicine, Indianapolis, IN, USA
e-mail: jwolfe@iupui.edu

J. M. Ehrenfeld
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_7

vasoconstriction, heart rate (chronotropism), and contractility (inotropism). Many patients who require surgery are dehydrated, have a significant systemic illness, or an underlying cardiovascular disease. As most anesthetic agents cause vasodilation and depress cardiac contractility, the temporary use of vasopressors is frequently required so that patients can tolerate anesthesia without suffering hypotension and risking organ injury. The two most common vasopressors used in the administration of anesthesia to adults are ephedrine and phenylephrine (Table 7.1).

Ephedrine is an indirect-acting vasopressor that has both alpha (vasoconstriction) and beta (increased heart rate and contractility) receptor effects. Ephedrine's principal mechanism of action is to cause the release of norepinephrine from neuronal storage vesicles at the nerve terminus. This additional norepinephrine in the synaptic space then binds to and activates adrenergic receptors. Ephedrine is usually administered to patients who have both low blood pressure and low heart rate. In addition to having vasopressor effects, ephedrine is also a bronchodilator, and it can be administered to treat bronchospasm.

Phenylephrine acts on alpha receptors causing increased vascular resistance and blood pressure. It has no beta agonist effects and frequently causes a reflex bradycardia (i.e. high blood pressure stimulates baroreceptors thereby decreasing heart rate). Phenylephrine is usually administered to patients who have low

Table 7.1 Actions of vasoactive receptor sites

Receptor	Receptor site action
α-1	Glycogenolysis, gluconeogenesis, constricts vascular smooth muscle, relaxes GI tract
α-2	Constricts vascular smooth muscle, decreases insulin secretion and norepinephrine release
β-1	Increases heart rate and contractility, secretion of renin
β-2	Glycogenolysis, gluconeogenesis, relaxes vascular smooth muscle and bronchioles
D-1	Increases renin release, dilates vascular smooth muscle
D-2	Constricts smooth muscle, inhibits norepinephrine release

blood pressure and high heart rates. It must be used with caution in patients with ischemic heart disease, as it can decrease cardiac output by increasing afterload.

Norepinephrine acts on both alpha and beta receptors, with alpha activity predominating. Norepinephrine leads to increases in blood pressure primarily by causing increased systemic vascular resistance. Similarly to phenylephrine, norepinephrine can cause a reflex bradycardia and can reduce cardiac output despite raising blood pressure.

Epinephrine is a direct-acting agent which activates both alpha and beta receptors. Like ephedrine, epinephrine will cause an increase in heart rate and contractility, increase vascular resistance, and cause bronchodilation. Epinephrine has a very short duration of action and is often administered as an infusion. Tachycardia can be significant, and epinephrine should be used cautiously in patients who may be harmed by an elevated heart rate.

Dopamine acts on alpha, beta, and dopamine receptors, depending on the dose administered. At low doses (<3 μg/kg/min), dopamine will redistribute blood flow to the kidneys and may increase urine output. At higher doses, alpha and beta receptor actions predominate, leading to increased heart rate, cardiac contractility, and systemic vascular resistance.

Table 7.2 depicts commonly used vasopressors and their sites of action, and Table 7.3 depicts dosing regimens for these drugs.

Table 7.2 Receptor actions of commonly used vasopressors

Drug	Direct	Indirect	Site of action
Ephedrine	+	++	α, β
Epinephrine	++		α, β
Phenylephrine	++		α
Norepinephrine	++		α > β
Dopamine	++	+	α, β, D

Table 7.3 Vasopressor dosing (adults)

Ephedrine	2.5–10 mg IV bolus
Phenylephrine	40–100 μg IV bolus or 20–150 μg/min infusion
Norepinephrine	0.01–0.1 μg/kg/min infusion
Epinephrine	20–100 μg IV bolus or 0.5–20 μg/min infusion
Dopamine	2–20 μg/kg/min infusion

Antiemetics

Postoperative nausea and vomiting (PONV) is one of the leading reasons for patient complaints, delayed postoperative discharge, and patient dissatisfaction with their anesthesia experience. There are various mechanisms by which surgery and anesthesia can cause nausea and vomiting, and there are many different drugs available for prevention and treatment of PONV.

Serotonin antagonists are the mainstay of PONV prophylaxis and treatment. These drugs work by blocking 5HT3 receptors. Ondansetron is by far the most commonly used serotonin antagonist, but granisetron is also available. Serotonin antagonists are commonly administered near the end of surgery and can also be used for PONV treatment in the recovery area. Side effects are unusual, but may include headache, lightheadedness, or drowsiness.

Promethazine is a common second line agent for treatment of nausea and vomiting that has not responded to a serotonin antagonist. Promethazine is a nonselective antihistamine that may lead to drowsiness or sedation, and should be used with caution in elderly patients and in situations where excessive sedation could be dangerous (for example, patients with obstructive sleep apnea).

Dexamethasone is recommended as part of a prophylactic regimen (typically in concert with a serotonin antagonist) for patients at moderate or high risk for postoperative nausea and vomiting. The exact mechanism by which dexamethasone decreases PONV is still unknown. Side effects are minimal at the recommended dose ranges.

Droperidol and haloperidol block the transmission of dopamine, serotonin, and GABA. They are typically used as third-line antiemetics and are effective in both prophylactic and rescue roles. In the past, there have been concerns about QT prolongation and dysrhythmias, particularly with droperidol. More recently, the FDA has clarified that the warning about QT prolongation applies to droperidol doses above 2.5 mg and therefore does not apply to typical antiemetic usage. Haloperidol and droperidol should probably be avoided in patients with known long QT's. Sedation is the main side effect of these medications. **Amisulpride**, another dopamine receptor antagonist but with fewer side effects, has been recently approved for the prevention of PONV.

Scopolamine is an anticholinergic drug which is often administered preoperatively via a transdermal patch (lasts up to 3 days). Patients should be counseled to wash their hands after the removal of a scopolamine patch, as inadvertent rubbing of the eyes may lead to prolonged pupillary dilation. Side effects include dry mouth, blurry vision, and drowsiness.

Aprepitant is a neurokinin-1 antagonist. It is an oral medication and should be given preoperatively. Aprepitant should only be used as a prophylactic antiemetic because it is relatively ineffective as a rescue antiemetic for patients already suffering PONV.

Commonly used antiemetics and their dosages are outlined in Table 7.4.

Table 7.4 Commonly used antiemetics[a]

Ondansetron	4 mg IV, may repeat × 1 (0.1 mg/kg up to 4 mg in children)
Granisetron	0.5–1 mg IV
Promethazine	12.5–25 mg IV, may repeat × 1
Dexamethasone	4–8 mg IV, best given early in the intraoperative period
Droperidol	0.625–1.25 mg IV
Haloperidol	0.5–1 mg IV
Aprepitant	40 mg PO

[a]All dosages for adults unless noted

Antihypertensives

A full discussion of all antihypertensive agents is beyond the scope of this text, but it is worth noting that many patients require blood pressure reduction perioperatively. As with many anesthetic agents, favored antihypertensives tend to be available intravenously and have short (or at least consistent) durations of action.

Beta blockers such as metoprolol or labetalol are easy to dose and have been shown in studies to positively affect outcomes in patients with preexisting coronary artery disease. Esmolol is a pure β1 receptor antagonist that is commonly used intraoperatively, because of its extremely quick onset and short duration of action. Calcium channel blockers can be administered as boluses or precisely titrated as infusions and are frequently used for tight control of blood pressure (nicardipine), or for control of arrhythmias (diltiazem). Hydralazine, a direct-acting smooth muscle relaxant which preferentially vasodilates the arterial system, is frequently used in the recovery room for treatment of refractory hypertension, due to its potency and longer duration of action.

Dexmedetomidine

Dexmedetomidine is an α2 agonist that can be used for sedation, analgesia, or balanced anesthesia. It is popular as a sedative because it provides minimal respiratory depression, and patients can be aroused from the sedation to follow commands. This is especially useful for sedation and weaning of mechanically ventilated patients prior to extubation in the ICU. Dexmedetomidine has also gained popularity for procedures such as awake fiberoptic intubations, TEEs, awake craniotomies, and other neurosurgical cases that require frequent intraoperative assessment. In addition to sedation, positive side effects include analgesia, amnesia, and activity as an antisialogues. Possible negative side effects include a reduction in serum catecholamines which can lead to bradycardia and hypotension. Dexmedetomidine has a slow onset of action (10–20 min), and is typically loaded as a bolus of 0.5–1 μg/kg over 10 min, followed by an infusion of 0.2–0.7 μg/kg/h.

NSAIDs (Nonsteroidal Anti-inflammatory Drugs)

NSAIDS are nonopioid medications that have analgesic, anti-inflammatory, and anti-fever properties. They act by inhibiting the enzyme cyclooxygenase (COX), preventing the conversion of arachidonic acid into prostaglandins.

Ketorolac is the most commonly available IV NSAID in the U.S. It is a nonselective COX inhibitor, which can reduce or eliminate the need for opioids in surgical patients. Debatable concerns exist over delayed bone healing, excessive bleeding, and renal toxicity (use half the dose in patients with mild renal failure, avoid in patients with severe renal failure), but these are typically not a concern with short-term perioperative dosing. The typical dose is 30 mg, or 0.5 mg/kg up to 60 mg.

Case Study

You are asked to provide anesthesia for a woman undergoing needle-directed breast biopsy. She has had several past anesthetics and has not had good experiences. She explains that she has had severe nausea after all her general anesthetics, and that she has been very somnolent after general anesthesia as well as after monitored anesthesia care (local anesthetic plus sedation). Review of her medical record shows that she received reasonably ordinary general anesthesia, with a potent inhaled agent, nitrous oxide, and fentanyl. For her MAC case, she received intravenous boluses of midazolam and fentanyl. After both anesthetics, she recalls experiencing significant pain but could not tolerate oral opioids prescribed for her. She is motivated to avoid general anesthesia and would like you to develop an anesthetic plan that reduces her risk of excessive somnolence and nausea. She is otherwise healthy, exercises regularly, does not smoke or drink, and takes no medication regularly. She has fasted overnight.

The surgeon believes that she can perform the procedure under local anesthesia plus intravenous sedation (MAC). What drugs will you select for sedation?

Her principal problem with sedation in the past has been excessive somnolence. Midazolam and fentanyl are both thought of as short acting drugs, although their effects are quite variable among individuals and are dose-related. A review of her previous record may reveal whether she is very sensitive to the effects or if large doses were used. Alternatives include intravenous infusions of drugs with rapid elimination or termination of effect (see the discussion of context sensitive half time, Chap. 4). You could consider propofol by infusion at doses less than that used for TIVA, 25–100 μg/kg/min. This drug has the additional advantage that it is associated with a low incidence of nausea. Dexmedetomidine would be an alternative, and has been used successfully for sedation during even complex and painful procedures such as awake fiber-optic intubation or awake craniotomy. It has little "hangover" sedation, and patients can generally be alert within minutes after discontinuing an infusion. It can cause bradycardia and hypotension, but in this healthy patient, these are likely to be well tolerated. Finally, it is possible to perform this case with only analgesia and sedation for the local anesthetic infiltration, and then no other sedatives during the case, if the patient is motivated, as she states she is. A popular approach is to use a bolus of a very short-acting analgesic just prior to infiltration by the surgeon that will provide 3–5 min of sedation and analgesia. Remifentanil, 1 μg/kg, given 75 s before the painful stimulus, offers such an effect and is very rapidly eliminated by ester hydrolysis shortly thereafter. Alfentanil, 1000–1500 μg, is an alternative with a similar but slightly slower elimination.

What strategy will you follow to control her pain?

This procedure should not cause much postoperative pain, so there is no need for large doses of opioids, which could contribute to both nausea and somnolence. A multimodal approach is therefore indicated, including careful use of local anesthetic by the surgeon both before incision

(which may reduce postoperative pain) and at the end of the procedure with a long-acting local anesthetic such as bupivacaine. If bleeding risk is not high, as it should not be in this case, a dose of an NSAID such as ketorolac, will help postoperatively and has an additional benefit of being anti-inflammatory, which may reduce pain even after its immediate analgesic effect has dissipated. Some drugs considered for sedation, notably dexmedetomidine and ketamine, have analgesic properties themselves. Finally, long-lasting pain control via nerve blocks can be offered. In breast surgery, a popular option is a PECS block, which provides analgesia for the breast. In this limited operation, this may be overly aggressive, but consultation with the surgeon regarding the extent of the resection, and with the patient, regarding her expectations and experiences with postoperative pain, are needed to decide.

What strategy will you follow to avoid postoperative nausea?

This healthy, nonsmoking woman, with a history of PONV, is at high risk of recurrent symptoms. By one popular risk assessment scale, she would be expected to have a 60% chance of PONV after outpatient general anesthesia. The use of the MAC technique should reduce her risk somewhat, particularly if opioids are avoided. Should she need general anesthesia, elimination of nitrous oxide, use of propofol for induction and maintenance of anesthesia, and avoidance of neuromuscular blockade, to avoid the emetogenic effects of NMB reversal agents, are all prudent choices. In any case, prophylactic antiemetics are indicated for this high risk situation. A popular combination is dexamethasone and ondansetron. Another good choice for outpatient surgery is a scopolamine patch, placed preoperatively. This patch elutes low dose scopolamine for up to 3 days, a distinct advantage over other drugs available on the day of surgery. It can be added as a third drug or substituted for dexamethasone. Patients should be counseled about its side

effects of dry mouth and blurry vision and instructed to wash their hands carefully after removing the patch, to avoid pupillary dilation should they get the drug in their eyes. Additionally, aprepitant could be administered in the pre-operative period.

Suggested Further Reading

1. Gan TJ, Belani KG, Bergese S, Chung F, Diemunsch P, Habib AS, Jin Z, Kovac AL, Meyer TA, Urman RD, Apfel CC, Ayad S, Beagley L, Candiotti K, Englesakis M, Hedrick TL, Kranke P, Lee S, Lipman D, Minkowitz HS, Morton J, Philip BK (2020) Fourth consensus guidelines for the management of postoperative nausea and vomiting. Anesth Analg 131(2):411–448
2. Katzung BG, Furst DE, Ulrich RW, Prakash S (2001) Chapter 36: Nonsteroidal anti-inflammatory drugs. In: Basic and clinical pharmacology. McGraw Hill, New York, pp 635–658
3. Butterworth JF, Mackey DC, Wasnick JD (2022) Chapter 14: Adrenergic agonists and antagonists. In: Clinical anesthesiology. McGraw Hill, New York, pp 235–249

Part III

Preoperative Considerations

The Preoperative Patient Evaluation

8

Angela F. Edwards and Naucika DeSouza

Introduction

Preoperative evaluation and risk stratification are critical elements in optimizing patients for surgery and postoperative recovery. Preoperative medical optimization requires a review of the patient's history, medications, review of systems, and a physical examination. The preoperative visit is more than preanesthesia assessment or clearance for surgery. This may represent the first careful cardiopulmonary evaluation for a patient in years as some patients lack access to primary care. This is an opportunity to evaluate the known, and previously undiagnosed, comorbidities relative to the anticipated stress of surgery and engage the patient in discussing potential outcomes. Mitigating risks of postoperative complications and discussing patient centric outcomes is the goal of the visit. Furthermore, this is an opportunity to ensure the patient is undergoing the right procedure at the right time for their current physiologic state. Generally, the goals of the preoperative evaluation are to assess and mitigate risk, not clear the patient for surgery. Clearance is rarely possible as there is no eliminating the inherent risks of surgery.

A. F. Edwards (✉) · N. DeSouza
Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA
e-mail: afedward@wakehealth.edu; nmdesouz@ncsu.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_8

Critical elements of the preoperative evaluation include:

- obtaining a thorough history and physical examination with functional status
- reviewing medical records, including previous anesthetic records
- performing a detailed airway assessment
- ordering only necessary tests and consultations that will change management
- adjust medications according to procedure and anticipated anesthetic management
- establishing rapport to engage in shared decision-making following risk stratification
- obtaining informed consent

The goals of the encounter include:

- Minimize perioperative risks for the patient; optimize medical conditions
- Qualify and quantify the known medical conditions. Plus, perform a detailed history and exam to identify the as yet undiagnosed conditions.

The Interview

A vital component of the preoperative evaluation is the initial interview. Fear, anxiety, uncertainty, loss of control, and/or vulnerability are common emotions experienced by patients prior to surgery. A high anxiety state may have a negative impact on recovery and lead to increased opioid use due to pain catastrophizing. Well-informed patients experience less anxiety, are more easily mobilized, tend to be more satisfied, and report better overall postoperative well-being. Hence, the development of a positive doctor-patient relationship can provide a strong foundation for better overall outcomes.

History and Physical

Obtaining a thorough history, review of systems, and physical examination is an essential part of establishing and mitigating risk in the perioperative period. A systematic approach to collecting patient history should be implemented to ensure all relevant systems are reviewed.

Cardiovascular

In evaluating the patient's cardiovascular risk, the main objective should be to decide whether a patient needs further cardiac testing (stress test) or intervention (cardiac catheterization or cardiac surgery) prior to elective surgery. The goal is to minimize postoperative risks of major adverse cardiac events (MACE) or myocardial injury after non cardiac surgery (MINS). There are several risk calculators, such as the Revised Cardiac Risk Index (RCRI), Myocardial injury or Cardiac Arrest (MICA or GUPTA), American College of Surgeons, National Surgical Quality Improvement Project (ACS NSQIP), which quantitate risks. Moreover, there are guidelines (American College of Cardiology/American Heart Association, ECC, etc.) established to assist and further risk stratify [1]. Use of any of the three surgical risk calculators (RCRI, MICA, or the ACS-NSQIP) is appropriate as part of the perioperative cardiovascular risk stratification process to determine if further testing or postoperative surveillance is in order [2]. Each one of these risk stratification tools incorporates comorbid conditions which pose varying degrees of risk relative to the surgical procedure, estimated blood loss, and inherent degree of medical management. Table 8.1 demonstrates the different characteristics of the three major cardiovascular risk calculators.

Initially, patients should be asked for a history of cardiopulmonary problems including dyspnea (during rest or with exertion), angina or anginal equivalents, chest tightness, edema,

Table 8.1 Characteristics of major cardiac risk calculators

	RCRI (Lee)	MICA (Gupta)	ACS NSQIP
Methodology	Prospective	Historical NSQIP	Historical NSQIP
# of patients	4315	468,795	1,414,006
Age	>50	>16	>16
Type of surgery	Nonemergent, noncardiac, anticipated LOS >2 days	21 categories, excluded trauma and transplant patients	1500+ CPT codes
# Risk factors	6-surgery, coronary artery disease, heart failure, CVA, diabetes mellitus, chronic kidney disease	5 - surgery, functional status, ASA class, age, chronic kidney disease	21 risk factors entered into online calculator
Outcomes	Myocardial infarction (MI), pulmonary edema, V fibrillation / cardiac arrest	MI, cardiac arrest	MI, cardiac arrest, multiple noncardiac
Time frame	In-hospital	30 days	30 days

Compiled from Cohn SL, et al. Am J Cardiol 2018;121(1):125–130
RCRI revised cardiac risk index, *MICA* myocardial injury or cardiac arrest, *ACS NSQIP* American College of Surgeons National Surgical Quality Improvement Project

hypertension, coronary artery disease, arrhythmias, myocardial infarction, cardiac surgery, cardiac implanted device, use of anticoagulants, antihypertensives, beta blockers, diuretics, recent electrocardiogram, echocardiogram, or stress test results.

Functional status and activities of daily living are vital to establishing need for further testing, risk of increased hospital length of stay (HLOS) and risk of hospital readmission. Using either the Duke Activity Index Score (DASI) or directly estimating metabolic equivalents (METs) based on patient activities is ideal since this is a major decision point when utilizing the 2014 ACC/AHA guidelines for evaluating the cardiac patient for noncardiac surgery [3].

There is a correlation between lower functional status (METS <4) and poor perioperative outcomes. Hence, additional testing or intervention may be recommended in this population if it will

change perioperative management or outcomes in patients whose activity level is <4 METs.

Table 8.2 illustrates the various activities associated with estimated energy requirements.

The DASI questionnaire, Table 8.3, uses specific questions to establish metabolic equivalents of activity. The specific questions are weighted according to estimated level of difficulty. The sum of the indices provides the total score and an estimate of METS. Examples are provided in specific terms such that a patient can answer independently. The METs trial provided comparative data regarding formal cardiopulmonary exercise testing, biomarkers (BNP) and the DASI questionnaire. In that trial, the DASI questions performed better at ascertaining functional status than

Table 8.2 Estimated energy requirements (METs) for various activities

Functional capacity	Estimated METs	Activity
Poor	1	Eating, getting dressed, working at a desk
	2	Showering, walking down eight steps
	3	Walking on a flat surface for one or two blocks
Moderate	4	Raking leaves, weeding or pushing a power mower
	5	Walking 4 miles per hour, social dancing, washing car
	6	Nine holes of golf carrying clubs, heavy carpentry, using push mower
Excellent	7	Digging, spading soil, singles tennis, carrying 60 lb
	8	Moving heavy furniture, jogging slowly, rapidly climbing stairs, carrying 20 lb. upstairs
	9	Bicycling at a moderate pace, sawing wood, slow jumping rope
	10	Brisk swimming, bicycling uphill, walking briskly uphill, jogging at 6 MPH
	11	Cross-country skiing, full court basketball
	12	Running continuously at 8 MPH

Adopted from Weinstein AS, et al. Anesthesiol Res Pract 2018;2018:5912726

Table 8.3 Duke Activity Score Index (DASI)

Are you able to do the following: (answer yes or no)	Yes	No	Index
Take care of yourself, that is, eat, dress, bathe, or use the toilet?			2.75
Walk indoors, such as around your house?			1.75
Walk 200 yards on level ground?			2.75
Climb a flight of stairs or walk up a hill?			5.50
Run a short distance?			8.00
Do light work around the house like dusting or washing dishes?			2.70
Do moderate work around the house like vacuuming, sweeping floors, or carrying groceries?			3.50
Do heavy work around the house like scrubbing floors or lifting or moving heavy furniture?			8.00
Do yard work like raking leaves, weeding, or pushing a lawn mower?			4.50
Have sexual relations?			5.25
Participate in moderate recreational activities like golf, bowling, dancing, doubles tennis, or throwing a ball?			6.00
Participate in strenuous sports like swimming, singles, tennis, football, basketball, or skiing?			7.50

Available at: https://www.mdcalc.com/duke-activity-status-index-dasi

stress testing, beta natriuretic peptide (BNP) and subjective assessments [4].

The addition of the indexes for the boxes checked "yes" provide DASI score and a corresponding metabolic equivalent; thus, providing the clinician with an objective assessment of functional status to be used in further cardiovascular assessment.

In summary, cardiovascular history and review of systems combined with an assessment of functional status (METS) determine need for additional cardiovascular testing or intervention if delay in the surgical procedure is an option.

Pulmonary

Postoperative pulmonary complications (PPCs) are a major cause of postoperative morbidity, mortality, and increased length of hospital stay. Several risk factors have been associated with PPCs, including age, chronic obstructive pulmonary disease (COPD), cigarette use, heart failure (HF), functional dependence, obesity, and obstructive sleep apnea (OSA) or sleep disordered breathing [5]. These elements are included in the ARISCAT risk calculator (Table 8.4) which provides an estimate of postoperative pulmonary complications [6, 7].

Table 8.4 Risk of postoperative pulmonary complications according to ARISCAT score

ARISCAT score variable	Answer choices	Pts
Patient age	≤50	0
	51–80	3
	>80	16
Preoperative SpO_2	≥96%	0
	91–95%	8
	≤90%	24
Respiratory infection in past month: Either upper or lower (URI, bronchitis, pneumonia), with fever and antibiotic treatment	No	0
	Yes	17
Preoperative anemia (Hb ≤10 g/dL)	No	0
	Yes	11
Surgical incision	Peripheral	0
	Upper abdominal	15
	Intrathoracic	24
Duration of surgery	<2 hrs	0
	2–3 hrs	16
	>3 hrs	23
Emergency procedure	No	0
	Yes	8

Available at: https://www.mdcalc.com/ariscat-score-postoperative-pulmonary-complications

PPCs are defined as respiratory failure, respiratory infection, pleural effusion, atelectasis, pneumothorax, bronchospasm, aspiration pneumonitis) [8].

As observed from the Table 8.5, the higher the score, the greater the risk of PPCs.

There are several risk calculators designed to estimate risk of PPCs. Each these come with inherent limitations and the inability to predict intraoperative anesthetic management using non-depolarizing neuromuscular blockade, train of four monitoring, and appropriately timed reversal agents. Some of these pulmonary risk calculators were developed before sleep disordered breathing (OSA) and opioid abuse were recognized risks for respiratory failure postoperatively.

When assessing risk for postoperative pulmonary complications, it is important to review patient and procedure-related risk factors, perform a clinical evaluation, and recommend risk-reduction strategies to improve patient care and outcome [9] (Table 8.6).

Clinical evaluation should encompass a thorough history, inquiring about dyspnea at rest or with exertion, wheezing, smoking history, recent fever/chills, bronchitis, asthma, COPD, OSA, emphysema, history of pneumonia or lung surgery, use of steroids, and a physical exam (auscultation for decreased breath sounds, wheezes, rhonchi, prolonged expiratory phase).

There are several risk stratification tools for postoperative respiratory complications including STOPBANG (Table 8.7) to

Table 8.5 The ARISCAT risk group related to postoperative pulmonary complications

ARISCAT score	Risk group	Risk of in-hospital postoperative pulmonary complications
<26	Low	1.6%
26–44	Intermediate	13.3%
>44	High	42.1%

Original table

Table 8.6 Clinical risk factors for postoperative pulmonary complications

Patient-related risk factors:
Smoking
Poor general health status (ASA >2)
Old age (>70)
Obesity
Sleep disordered breathing (sleep apnea)
Chronic obstructive pulmonary disease
Reactive airway disease (asthma)
Opioid use
Procedure-related risk factors
Surgery >3 hours
General anesthesia
Type of surgery and location of incision
Use of long- or intermediate-acting non-depolarizers

Adapted from Gupta and Shiveley [34]

Table 8.7 Clinical risk factors used to assess risk for obstructive sleep apnea [9, 10]

S	**S**noring
T	**T**iredness
O	**O**bserved Apnea
P	High blood **p**ressure
B	**B**MI > 35
A	**A**ge > 50
N	**N**eck > 40 cm
G	Male **g**ender

assess risk of sleep disordered breathing or obstructive sleep apnea and the ARISCAT tool to assess for overall PPC risk.

A preoperative sleep apnea screening tool with highest sensitivity to detect patients at risk for occult sleep disordered breathing is the STOPBANG risk score. This is not a diagnostic tool as the gold standard diagnosing OSA is a sleep study with threshold apnea hypopnea index (AHI). There is an increased risk of moderate to severe OSA in patients with STOPBANG ≥5 (5% probability of severe OSA) with recognized increased risk of postoperative

Table 8.8 Risk reduction strategies for postoperative pulmonary complications

Preoperative
Smoking cessation (at least 1–2 weeks; optimal timeframe 8 weeks)
Treat airflow obstruction (COPD or asthma) with long and short acting beta agonists
Pulmonary function tests may be helpful (limited data to support)
Prescribe antibiotics / postpone surgery in presence of respiratory infection
Educate patients about lung-expansion maneuvers, use incentive spirometry preoperatively
Intraoperative
Limit surgical duration < 3 hours
Avoid long-acting non-depolarizing neuromuscular blockade
TOF monitoring use with appropriately timed reversal agents
Consider alternative surgical approach with regional analgesia for postoperative pain management
Postoperative
Encourage incentive spirometry and deep breathing exercises
Initiate CPAP (continuous positive airway pressure) or BIPAP when indicated (OSA)
Consider regional analgesia alternatives to minimize opiate use in the postoperative period

Adapted from Gupta and Shiveley [34]

pulmonary complications if STOPBANG is ≥6. Further evaluation before surgery is justified if the STOPBANG score is ≥5 and there is an uncontrolled systemic condition [10, 11]. However, the procedure need not be delayed or canceled for definitive diagnosis. Once all information is gathered, risk-reduction strategies can be implemented to optimize patient care. These are included in Table 8.8.

Hepatic and Gastrointestinal Disease

Severe liver disease increases perioperative risks, especially with major surgery. Hepatic insufficiency progressing to end stage liver disease (ESLD) involves a spectrum of disorders complicating perioperative management. A thorough physical

examination and review of systems, lab values, and medications is needed to ascertain severity of disease. Predictors of increased risk include Child-Pugh-Turcotte, class C, MELD (model for end stage liver disease) score > 15, acute fatty liver, and acute alcoholic hepatitis and a serum bilirubin >188 μmol/L. MELD scores can be calculated using serum creatinine, bilirubin levels, and the INR. This is easy using an online risk calculator [12]. Significant ascites can also affect pulmonary function by causing a reduced functional residual capacity (FRC). Renal insufficiency in association with hepatic disease is associated with poor prognosis. Higher risk surgeries for this population of patients are abdominal, cardiac, and emergency procedures as well as those with higher estimated blood loss. Patients with underlying liver disease have increased risk of ascites, esophageal varices, abnormal coagulation, and altered drug pharmacokinetics.

Gastrointestinal diseases may increase the potential for aspiration, dehydration, electrolyte disturbances, and anemia. Proton pump inhibitors, used to treat GERD, are causative in iron deficiency anemia, due to a mechanism limiting iron absorption. While screening for gastrointestinal disease, it is important to inquire about history of nausea, vomiting, heartburn, food regurgitation, diarrhea, bloody stools, hiatal hernia, gastric ulcers, viral hepatitis, and alcoholism.

Hematologic Disorders

Preoperative anemia is common in the presurgical population (30–60%). It is associated with increased risk of complications including higher transfusion rates, increased HLOS, and mortality. Iron deficiency anemia (IDA) can be the result of increased blood loss, poor iron intake or absorption. IDA is the leading cause of anemia in the surgical population.

Furthermore, due to the underlying inflammatory process, most surgical patients have increased levels of hepcidin, which interferes with normal iron metabolism, including oral iron absorption [13].

Appropriate laboratory values to obtain when evaluating anemia are a complete blood count, estimate of glomerular filtration (eGFR), and a serum creatinine. If the hemoglobin is <12 mg/dl, the mean corpuscular volume is <80, it is reasonable to obtain iron level, transferrin saturation (TSAT %), Ferritin, vitamin B12, and folic acid. Absolute iron deficiency is present when the ferritin level is <30 mg and transferrin saturation (TSAT) is <20%. Functional iron deficiency is present if the ferritin is <100–300 mg. It is important to remember that ferritin is an acute phase reactant which can be elevated in certain conditions.

Treating iron deficiency anemia with oral iron preparations is possible. However, there are several limitations. Oral iron can be poorly absorbed and not well tolerated (gastrointestinal side effects), leading to a slow correction of IDA (6–8 weeks). The preferred formulation for rapid correction of IDA is intravenous iron [14].

It is generally well accepted and supported by international guidelines that presurgical patients with iron deficiency anemia for whom a surgical blood loss of > 500 mL is expected, should have their preoperative anemia corrected by administering intravenous iron preoperatively. However, in a recent metanalysis, the PREVENTT trial did not detect lower rates of transfusion in patients receiving intravenous iron when compared with no iron [15]

It is important to remember that anemia is not solely a concern of the preoperative encounter. Rather, anemia must be actively addressed throughout the perioperative spectrum of patient care in order to minimize the risks associated with transfusions and unanticipated prolonged hospitalizations.

Bleeding disorders may increase the risk of perioperative complications and necessitate further preoperative evaluation and planning. This may be due to medications treating specific comorbidities (warfarin, antiplatelet agents, direct acting oral anticoagulants), disorders of coagulation (e.g., hemophilia, Von Willebrand's disease), thrombocytopenia, leukemia, platelet disorders (e.g., iatrogenic, Bernard–Soulier syndrome, uremia), cancer therapies, and hepatic disease. The risk of increased surgical bleeding relative to the need for continued anticoagulation (concurrent mechanical heart valve or thromboses) for thromboprophylaxis must be considered. Utilizing the **HAS_BLED** score to assess a patient's inherent risk of bleeding may be useful during the proce-

dure. A patient with a **HAS_BLED** score > 3 has shown an increased predictive risk of bleeding [16].

Hypertension
Abnormal kidney/liver function
Stroke
Bleeding history or predisposition (previous major bleeding)
Labile INR values
Elderly (> 65 years)
Drugs/Alcohol

Additional factors to consider are whether the patient is simultaneously taking any anticoagulant or antiplatelet agents, has a qualitative platelet abnormality, or has bled during prior bridging therapy. Certain procedures have inherent increased risk of bleeding. Table 8.9 shows high-versus low-risk bleeding procedures [17]. High-risk procedures warrant the cessation of anticoagulation, while other procedures with very low risk of bleeding enable continuation of anticoagulation.

In addition, cessation of anticoagulants used to treat certain medical conditions must be considered. Patients with atrial fibrillation are often treated with dual anticoagulant therapy depending on the etiology of the arrhythmia. This could include aspirin, warfarin, direct acting oral anticoagulants, or others. Using the **CHA2DAS-VASc** score is helpful to assist with decisions to continue or temporarily discontinue anticoagulation in the perioperative period [18] (Table 8.10). Patients with **CHA2DAS-VASc** > 6

Table 8.9 Low- versus high-risk procedures for bleeding

Very low risk	Low risk (<2% 48 h risk)	High risk (>2% 48 h risk)
Minor dermatologic	Hernia surgery	Orthopedic
Dental procedures	Eye surgery	Cardiac
Electroconvulsive therapy (ECT)	Cholecystectomy	Urology
Cataract surgery	Hysterectomy	ENT
Endoscopic procedures (no mucosal disruption)	Arthroscopy	Vascular
	Colonoscopy with biopsy	Neurosurgery

Adapted from Spyropoulos AC, et al. J Thromb Haemost 2016;14(5):875–85

Table 8.10 CHA_2DS_2-VASc stroke risk stratification for subjects with non-valvular atrial fibrillation

CHA2DAS-VASc	SCORE	CHA_2DS_2-VASc score	(Stroke risk)
CHF (heart failure)	1	0	0
Hypertension	1	1	1.3
Age > 75 years	2	2	2.2
Diabetes mellitus	1	3	3.2
Stroke/TIA/TE	2	4	4.0
Vascular disease (prior MI, PAD aortic plaque)	1	5	6.7
Age years 65–74	1	6	9.8
Sex category (female)	1	7	9.6
Total (maximum) score	9	8	6.7
Total (maximum) score		9	15.20

Adapted from January CT, et al. J Am Coll Cardiol 2014;64(21):e1–76 Predicting stroke risk during cessation of anticoagulation therapy
CHF congestive heart failure, *TIA* transient ischemic attack, *TE* thromboembolism, *MI* myocardial infarction, *PAD* peripheral artery disease

or **CHADS2** of 5–6 often require continuation of therapy [19]; whereas patients with scores <3 may often safely temporarily discontinue therapy for a brief period of time. Discontinuation, although brief, must be weighed against the risk of bleeding during the procedure with consideration of bridging therapy if the CHA2DAS-VASc score is high.

With regards to aspirin therapy, in most circumstances, the 2014 ACC/AHA guidelines recommend continuation of aspirin therapy throughout the perioperative period when used for secondary prevention of thromboembolic events [20].

Endocrine

Endocrinopathies carry a high risk for morbidity, mortality, and postoperative complications. Patients should be assessed for a history of risk factors for diabetes mellitus, thyroid disease, and/or adrenal insufficiency.

Diabetic patients should be evaluated with regard to the type, duration, and severity of disease. Current medication management, daily glucose range, and recent hemoglobin A1C provide baseline information regarding degree of optimization. Cardiac surgery patients with HGA1C > 8.5 have been shown to have increased risks of postoperative complications [21]. However, there is no formal threshold beyond which surgery must be canceled. Each individual patient relative to their surgical urgency is to be considered. Good glycemic control should be established to avoid dehydration, electrolyte imbalances, and risk of diabetic ketoacidosis.

All diabetic patients should be evaluated for the presence of coronary artery disease and hypertension. Additionally, a serum creatinine level should be drawn to assess the degree of nephropathy, if present. Patients can be instructed to continue basal insulin therapy on the day of surgery or instructed to take half their morning dose of insulin depending upon formulation, degree of control and risk of hypoglycemia the day of surgery. Implantable devices (continuous glucose monitoring devices) with basal rates are often maintained. Patients with insulin dependent diabetes should be scheduled for elective surgery earlier in the day to minimize the impact of prolonged fasting on glucose management.

Patients with a history of thyroid disease with hypothyroidism or hyperthyroidism may need a laboratory values reviewed (TSH, Free T4, thyroxine) in order to ensure the condition is well controlled. Patients who have uncontrolled hyperthyroidism are at risk for thyroid storm which has a 50% mortality. It is important to review when thyroid medications have been adjusted and review recent laboratory values.

Patients with adrenal insufficiency, primary or secondary (pituitary insufficiency), must have medications reviewed. These patients may be taking chronic prednisone which if discontinued could result in hypotension intraoperatively and/or postoperatively. Secondary adrenal insufficiency may result from chronic therapy related severe COPD or autoimmune diseases. For patients on chronic steroid therapy, continuation is advised to avoid perioperative hemodynamic changes. Supplemental stress

dose steroids may or may not be needed postoperatively. Automated supplementation is no longer recommended.

Screening patients for history of thyroid, parathyroid, adrenal, or pituitary disease, and carcinoid syndrome may help reduce potential perioperative risks.

Renal

Renal disease increases perioperative risks, especially cardiopulmonary complications. Chronic kidney disease (CKD) is included in several risk calculators. A creatinine >170 μmol/L is an RCRI risk factor equivalent to stable ischemic heart disease in predicting cardiac risk [22]. Estimated glomerular filtration rate (eGFR) is a more accurate measure of renal function. The eGFR predicts short- and long-term 30-day mortality. Preoperative kidney disease is the strongest predictor of postoperative renal failure. Risk factors for CKD include age > 55 years, smoking, diabetes, hypertension, dyslipidemia, and heart failure.

Acute kidney Injury (AKI), even mild stages, is an underrecognized yet severe clinical condition. AKI is associated with adverse outcomes including delirium, infections, bleeding, chronic kidney disease, chronic dialysis dependency, cardiovascular diseases and death. There are several different definitions of AKI including RIFLE (2004), AKIN (2006) and KDIGO (2012). Consensus criteria have been developed to harmonize definitions and illustrate the broad spectrum of this clinical syndrome. Monitoring biomarkers, serum creatinine, and urine output is the current strategy. Avoiding nephrotoxic agents, hyperglycemia, hypotension, and maintaining adequate perfusion in the perioperative period is equally important.

Neurologic Disease

When screening for neurologic disease, it is important to elicit a history of seizures, tremors, headaches, paresthesias, or weakness of an extremity suggesting nerve impairment or progressive motor dysfunction. Performance of a general anesthetic using neuro-

muscular blocking agents, neuraxial or regional techniques requires knowledge of previous nerve injury, deficits, or progressive myelopathy. Documentation of symptom origin, specific location, and/or progression is important.

Myasthenia gravis, an autoimmune disease that attacks postsynaptic acetylcholine receptors at the neuromuscular junction, impacts respiratory function, and results in muscle weakness and fatigue. Medications used to treat this disorder, acetylcholinesterase inhibitors and steroids, can impact perioperative outcomes. Preoperative management includes documenting course of the disease, acetylcholinesterase inhibitor medications, ensuring continuation of these as usual. These patients are at risk for postoperative mechanical ventilation if treatment is interrupted due to respiratory muscle function weakness. Certain disease factors support the need for postoperative ventilation and including disease duration (> 6 years), concomitant pulmonary disease, peak inspiratory pressure < −25 cm H_2O, vital capacity <40 mL/kg, pyridostigmine dose >750 mg/day [23].

Multiple Sclerosis is an autoimmune disease of inflammation, demyelination, and axonal damage to the central nervous system. In the preoperative evaluation, a baseline neurologic history and exam should be performed. Patients will be taking a myriad of treatments including corticosteroids, interferon beta, azathioprine, and methotrexate. All of these medications should be continued the day of surgery. Typically, general anesthesia is employed, with concern that regional anesthesia can cause postoperative exacerbations. However, both epidural and spinal anesthetics have been performed successfully with no postoperative complications in parturients [24].

Nutritional Status

Malnourished patients have higher rates of morbidity or mortality, poor wound healing, increased length of stay, and infections. Low albumin levels predict increased morbidity and mortality [25]. Adequate perioperative nutritional support decreases postoperative complications. Improved preoperative nutritional status and hydration are basic tenets of prehabilitation and enhanced recov-

ery after surgery programs. Both are focal points to improve frail patients' outcomes and minimize risks as outlined above.

The Aging Patient

Caring for the aging patient is complex. Preoperative evaluation must involve assessments of physical, cognitive, and social support status. Unrecognized frailty and preexisting cognitive decline are guaranteed indicators of poor outcomes. Hence, there is an evolving need to establish evaluation protocols and interventions for this special population [26, 27].

The stress of surgery is less well tolerated by geriatric and frail patients owing to reduced physiologic reserves. Frailty is a syndrome of physiologic decline and decreased physiologic reserve characterized by marked vulnerability to adverse health outcomes. These patients are at risk for delirium, postoperative cognitive decline, morbidity, mortality and readmission due to factors unrelated to surgery. Social determinants play a large role in postoperative return to function. Hence, patients and caregivers should be included in perioperative planning to minimize risk of preexisting unrecognized frailty and cognitive decline impacting postoperative recovery of function. Several screening tools have been useful in assessing geriatric patients. These can include the clinical frailty scale, Fried Frailty Index, mini-cognitive assessment (3-word recall, clock draw), nutritional and functional (mobility) assessments as well as the aforementioned risk assessment tools. Independent living with normal functional status is a good predictor of outcome. However subclinical frailty (pre-frail patient) and slight cognitive impairment are associated with postoperative delirium yet infrequently assessed preoperatively. This may be due to the time and burden required for screening [28, 29].

Evaluating the aging patient for frailty and cognitive impairment can occur using several different frailty scales but should be measured using objective data rather than assuming such status. One of the most commonly cited tools for physical frailty is a Fried Frailty Index [30].

Frailty phenotype is confirmed by the presence of three or more of the five criteria listed in the Fried Frailty Index [30].

These include unintentional weight loss, exhaustion, weakness, slow walking speed, and decreased physical activity. Using the brief FRAIL (measuring fatigue, resistance, ambulation, illness, and weight loss) scale and the Animal Verbal Fluency test in older surgery patients identifies those at high risk for the development of postoperative delirium [31]. Table 8.11 reviews anticipated

Table 8.11 Physiologic alterations with aging and clinical implications for anesthesia

	Physiologic alterations	Clinical implications
Cardiovascular	Decreased sympathetic response Decreased venous compliance Decrease in preload Baroreceptor response impaired Cardiac diastolic dysfunction	Labile blood pressure Susceptibility to hypotension Susceptibility to volume overload Exaggerated decline in cardiac function with inadequate cardiac filling
Pulmonary	Increased pulmonary arterial pressures Decreased response to hypoxia and hypercarbia Decreased muscle mass and lung elasticity Decreased cough reflex and esophageal mobility	Increase A-a gradient Susceptibility to hypoxemia and hypercarbia Susceptibility to residual anesthetic effects Increased work of breathing Increased dead space ventilation Aspiration risk
Nervous system	Decreased neurotransmitters	Increased risk of postoperative delirium and cognitive dysfunction
Endocrine system Hepatic/Renal system Thermoregulation	Impaired glucose tolerance Altered drug metabolism Decreased muscle mass Decreased vascular reactivity	Increased intraoperative hyperglycemia Decreased drug clearance Susceptible to acute kidney injury Increased risk of hypothermia

From: Optimal Perioperative Management of the Geriatric Patient: Best Practices Guideline from AS NSQIP/American Geriatrics Society. Available at: https://www.facs.org/-/media/files/quality-programs/geriatric/acs-nsqip-geriatric-2016-guidelines.ashx

Table 8.12 Katz Index of Independence in activities of daily living

Activities Points (1 or 0)	**Independence** (1point)	**Dependence** (0 points) WITH supervision, direction, personal assistance, or total care.
Bathing Points:	(1 POINT): Bathes self completely or needs help in bathing only a single part of the body such as the back, genital area or disabled extremity.	(0 POINTS): Need help with bathing more than one part of the body, getting in or out of the tub or shower. Requires total bathing.
Dressing Points:	(1 POINT): Get clothes from closets or drawers and puts on clothes and outer garments complete with fasteners. May have help tying shoes.	(0 POINTS): Needs help with dressing self or needs to be completely dressed.
Toileting Points:	(1 POINT): Goes to toilet, gets on and off, arranges clothes, cleans genital area without help.	(0 POINTS): Needs help transferring to the toilet, cleaning self or uses bedpan or commode.
Transferring Points:	(1 POINT): Moves in and out of bed or chair unassisted. Mechanical transfer aids are acceptable.	(0 POINTS): Needs help in moving from bed to chair or requires a complete transfer.
Continence Points:	(1 POINT): Exercises complete self-control over urination and defecation	(0 POINTS): Is partially or totally incontinent of bowel or bladder
Feeding Points:	(1 POINT): Gets food from plate into mouth without help. Preparation of food may be done by another person.	(0 POINTS): Needs partial or total help with feeding or requires parental feeding.

SCORING: 6 = High (Patient independent) to 0 = Low (patient very dependent)

physiologic changes with aging and subsequent perioperative clinical implications. Table 8.12 provides a detailed assessment regarding activities of daily living. Both highlight the complexities in evaluating the aging patient prior to surgery.

Several interventions have been proposed to minimize the impact of frailty and preexisting cognitive decline on the aging patient in the postoperative period. Some suggest a brief period of

prehabilitation, physical exercise, nutritional intervention, and cognitive therapy. Additional work is needed in this area to ascertain which is of greatest benefit.

Physical Exam

A preoperative physical exam begins with noting the patient's baseline vital signs. During the airway examination, first document the Mallampati score (see Chap. 9, Airway Evaluation and Management), noting also the thyromental distance, oral aperture, teeth, cervical range of motion. Physical factors affecting mask ventilation can be determined from age and history as shown in [32] Table 8.13.

The **cardiopulmonary exam** includes assessment of rate and rhythm, murmurs, wheezing, rhonchi, stridor (inspiratory versus expiratory), peripheral pulses, and baseline pulse oximetry saturation. **Gastrointestinal exam** includes looking for signs of ascites, abdominal distension, and guarding. **Musculoskeletal exam** may include neck range of motion, scoliosis, and assessment of pectus excavatum/carinatum. Finally, a **neurologic exam** may include an assessment of baseline muscle strength, mental status and any signs of preexisting nerve injury. Patient comorbid conditions may dictate a more extensive physical examination depending upon degree of medical management.

Table 8.13 Factors affecting mask ventilation

Presence of a beard
Body mass index > 30 kg/m^2
Age > 55
History of snoring
Large tongue
Edentulous
Failed mandibular or lower jaw protrusion

Adapted from Langeron O. Anesthesiology 2000;92(5):1229–36

Medications/Allergies

The generic name of all medications with the route, dosage, and timing (including time of last dose) should be noted. In some cases, it is helpful to include the length of time the patient has been taking a given medication—particularly opioids, as chronic use may lead to higher perioperative opioid requirements. Additionally, long-term steroid use (>3 months) may result in adrenal insufficiency and steroid supplementation during surgery may be warranted.

A medication history should also encompass any over-the-counter or alternative medicines (i.e., herbal medications). A review of allergies to medications, foods, and environmental agents is important. Note the allergic reactions caused by each medication, and the severity of those reactions. A penicillin allergy may have been a reaction or rash experienced as a child, rather than anaphylaxis. If 10 years have passed since the reaction, a test dose is reasonable for cephalosporin antibiotics due to the low cross-reactivity. Otherwise, allergy testing may be warranted.

Furthermore, it is important to differentiate allergic reactions from medication side effects (e.g., nausea and vomiting induced by morphine is a side effect and not a true allergy). Allergies to latex, iodine, and shellfish are essential to elicit.

Medical Records/Family History

Medical records often contain a substantial amount of a patient's medical history, some of which the patient may or may not be aware. They may include information that could alter the anesthetic plan. For example, a history of a difficult airway may lead to a decision to perform an awake fiberoptic intubation. A history of severe postoperative nausea and vomiting or hemodynamic problems during previous surgery may also help the anesthesia provider make adjustments to the planned anesthetic. Reviewing and screening for a family history of anesthetic complications

may alert the anesthesiologist to potential problems (e.g., history of pseudocholinesterase deficiency or malignant hyperthermia) and should therefore be elicited.

Laboratory Data

In the United States, up to four billion dollars are spent annually on preoperative laboratory values and diagnostic studies. Reflexive preoperative testing is regarded as low value. Preoperative labs should only be ordered if they will change medical management. These types of investigations should be only be ordered following a thorough history and physical examination if the results would change medical management, anesthetic plan or postoperative monitoring. Unnecessary reflexive testing often results in incidental findings which do not add value, change management, and result in operating room delays or cancelations.

A few key points regarding preoperative labs to remember:

1. Pregnancy testing is not mandatory in all female patients of reproductive age though many centers do routinely perform it
2. Urinalysis is not required prior to orthopedic procedures. Asymptomatic bacteriuria is common and need not be treated. This, however, may be of value for surgeons prior to urologic procedures.
3. Coagulation Studies are low value in the absence of personal or family history of bleeding. A PT/INR or PTT is rarely indicated or beneficial.
4. Chest x-rays are almost never indicated unless to diagnose clinically significant pathology discovered during physical examination
5. Cardiovascular stress testing is of value only if it will change medical management of the patient irrespective of the upcoming surgical procedure. (see 2014 AHA/ACC guidelines)
6. Complete blood count is reasonable if expected blood loss or risk for anemia is high

7. Basic metabolic panel is reasonable if patient is taking ACEI, ARB, diuretic, NSAIDS or has a history of kidney disease or hypertension.
8. Type and screen is reasonable if a large amount of blood loss is expected.
9. Liver function panel is low value test unless patient has known liver disease or major risk factors.
10. Albumin and prealbumin are poor prognostic indicators unless utilized as marker of malnutrition or inflammation, or severity of illness [31].
11. Do not obtain baseline laboratory studies in patients without systemic disease (ASA 1 or 2) undergoing low risk surgery. (https://www.choosingwisely.org/societies/american-society-of-anesthesiologists/)

Perioperative Risk Evaluation

Upon gathering information from a patient's history, exam, physical and laboratory results, the patient is then assigned an ASA (American Society of Anesthesiologists) physical status classification (Table 8.14). The ASA status is a standardized way to describe overall medical condition, however, this classification system was designed solely for the purposes of billing.

Table 8.14 ASA physical status classifications

ASA class I	A normal healthy patient
ASA class II	A patient with mild systemic disease
ASA class III	A patient with severe systemic disease that limits activity, but is **not** a constant threat to life
ASA class IV	A patient with incapacitating system disease that is a constant threat to life
ASA class V	A moribund patient not expected to survive 24 h with or without surgery
E	Designates an emergency surgical procedure (i.e., class IE)

American Society of Anesthesiologists Newsletter, 1963

ASA classification is occasionally inaccurate in describing patient's comorbid conditions and degree of optimization. Yet, this system is widely utilized within several risk calculators. The ASA classification is a subjective tool that can vary between different providers.

The information obtained from a history, physical exam, and discussion with the patient can help generate a reasonable risk assessment. The purpose of the risk assessment is to ascertain fitness for surgery and develop an appropriate anesthetic tailored to the individual patient for the anticipated procedure.

Deciding general versus regional anesthesia technique (or combination) depends on the patient's comorbidities and the nature of the operation. Performing an awake intubation instead of intubating after inducing general anesthesia may be indicated for patients with history of a difficult airway and/or mask ventilation. The perioperative plan includes intraoperative management, postoperative pain management, monitoring high-risk patients, and disposition for recovery after surgery (PACU versus ICU). The preoperative evaluation is an opportunity to proactively evaluate patient comorbidities to formulate an appropriate anesthetic and postoperative management plan. This often requires a multidisciplinary, coordinated approach to ensure patient safety and optimal outcomes.

Anesthesia Consent Form

The purpose of the anesthesia consent (Chap. 31, Ethical Issues) is to discuss types of anesthetic options available for the planned procedure and to explain possible risks and benefits that encompass the perioperative management plan.

Types of anesthesia typically discussed include general, monitored anesthesia care (MAC), regional, and local. While patients might prefer one type of anesthetic over another, the final decision should involve collaboration patient, anesthesiologist, and surgeon.

Some of the more common risks of anesthesia that should be mentioned include infection and bleeding if a regional technique

is performed, nerve injury from improper positioning or regional anesthetics, postoperative nausea and vomiting, dental injury, risk of viral hepatitis and HIV from blood transfusions, awareness under anesthesia and a need for postoperative mechanical ventilation (if the patient fails to meet extubation criteria after surgery). The aim of the consent process is to provide the patient with all available anesthetic options and possible risks due to the selected anesthetic technique and the surgical procedure. The process of informed consent culminates in the signing of a legal document (consent form) and must be signed by the patient (or his/her guardian or healthcare power of attorney) and the anesthesia provider. It is important to note that informed consent is a process of ensuring a patient understands the risks, benefits, and available anesthetic options. This is an ideal opportunity for shared decision making to confirm this is the best procedure for this patient in their current physiologic state.

Postoperative Opioid Prescribing

Counseling patients about perioperative pain including expected pain level and plan for pain management may improve perceived pain scores and decrease the needs for narcotic pain medications [33]. In the postoperative period, opioids can be useful for pain control. When the patient is in the hospital, IV pain medications can be given which will transition to oral medications when the patient is discharged. Instructing the patient to take the opioid or other multimodal analgesics as prescribed is imperative to ensure adequate pain control and safety.

Case Study*

You are seeing a 64-year-old male scheduled for elective total hip replacement with past medical history of hypertension, coronary artery disease, s/p STEMI 2 years prior with

bare metal stent (BMS), known COPD, suspected obstructive sleep apnea with well controlled diabetes mellitus (type 2), peripheral arterial disease with known nonobstructive disease. He continues to smoke cigarettes (35-year pack history) and experiences occasional dyspnea on exertion with URI.

He works as a carpenter, carrying boards around the job site, and he does his own yard work. His medications at present are aspirin 81 mg once per day, atenolol 10 mg daily, metformin, exenatide (Byetta), as well as an albuterol inhaler and sublingual nitroglycerin as needed.

**Case adapted from* Gupta and Shively [35]

What ASA physical status class is this patient?

This patient has multiple significant comorbidities, making him at least an ASA class II. Whether he is class II, III, or IV depends on your assessment of the severity of his diseases. He is likely not class IV, which implies his systemic disease is a constant threat to life. The distinction between class II and III is based on your judgment as to whether he has "mild" or "severe" disease. Given that he has had a myocardial infarction and not just stable angina, it would be reasonable to classify him as III.

How would you assess his overall cardiac risk and prepare him for surgery?

The patient's myocardial ischemic (MI) event was not recent (in the last 3–6 months) so the immediate risk of long-term damage has passed. He underwent BMS stent placement over 2 years ago and is no longer taking clopidogrel (Plavix). So, his risk of stent restenosis or occlusion and/or need for continued anticoagulation has passed. However, we should assume that he remains at risk for myocardial ischemia. The best way to assess this risk is also the simplest: assess his exercise tolerance. He does moderately heavy exertion at work and at home, so we can conclude that his exercise tolerance is good. He is taking a beta-blocker and aspirin, both recommended for patients with

elevated cardiovascular risk. He should continue both medications through the morning of surgery. There is no evidence to support imaging or further testing prior to surgery for this patient given his functional status (METS) and concurrent medical management.

How would you assess his risk of postoperative pulmonary complications?

Pulmonary complications (unanticipated respiratory depression, prolonged postoperative ventilation, unanticipated reintubation, pneumonia) are as common as cardiovascular complications, and actually are more costly to manage. There are risk stratification systems for pulmonary complications, though many include unmodifiable risk factors. This patient is at elevated risk due to advanced age, COPD, ASA class > II, and cigarette smoking. In general, neither a chest X-ray nor pulmonary function testing (spirometry) is indicated. If he feels that he is at his baseline with regard to symptoms (dyspnea on exertion, use of albuterol), then he should plan to bring his inhaler on the day of surgery and use it prior to going to the OR. However, if he feels that he is not at his personal best, it is reasonable to have him intensify his pulmonary regimen preoperatively, since the procedure is elective. He might benefit in such cases by increased use of long and/or short acting beta agonists (inhaled), use of inhaled or oral corticosteroids, and in some cases antibiotics.

He asks you if he should quit smoking before the surgery. How would you respond?

While every physician should encourage smoking cessation, the immediate preoperative period may not be the optimal time. Studies suggest smokers who abstain for 8 weeks or more can lower their risk of pulmonary complications nearly to that of nonsmokers, in the absence of severe irreversible COPD. However, quitting a shorter period of time prior to surgery may result in increased cough and sputum production so symptoms may worsen

temporarily (1–2 weeks) although this is variable. The postoperative period may be a good time to quit, since hospitals generally disallow smoking anyway, and thus his admission may be an opportune time.

How should his diabetes be managed for surgery? Would your recommendation be different if he were taking insulin?

Metformin and other oral hypoglycemic agents should not be taken on the day of surgery and are generally stopped the evening before surgery. It is reasonable to hold metformin the morning of surgery. Historically there has been a very small risk of lactic acidosis when taking metformin (3–8 cases/100,000 patient-years), which may be increased in conditions, such as hypovolemia and hypoxia. Glucose should be checked on admission to the preop unit. Perioperative hyperglycemia should be treated with intravenous insulin therapy keeping the upper limit of blood glucose below 180 mg/dl. If the patient were taking insulin, the recommendations would be to hold short acting or prandial insulin the day of surgery, such as aspart (NovoLog) or lispro (Humalog). However, basal insulin, such as glargine (Lantus), should be continued at the usual dose. NPH is intermediate acting so the recommendation is often to half the usual morning dose. As with patients managed on oral agents, it is prudent to monitor blood glucose perioperatively to avoid significant hypo- or hyperglycemia.

What other information would you like to obtain to complete your preoperative evaluation?

All patients should undergo a comprehensive airway examination such as determination of the Mallampati class (oropharyngeal structures visualized), thyromental distance, and cervical spine flexibility. It is useful to inquire about previous experiences with anesthesia, with particular attention to complications, but also to help characterize the patient's risk for postoperative nausea and vomiting and approach to pain management. A physical examination,

especially directed at the cardiopulmonary systems, presence of vascular access sites, and possibly suitability for regional analgesia is essential. Dentition, facial features predictive of difficult mask ventilation, and difficulty with expected positioning (this case may be performed in low lithotomy position or supine and flexed with head down) should also be sought on physical exam. One should ensure that the patient and family members have the opportunity to voice any concerns about the surgery or the anesthetic, and an attempt should be made to address them. Finally, anesthesia consent should be obtained, and presence of surgical consent should be verified before proceeding.

References

1. Wanderer JP, Rathmell JP (2018) A calculated risk: comparing perioperative assessment tools. Anesthesiology 129(5):A17. https://doi.org/10.1097/ALN.0000000000002479
2. Cohn SL, Fernandez RN (2018) Comparison of 4 cardiac risk calculators in predicting postoperative cardiac complications after noncardiac operations. Am J Cardiol 121(1):125–130. https://doi.org/10.1016/j.amjcard.2017.09.031
3. Tang WH, Topol EJ, Fan Y, Wu Y, Cho L, Stevenson C et al (2014) Prognostic value of estimated functional capacity incremental to cardiac biomarkers in stable cardiac patients. J Am Heart Assoc 3(5):e000960. https://doi.org/10.1161/JAHA.114.000960
4. Wijeysundera DN, Pearse RM, Shulman MA, Abbott TEF, Torres E, Ambosta A et al (2018) Assessment of functional capacity before major non-cardiac surgery: an international, prospective cohort study. Lancet 391(10140):2631–2640. https://doi.org/10.1016/S0140-6736(18)31131-0
5. Mazo V, Sabaté S, Canet J, Gallart L, de Abreu MG, Belda J et al (2014) Prospective external validation of a predictive score for postoperative pulmonary complications. Anesthesiology 121(2):219–231. https://doi.org/10.1097/ALN.0000000000000334
6. Canet J, Gallart L, Gomar C, Paluzie G, Vallès J, Castillo J et al (2010) Prediction of postoperative pulmonary complications in a population-based surgical cohort. Anesthesiology 113(6):1338–1350. https://doi.org/10.1097/ALN.0b013e3181fc6e0a

7. Ball L, Almondo C, Pelosi P (2020) Perioperative lung protection: general mechanisms and protective approaches. Anesth Analg 131(6):1789–1798. https://doi.org/10.1213/ANE.0000000000005246
8. Gupta S, Fernandes RJ, Rao JS, Dhanpal R (2020) Perioperative risk factors for pulmonary complications after non-cardiac surgery. J Anaesthesiol Clin Pharmacol 36(1):88–93. https://doi.org/10.4103/joacp.JOACP_54_19
9. Kheterpal S, Vaughn MT, Dubovoy TZ, Shah NJ, Bash LD, Colquhoun DA et al (2020) Sugammadex versus neostigmine for reversal of neuromuscular blockade and postoperative pulmonary complications (STRONGER): a multicenter matched cohort analysis. Anesthesiology 132(6):1371–1381. https://doi.org/10.1097/ALN.0000000000003256
10. Chung F, Subramanyam R, Liao P, Sasaki E, Shapiro C, Sun Y (2012) High STOP-bang score indicates a high probability of obstructive sleep apnoea. Br J Anaesth 108(5):768–775. https://doi.org/10.1093/bja/aes022
11. Chung F, Abdullah HR, Liao P (2016) STOP-bang questionnaire: a practical approach to screen for obstructive sleep apnea. Chest 149(3):631–638. https://doi.org/10.1378/chest.15-0903
12. MELD Score (Model for End-stage Liver Disease) (12 and older). Available at: https://www.mdcalc.com/meld-score-model-end-stage-liver-disease-12-older. Accessed 10 Jan 2021
13. Warner MA, Shore-Lesserson L, Shander A, Patel SY, Perelman SI, Guinn NR (2020) Perioperative qnemia: prevention, diagnosis, and management throughout the spectrum of perioperative care. Anesth Analg 130(5):1364–1380. https://doi.org/10.1213/ANE.0000000000004727
14. Okocha O, Dand H, Avram MJ, Sweitzer B (2020) An effective and efficient testing protocol for diagnosing iron-deficiency anemia preoperatively. Anesthesiology 133(1):109–118. https://doi.org/10.1097/ALN.0000000000003263
15. Richards T, Baikady RR, Clevenger B, Butcher A, Abeysiri S, Chau M et al (2020) Preoperative intravenous iron to treat anaemia before major abdominal surgery (PREVENTT): a randomised, double-blind, controlled trial. Lancet 396(10259):1353–1361. https://doi.org/10.1016/S0140-6736(20)31539-7
16. Doherty JU, Gluckman TJ, Hucker WJ, Januzzi JL Jr, Ortel TL, Saxonhouse SJ et al (2017) 2017 ACC expert consensus decision pathway for periprocedural management of anticoagulation in patients with nonvalvular atrial fibrillation: a report of the American College of Cardiology Clinical Expert Consensus Document Task Force. J Am Coll Cardiol 69:871–898. https://doi.org/10.1016/j.jacc.2016.11.024
17. Spyropoulos AC, Al-Badri A, Sherwood MW, Douketis JD (2016) Periprocedural management of patients receiving a vitamin K antagonist or a direct oral anticoagulant requiring an elective procedure or surgery. J Thromb Haemost 14(5):875–885. https://doi.org/10.1111/jth.13305

18. January CT, Wann LS, Alpert JS, Calkins H, Cigarroa JE, Cleveland JC Jr et al (2014) 2014 AHA/ACC/HRS guideline for the management of patients with atrial fibrillation: a report of the American College of Cardiology/ American Heart Association Task Force on Practice Guidelines and the Heart Rhythm Society. J Am Coll Cardiol 64(21):e1–e76. https://doi.org/10.1016/j.jacc.2014.03.022
19. Karamchandani K, Khanna AK, Bose S, Fernando RJ, Walkey AJ (2020) Atrial fibrillation: current evidence and management strategies during the perioperative period. Anesth Analg 130(1):2–13. https://doi.org/10.1213/ANE.0000000000004474
20. Gerstein NS, Albrechtsen CL, Mercado N, Cigarroa JE, Schulman PM (2020) A comprehensive update on aspirin management during noncardiac surgery. Anesth Analg 131(4):1111–1123. https://doi.org/10.1213/ANE.0000000000005064
21. Chen P, Hallock KK, Mulvey CL, Berg AS, Cherian VT (2018) The effect of elevated A1C on immediate postoperative complications: a prospective observational study. Clin Diabetes 36(2):128–132. https://doi.org/10.2337/cd17-0081
22. Roshanov PS, Walsh M, Devereaux PJ, MacNeil SD, Lam NN, Hildebrand AM et al (2017) External validation of the revised cardiac risk index and update of its renal variable to predict 30-day risk of major cardiac complications after non-cardiac surgery: rationale and plan for analyses of the VISION study. BMJ Open 7(1):e013510. https://doi.org/10.1136/bmjopen-2016-013510
23. Myasthenia gravis preop risk eval. https://www.openanesthesia.org/myasthenia_gravis_preop_risk_eval/. Accessed 20 Jan 2021
24. Multiple sclerosis: Periop mgmt. https://www.openanesthesia.org/multiple_sclerosis_periop_mgmt/. Accessed 20 Jan 2021
25. Kim S, McClave SA, Martindale RG, Miller KR, Hurt RT (2017) Hypoalbuminemia and clinical outcomes: what is the mechanism behind the relationship? Am Surg 83(11):1220–1227. https://doi.org/10.1177/000313481708301123
26. Cooper L, Abbett SK, Feng A, Bernacki RE, Cooper Z, Urman RD et al (2020) Launching a geriatric surgery center: recommendations from the Society for Perioperative Assessment and Quality Improvement. J Am Geriatr Soc 68(9):1941–1946. https://doi.org/10.1111/jgs.16681
27. Callahan KE, Clark CJ, Edwards AF, Harwood TN, Williamson JD, Moses AW, et al. Automated frailty screening at-scale for pre-operative risk stratification using the electronic Frailty Index. J Am Geriatr Soc. 2021; In Press. https://doi.org/10.1111/jgs.17027
28. Alvarez-Nebreda ML, Bentov N, Urman RD, Setia S, Huang JC, Pfeifer K et al (2018) Recommendations for preoperative management of frailty from the Society for Perioperative Assessment and Quality Improvement (SPAQI). J Clin Anesth 47:33–42. https://doi.org/10.1016/j.jclinane.2018.02.011

29. Culley DJ, Flaherty D, Fahey MC, Rudolph JL, Javedan H, Huang CC et al (2017) Poor performance on a preoperative cognitive screening test predicts postoperative complications in older orthopedic surgical patients. Anesthesiology 127(5):765–774. https://doi.org/10.1097/ALN.0000000000001859
30. Fried LP, Tangen CM, Walston J, Newman AB, Hirsch C, Gottdiener J et al (2001) Frailty in older adults: evidence for a phenotype. J Gerontol A Biol Sci Med Sci 56(3):M146–M156. https://doi.org/10.1093/gerona/56.3.m146
31. Susano MJ, Grasfield RH, Friese M, Rosner B, Crosby G, Bader AM et al (2020) Brief preoperative screening for frailty and cognitive impairment predicts delirium after spine surgery. Anesthesiology 133(6):1184–1191. https://doi.org/10.1097/ALN.0000000000003523
32. Langeron O, Masso E, Huraux C, Guggiari M, Bianchi A, Coriat P et al (2000) Prediction of difficult mask ventilation. Anesthesiology 92(5):1229–1236. https://doi.org/10.1097/00000542-200005000-00009
33. Oltman J, Militsakh O, D'Agostino M, Kauffman B, Lindau R, Coughlin A et al (2017) Multimodal analgesia in outpatient head and neck surgery: a feasibility and safety study. JAMA Otolaryngol Head Neck Surg 143(12):1207–1212. https://doi.org/10.1001/jamaoto.2017.1773
34. Gupta A, Shiveley TJ (2016) The preoperative patient evaluation. In: Ehrenfeld JM, Urman RD, Segal S (eds) Anesthesia student survival guide: a case-based approach, 2nd edn. Springer, Cham, pp 89–106
35. Gupta A, Shively T (2016) Chapter 8: Preoperative assessment. In: Anesthesia student survival guide. Springer, Cham

Airway Evaluation and Management

9

Dongdong Yao and Stephen Raithel

Introduction

The link between the practice of anesthesia and airway management is not entirely intuitive. How could anesthetizing a patient for a lower extremity procedure possibly impact that patient's airway or respiratory status? The answer lies largely in the profound respiratory side effects of most anesthetic medications. Despite the site of surgery or the anesthetic technique chosen, every patient receiving anesthetic care is exposed to a varying degree of risk of airway compromise. That is, all levels of sedation, general anesthesia, and regional anesthesia carry with them at least a small risk of airway obstruction and apnea. Therefore, every anesthesia provider must examine each patient in anticipation of a need to intubate and mechanically ventilate, regardless of whether or not such interventions were part of the primary anesthetic plan. A thorough airway examination and history, combined with expert airway management, guard against the life-threatening risks of airway obstruction and apnea.

D. Yao (✉) · S. Raithel
Department of Anesthesiology, Perioperative and Pain Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA
e-mail: dyao1@bwh.harvard.edu; sraithel@bwh.harvard.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_9

It is during the provision of general anesthesia that airway management is most commonly employed. General anesthesia renders patients insensate to noxious stimuli throughout their bodies and is therefore employed during a wide variety of surgical procedures from craniotomy and tonsillectomy to liver resection and prostatectomy. The intravenous induction of general anesthesia and apnea are most often synonymous. Expert airway management is the cornerstone of safety for any general anesthetic.

Airway management is not routinely employed during regional anesthesia. However, airway management could become necessary should the patient suffer an intravascular injection of local anesthetic that precipitates seizure or cardiovascular collapse. The same risks of apnea during sedation also apply, should the patient receive sedation either for the regional anesthetic itself, or during the ensuing surgical procedure.

Airway Anatomy

The human airway is a dynamic structure that extends from the nares and/or mouth to the alveoli. Obstruction can occur at any point because of anatomic collapse or a foreign body which includes liquids such as mucous, blood, and gastric contents.

Airway Evaluation

In addition to the inherent risks of apnea with all anesthetic techniques, management of the difficult airway continues to be a clinically important source of liability. The goal of airway evaluation is to risk stratify and predict which patients will be difficult to ventilate and/or intubate and form contingent strategies. Difficult mask ventilation occurs when there is an inadequate seal between the patient's face and the mask, there is a leak of oxygen from the facemask, or there is excessive resistance to the inflow or outflow of oxygen. Difficult laryngoscopy occurs when no portion of the glottis is visualized after multiple laryngoscopic attempts. A patient is defined as having a difficult airway if a conventionally

trained anesthesiologist experiences difficulty with facemask ventilation of the upper airway, difficulty with tracheal intubation, or both (Fig. 9.1).

In order to predict difficult mask ventilation or difficult endotracheal intubation, each patient receiving anesthetic care should have a comprehensive airway history and physical examination performed (also see Chap. 8). Patients should be queried about airway complications that occurred during past anesthetics. A history of trauma during previous airway management to the patient's lips, teeth, gums, or mouth may indicate the presence of a difficult airway. Similarly, if the patient reports that many attempts were made to "insert the breathing tube" or that he or she was "awake" during previous intubations, a difficult airway should be considered. Medical conditions that classically may portend a difficult airway include a recent or remote history of facial trauma or surgery, obstructive sleep apnea, rheumatoid arthritis, pregnancy, epiglottitis, previous cervical fusion, neck masses, Down's syndrome, and other genetic syndromes such as Treacher-Collins and Pierre-Robin that have associated facial abnormalities. With a positive history, documentation regarding previous airway management should be reviewed.

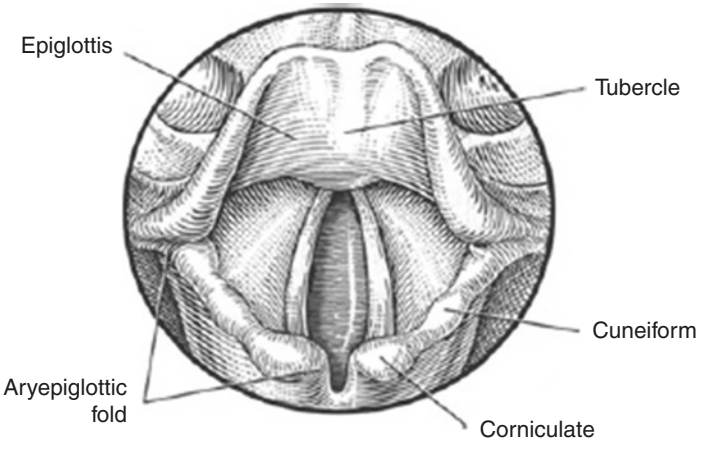


Fig. 9.1 The glottis and epiglottis. (Reproduced with permission from Finucane and Santora [3])

Multiple physical examination features have been correlated with a difficult airway (Table 9.1).

Every patient receiving anesthetic care should be thoroughly examined for the presence of these features. An adequate exam is difficult to accomplish without active participation and cooperation of the patient. That is, examinations performed solely by inspection may not only be incomplete, but may also be inaccurate. The most common examination performed to evaluate patients for the presence of a difficult airway is determination of what is known as the Mallampati Class. This classification system, first developed in 1985, seeks to predict difficult intubation by functionally assessing the ratio of the size of one's tongue to the size of one's oral cavity (Fig. 9.2).

Increasing difficulty with direct laryngoscopy has been correlated with Mallampati Class III and IV examinations. While no

Table 9.1 Components of the preoperative airway physical examination

Component	Nonreassuring finding
Length of upper incisors	Relatively long
Relation of maxillary and mandibular incisors during normal jaw closure	Prominent "overbite" (maxillary incisors anterior to mandibular incisors)
Relation of maxillary and mandibular incisors during voluntary protrusion of the jaw	Patient's mandibular incisors anterior to (in front of) maxillary incisors
Inter-incisor distance (mouth opening)	<3 cm
Visibility of uvula	Not visible when tongue is protruded with patient in sitting position (e.g., Mallampati class >II)
Shape of palate	Highly arched or narrow
Compliance of submandibular space	Stiff, indurated, occupied by mass, or non-resilient
Thyromental distance	<3 finger breadths or 6–7 cm
Length of neck	Short
Thickness of neck	Thick (neck size > 17 in.)
Range of motion of head and neck	Patient cannot touch tip of chin to chest or cannot extend neck

Reproduced with permission from Caplan et al. [2]

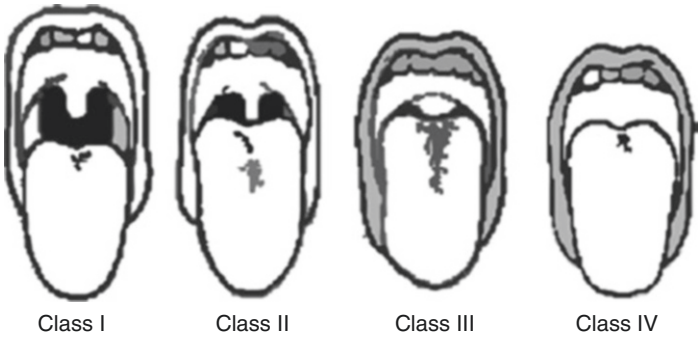


Fig. 9.2 Modified Mallampati classification system (Samsoon and Young)

single physical examination feature in isolation can accurately predict a difficult airway, most anesthesia providers incorporate the presence of multiple features to predict a difficult airway.

Mask Ventilation

Face mask ventilation is the most basic airway management intervention and is the first skill any student of anesthesia should seek to develop. Three goals need to be achieved for optimal facemask ventilation:

1. An optimal seal must be made between the mask and the patient's face
2. The patient's oropharynx must be opened by anterior displacement of the mandible into the facemask and extension of the head as seen in Fig. 9.3. Placement of an oral or nasal airway during facemask ventilation may assist in opening the oropharynx by creating an artificial passage for gases between the tongue and the posterior pharyngeal wall as seen in Fig. 9.4.
3. Sufficient positive pressure must be generated to overcome the resistance of the patient's upper airway, chest wall, and diaphragm to effect efficient gas exchange at the alveoli.

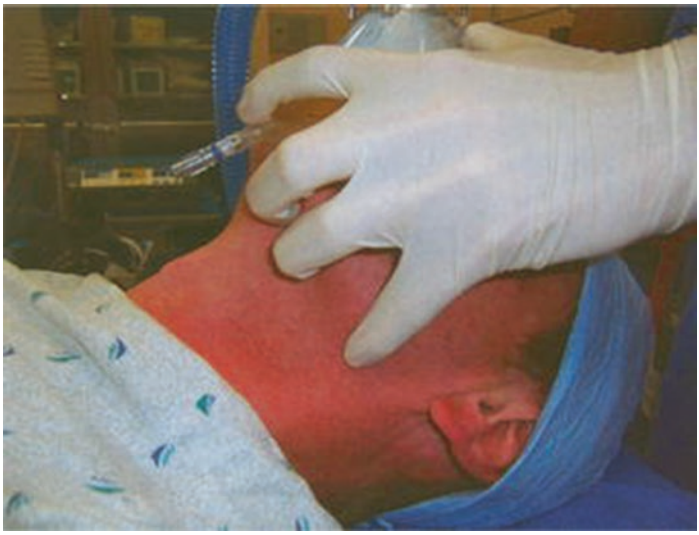


Fig. 9.3 Optimal facemask ventilation

Mask ventilation can be employed to augment patient's spontaneous tidal volumes as a temporizing measure before definitive airway management occurs via endotracheal intubation – as in the case of an intensive care unit patient slowly succumbing to respiratory failure from pneumonia. In the operating room, mask ventilation is most commonly employed to oxygenate and ventilate patients who are apneic from general anesthetic induction agents. Common errors in mask ventilation include pressing down too forcefully on the mask, causing posterior movement of the mandible and collapsing the oropharyngeal space; focus should be placed on anterior displacement of the mandible and "lifting" the mandible up to the mask. Another common source of improper technique is to have the fingertips of the hand holding the mask pressing into the submental tissue, collapsing the oral passageway; proper technique involves keeping the fingertips on the mandibular bone.

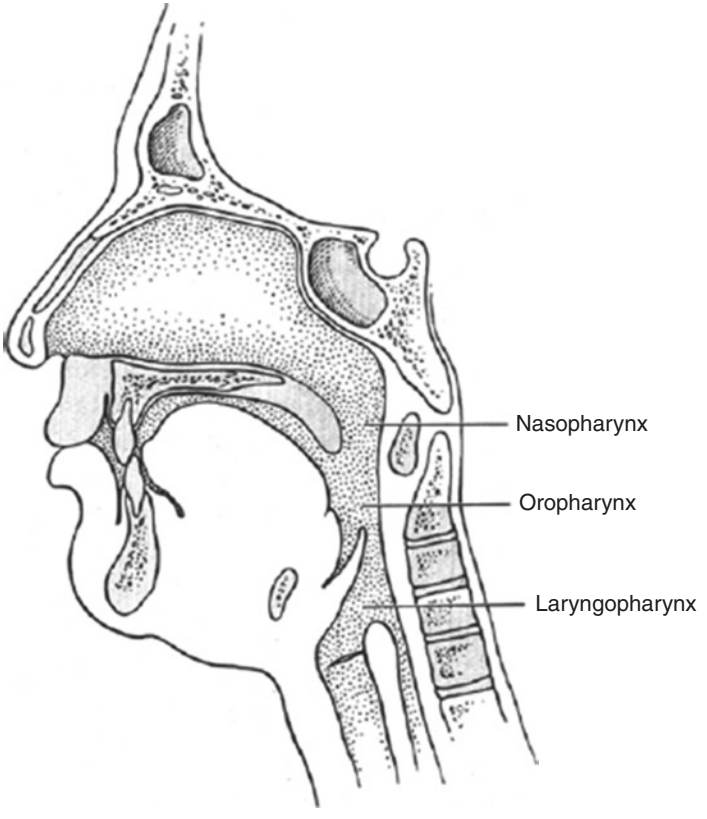


Fig. 9.4 Upper airway anatomy. (Reproduced with permission from Finucane and Santora [3])

Supraglottic Airway

The supraglottic airway (SGA) device – frequently refered to as a Laryngeal Mask Airway or LMA based on a commonly used commercial model – was first introduced in the United States in 1988 and FDA approved in 1991. The soft plastic device, seen in Fig. 9.5, has revolutionized the care of patients receiving general anesthesia and serves an alternative airway management device in

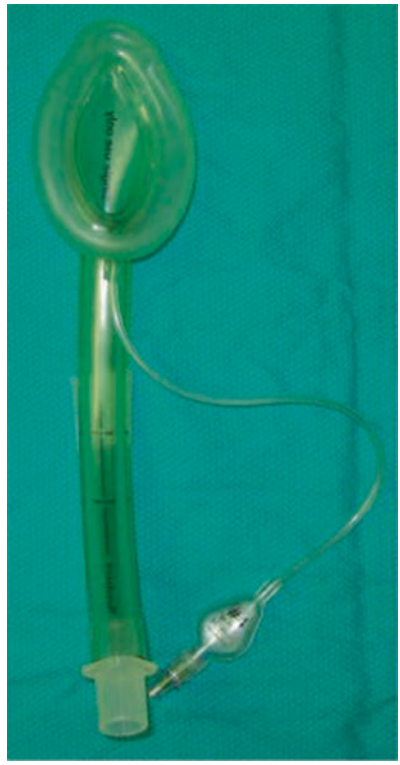


Fig. 9.5 Supraglottic airway. (Photo courtesy J. Ehrenfeld)

selected patients. Its use has largely supplanted the delivery of facemask anesthesia. During a difficult intubation, the insertion of an SGA can be lifesaving. Indeed, the most recent version of the American Society of Anesthesiologists Difficult Airway Algorithm (see Appendix A) places special significance on the use of the SGA as a rescue device when an anesthesiologist is unable to intubate and/or mask ventilate a patient.

The lubricated device is inserted blindly into a patient's mouth following the hard palate, past the tongue, and seated with the tip in the hypopharynx. The cuff is inflated isolating the gastrointestinal tract from the respiratory tract above the glottis. Multiple different forms of supraglottic airway devices have been devel-

oped during the past few decades. However, being supraglottic, the SGA does **not** protect against pulmonary aspiration to the same degree as an endotracheal tube. Other than for emergency ventilation, *relative* contraindications to the use of the SGA include:

- patients at increased risk for pulmonary aspiration
- patients or procedures requiring excessive positive pressure ventilation
- lengthy procedures
- procedures in any position other than supine

Direct Laryngoscopy and Tracheal Intubation

Direct laryngoscopy is the most common means of accomplishing endotracheal intubation. It is the process of visualizing a patient's glottis through his/her mouth by aligning the axes of the oral cavity, the pharynx, and the larynx as seen in Fig. 9.6.

Using direct laryngoscopy, endotracheal tubes are most commonly passed through the patient's mouth and into the glottis using a laryngoscope. A laryngoscope consists of a handle and an interchangeable blade with a light bulb on the end. The blades come in a variety of shapes and sizes, but the most commonly used are the Macintosh 3 (curved) and Miller 2 (straight) (see Fig. 9.7). Once the endotracheal tube passes through the glottis, a seal is formed between the endotracheal tube and the tracheal wall by inflating a cuff near the distal end of the tube with air. For intraoral procedures (such as the excision of a tongue lesion), endotracheal tubes can be placed into the glottis via a nasal approach utilizing either direct or fiber-optic laryngoscopy. Common errors in direct laryngoscopy include inserting the laryngoscope blade too deeply exposing the patient's esophagus or too superficially to expose the larynx, rocking the laryngoscope back on the upper incisor or upper lip instead of lifting the laryngoscope up and away from the laryngoscopist, and improperly sweeping the tongue from the line of sight.

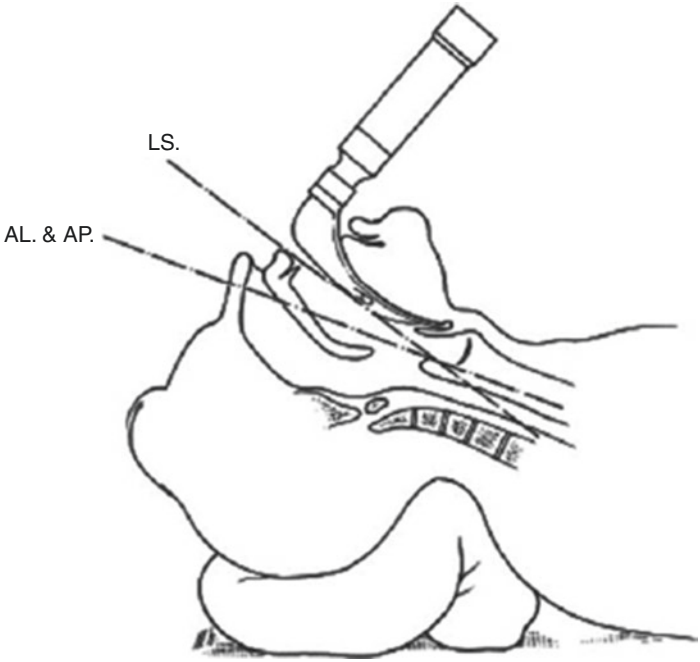


Fig. 9.6 Relationship of the oral, pharyngeal, and laryngeal axes for intubation. (Reproduced with permission from Ref. [3])

The placement of an endotracheal tube is considered the "gold standard" – the definitive airway management for two principal reasons. First, particularly with the placement of a cuffed endotracheal tube, the possibility of aspiration of gastric contents into the airways is greatly reduced. Second, it is via an endotracheal tube that a relatively greater positive pressure can be tolerated for optimal mechanical ventilation.

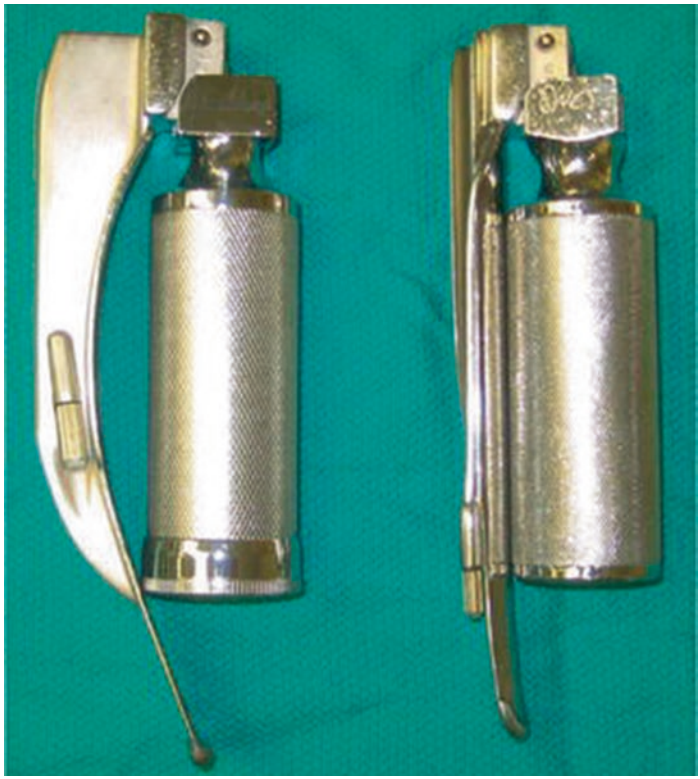


Fig. 9.7 Laryngoscopes: Macintosh and Miller blades. (Photo courtesy J. Ehrenfeld)

Rapid Sequence Induction

The reflux of gastric contents from the stomach into the distal airways via the glottis is a universal concern at all stages of anesthetic care. Fasting prior to elective surgery is the main intervention that guards against pulmonary aspiration. Risk factors for pulmonary aspiration may include:

- trauma patients
- patients undergoing emergency surgeries (fasting guidelines do not apply)
- pregnant patients
- patients with severe gastroesophageal reflux disease
- diabetics (decreased gastric emptying) or obese patients
- patients with neurological impairment

In order to decrease the interval between when a patient is awake with intact laryngeal muscles protecting their airway from aspiration and when the endotracheal tube is in place guarding against aspiration, a rapid sequence induction (RSI) may be performed. An RSI differs from a standard induction after the induction of general anesthesia in three ways:

1. During an RSI, face mask ventilation is **not used** to ventilate the patient. This is to avoid distension of the stomach with oxygen that can occur with facemask ventilation.
2. Cricoid pressure is maintained from before the time the patient receives induction agents until the endotracheal tube placement in the trachea is confirmed. The cricoid cartilage is the only tracheal cartilage that surrounds the entire trachea. Applying pressure to the anterior aspect of the cricoid cartilage occludes the esophagus by closing its lumen between the posterior aspect of the cricoid cartilage and the anterior aspect of the body of the cervical vertebrae.
3. Succinylcholine is classically used as the muscle relaxant of choice to facilitate intubation due to its short onset time. Rocuronium is another choice for patients who might have detrimental side effects from succinylcholine use (e.g. major burn and spinal cord injury patients, patients with personal of familial history of malignant hyperthermia, etc.).

During the coronavirus disease 2019 (COVID-19) pandemic, mask ventilation was avoided when possible, due to concern that it generated aerosols and thereby facilitated viral transmission. An

RSI technique was recommended and widely employed for endotracheal intubations during this time period.

Fiber-Optic Intubation

Endotracheal intubation can be accomplished via fiber-optic guidance. This is accomplished by passing the distal end of a bronchoscope through the glottis and then sliding an endotracheal tube off of the scope into the trachea under direct vision. Fiber-optic intubation can be accomplished in awake as well as anesthetized patients. Awake patients only tolerate the procedure with sufficient local anesthesia delivered to their airway beforehand via topicalization and/or nerve blockade. Sedation may be given to awake patients having fiber-optic intubation. Patients with anticipated difficult airways are often intubated using an awake fiber-optic technique.

Video Assisted Endotracheal Intubation (Glidescope, C-Trach, C-MAC, etc.)

There have been several airway management tools introduced that combine traditional laryngoscopy with fiber-optic or digital optical technology such as the Glidescope, C-Trach, or C-MAC. One of the benefits of these instruments is that they may allow intubation under conditions such as limited mouth opening that might have been more difficult or impossible with direct laryngoscopy. Video laryngoscopy has gained in popularity for airway management since its introduction because of its higher success rate for intubation on the first attempt, especially for management a potentially difficult airway. All training programs for airway management should offer comprehensive teaching for this potentially life-saving technology.

Evaluation and Management of the Difficult Airway

The ASA Difficult Airway Algorithm is a step-wise approach to managing a challenging airway (also see, Appendix A, ASA Difficult Airway Algorithm). The algorithm is designed to present a rational and safe approach to utilizing a number of different management techniques for securing the airway. These may include various types of equipment such as the intubating SGA, Lightwand, Combitube, and fiber-optic laryngoscope. Ultimately, if noninvasive attempts at airway management fail, options include waking the patient up or performing a surgical airway, such as cricothyroidotomy or tracheostomy.

Case Study

You are preparing to anesthetize a 50-year-old man for abdominal hernia repair with mesh. He is 68 in. tall and weighs 260 lb. He has a full beard and mustache. He has no other major comorbidities. He underwent general anesthesia 20-years-ago for arthroscopy of his knee and is not aware of any problems with the anesthetic. You are planning general endotracheal anesthesia.

What factors in this patient worry or reassure you regarding his airway management?

The patient is obese (BMI = 39.5). In itself, this is likely a risk factor for both difficult mask ventilation and difficult laryngoscopy. He also has a full beard, which can interfere with mask fit and make mask ventilation difficult. Conversely, he appears to have had an uncomplicated general anesthetic in the past. While reassuring, there are some caveats: his lack of awareness of problems does not mean that some did not occur but were not reported to the patient or recalled, and his physique may have been quite different 20 years ago.

How will you further assess his airway?

You will perform basic airway examinations on the patient. No one test is definitive, but most anesthesiologists use the Mallampati test, the thyromental distance, and a subjective assessment of neck mobility. Some use other tests as well, such as neck circumference (cut off >17 in. or 43 cm), ability to protrude the lower incisors anterior to the upper incisors, mouth opening, or sternomental distance. Each correlates somewhat with difficult intubation, but ultimately the judgment is likely more subjective and reflects the clinical gestalt of the experienced anesthesiologist.

You decide to proceed with induction of anesthesia. After administering propofol you attempt mask ventilation. You find it difficult to obtain a good mask fit and mask ventilation is difficult. How will you proceed?

You anticipated this problem preoperatively, so you have backup plans already in place. You can try an oral or nasal airway, which may reduce the pressure required to ventilate the patient by helping hold the upper airway patent. In some cases, using both may be helpful. You can also perform two-person ventilation, with one person holding the mask fit with both hands and the other ventilating by squeezing the reservoir bag. Finally, you can consider placement of an SGA to assist ventilation, or proceed directly with intubation.

You are now successfully ventilating the patient. You administer rocuronium to facilitate intubation. After ventilating the patient for 3 minutes, you perform direct laryngoscopy with a Macintosh 3 blade. You can only visualize the tip of the epiglottis. How wil you proceed?

As before, you have anticipated the possibility of this situation and have alternative plans in place for intubation, but you will not simply try again with the same technique: Plan B is not more of Plan A! A common initial step is to apply external laryngeal pressure either yourself, watching the laryngoscopic view as you do, or with a skilled assistant. In any difficult situation, consider calling for help

early; it is better to ask for help and not need it than it is to be in trouble and unable to get it. Next, change the head position, laryngoscope blade, or operator. In obese patients, ramping the head of the bed, by putting several blankets under the shoulders, and more under the head (or using a specialized pillow such as the Troop elevation device), can potentially improve the view. A straight blade (Miller) can sometimes lift the epiglottis more efficiently than the curved (Macintosh) blade. Always ensure you have a good mask airway between efforts. No one ever died from lack of intubation per se, but lack of ventilation will kill! Use of the SGA, can be lifesaving if mask ventilation becomes impossible. This technique is now a standard part of the ASA Difficult Airway algorithm (see Appendix A).

Your initial efforts are still yielding only a view of the epiglottis. You decide to use an alternative airway device to assist you. What are some of your options?

In cases such as this, you can often successfully intubate the patient even without a view of the vocal cords. Some experienced anesthesiologists may attempt a blind pass of the stylet-angled endotracheal tube under the epiglottis. More frequently, an alternative device, such as the Bougie, is passed under the epiglottis first. One can often feel a clicking sensation as the tip brushes along the cartilage rings of the trachea. Then, an endotracheal tube can be passed over the Bougie into the trachea. Other options are to improve the view with different laryngoscopes. A video enhanced device, such as the GlideScope, Bullard laryngoscope, or C-Mac can display a better view than a conventional laryngoscope because of the integration of a camera or fiber-optic port on the distal aspect of the laryngoscope blade. Still another option is to use a flexible fiber-optic bronchoscope with an endotracheal tube threaded over it to locate the glottis. The endotracheal tube is then threaded off the bronchoscope into the trachea. Still other options include use of the SGA for the case, intubation through the

SGA with a fiber-optic technique or with the intubating SGA (which is specially adapted for passage of an endotracheal tube without the need for a fiber-optic scope), or even to awaken the patient and cancel the case. Note that with the FDA approval of sugammadex in 2015, you can rapidly reverse the neuromuscular blockade from an intubating dose of rocuronium. With the patient awake and spontaneously breathing, one can prepare for an awake fiberoptic intubation with local anesthetics employed for topicalization and/or nerve blocks of the airway.

For an alternative scenario, your surgical collegues tell you this is an emergent surgery due to an incarcerated abdominal hernia. How does this change your airway plan?

Due to the emergent nature of the surgery, the patient has likely not followed appropriate fasting guidelines for aspiration prevention, and regardless is at higher aspiration risk due to disruption of normal gut transit. For these reasons an RSI should be performed. Of note, a careful airway examination should *always* be performed. It is the anesthesiologistis responsibility to avoid the dangerous situation of encountering a difficult airway without appropriate backup plans and equipment – this is no less true for emergent surgery. Furthermore, it is generally prudent to use a technique that you are experienced with, rather than attempting something unfamiliar in an emergency situation. For this reason, trainees should gain experience in elective situations with as many different devices and techniques as possible.

Acknowledgements We would like to thank Drs. Shawn T. Beaman, Patrick J. Forte, and David G. Metro for their contributions to the prior edition of this chapter.

Suggested Further Reading

1. Apfelbaum JA, Hagberg CA, Kaplan RA et al (2013) Practice guidelines for the management of the difficult airway: an updated report by the American Society of Anesthesiologist's Task Force on management of the difficult airway. Anesthesiology 118:251–270
2. Caplan RA, Benumof JA, Berry FA (2003) Practice guidelines for the management of the difficult airway: an updated report by the American Society of Anesthesiologist's Task Force on management of the difficult airway. Anesthesiology 98:1269–1277
3. Finucane B, Santora A (2003) Principles of airway management, 3rd edn. Springer, New York
4. Hagberg CA (ed) (2007) Benumof's airway management, 2nd edn. Mosby Elsevier, Philadelphia
5. Mallampati SR, Gatt SP, Gugino LD et al (1985) A clinical sign to predict difficult tracheal intubation: a prospective study. Can J Anaesth 32:429
6. Moore KL, Dalley AF (1999) Clinical anatomy, 4th edn. Lippincott, Williams, and Wilkins, Philadelphia
7. Orebaugh SL (2007) Atlas of airway management techniques and tools. Lippincott, Williams, and Wilkins, Philadelphia
8. Peterson GN, Domino KB, Caplan RA et al (2005) Management of the difficult airway: a closed claims analysis. Anesthesiology 103:33–39

The Anesthesia Machine

10

Alvaro Andres Macias

Key Learning Objectives

- Understand the flow of gas from the central hospital supply to the patient
- Learn the key components of an anesthesia machine (vaporizers, flowmeters, breathing circuits, scavenger system, alarms)
- Understand the safety mechanisms incorporated into the anesthesia machine

The anesthesia machine is designed to receive gases from the hospital central supply, control their flow, vaporize volatile agents, and deliver a measured amount of gas to the breathing circuit. Modern machines utilize advanced electronics and integrated components to achieve these goals, while incorporating a number of important safety features which have been progressively engineered over the last several decades.

A. A. Macias (✉)
University of California San Diego, San Diego, CA, USA
e-mail: a4macias@health.ucsd.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_10

The Anesthesia Machine Components

The anesthesia machine can be divided into sub-systems, each with its own function and characteristics. One way to look at the machine is in terms of the pressure of the gases inside of each part of the machine. Using this approach one can divide the machine into a **high** pressure and a **low** pressure system.

The high pressure system includes the components needed to take the gases from the wall to the flow control valve. The low pressure system takes the gases from the flow control valve to the patient. This prevents high pressures (that could induce barotrauma, or lung damage) from being delivered to the patient (Table 10.1).

Gases flow from the pipeline (or cylinder) into the machine, where they are directed through the fail-safe valve and into the flow control valve. From there gases then go into the flowmeters, then into the vaporizers, and finally the anesthesia circuit and patient via the common gas outlet (see Fig. 10.1).

Table 10.1 Components of the high and low pressure systems

High pressure system
Pipelines & cylinders for the gases delivered
Fail-safe valve
Pressure regulator
Oxygen flush valve
Low pressure system
Flowmeters
Vaporizers
Flow control valve
Check valve
Common gas outlet

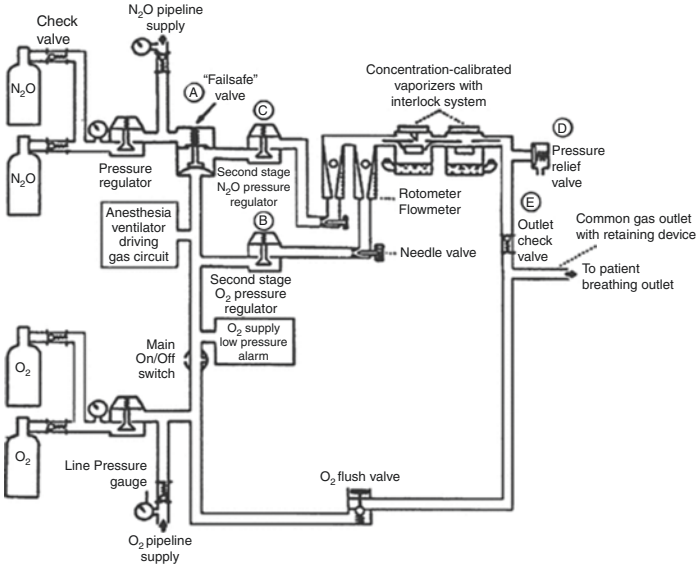


Fig. 10.1 Flow arrangement of a basic two-gas anesthesia machine. (Reproduced with permission from Check-out: a guide for preoperative inspection of an anesthesia machine, ASA, 1987. Reproduced by permission of the American Society of Anesthesiologists, 520 N. Northwest Highway, Park Ridge, Ill)

Basic anesthesia machine components
Source of gases (O_2, N_2O, air)
Flowmeters
Vaporizers
Scavenging system

Note: the breathing circuit & CO_2 absorber are separate from the machine

Pipeline Inlets

Gases arrive from a central hospital supply via a pipeline system that connects to the anesthesia machine. The pipeline and the hoses are both color coded: green for oxygen, yellow for air, and blue for nitrous oxide. The hoses connect to the machine using a diameter-index safety system (DISS). The DISS (Fig. 10.2) is a

Fig. 10.2 Diameter index safety system

non interchangeable threaded connection that makes it physically impossible to attach an oxygen hose to any port other than an oxygen outlet – because the size and diameter of the wall connections and hose adapters are gas specific.

Cylinder Inlets

Gas cylinders use the pin index safety system (PISS) to prevent connection errors. On the back of the anesthesia machine, one can find places for at least one back-up gas cylinder (oxygen). As with the pipeline and the hoses, every cylinder is color coded to prevent errors. These cylinders are generally reserved for back-up use in case of a pipeline or central gas supply failure (Fig. 10.3).

Cylinders

Cylinders come in a variety of standard sizes. The most commonly used in the operating room are E-cylinders (Table 10.2). By understanding the physical properties of the gases stored in a cylinder, one can calculate the amount of gas (and or time) left in a cylinder.

Pressure Regulation

Gases coming from the pipeline or central hospital supply have a wall pressure of 50–60 psi. A full oxygen tank delivers gas at 2200 psi and a full nitrous oxide tank delivers gas at 745 psi. In

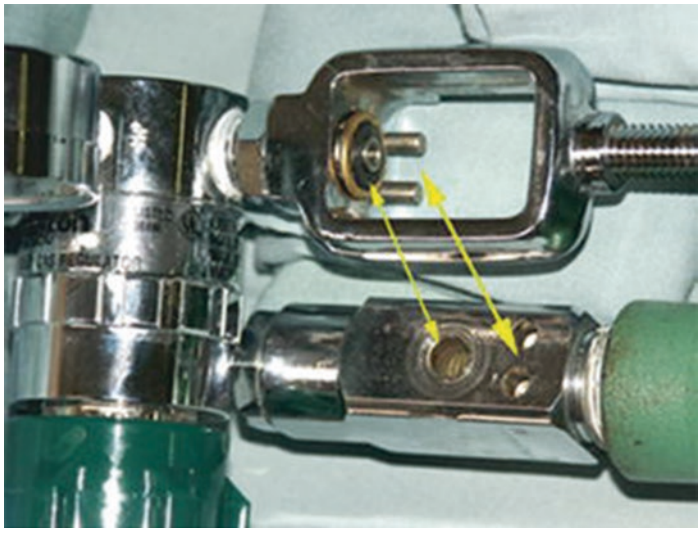


Fig. 10.3 Pin index safety system

Table 10.2 Properties of E cylinders

Properties of E cylinders	Oxygen	Air	Nitrous oxide
Color of cylinder	Green	Yellow	Blue
Capacity	625 l	625 l	1590 l
Pressure when full	2200 psi	750 psi	1800 psi
Physical state	Gas	Gas	Liquid & gas

For example: if the pressure gauge on an oxygen cylinder reads 1100 psi and you plan to deliver oxygen at a rate of 6 L/min → one could estimate that there are 312 l remaining in the tank (1100 psi/2200 psi × 625 l). At 6 L/min, one could deliver oxygen for approximately 52 min

order to ensure a consistent and acceptable pressure is delivered to the patient, machines have pressure regulators incorporated into the gas flow. These regulators will drop cylinder gas pressures to 45–47 psi and pipeline pressures to no more than 50–60 psi. This allows gas to be preferentially taken from the central pipeline supply, rather than the cylinders, to ensure that cylinders are not unnecessarily drained. Finally, there is also a high-pressure relief valve for each individual gas that opens when pressure in the machine exceeds (95–110 psi).

Fail-Safe System

In the event of a failure in the oxygen supply, if the oxygen pressure *(not flow)* drops below a critical point, the supply of other gases will be interrupted and an alarm will sound. This is known as the **fail-safe system**. This system **does not prevent against delivering hypoxic gas mixtures** because if the oxygen pressure is normal, other gases still be delivered. This is why inclusion of a working oxygen analyzer (see below) in the inspiratory limb of the breathing circuit and a proportioning system in the machine are critical.

Flowmeters

Flowmeters are the division line between the high pressure and the low pressure systems. The pipeline, cylinders and gas lines before the flow meters are considered part of the high-pressure circuit whereas those after them are considered part of the low-pressure system. There are three types of flow meters: variable-orifice, electronic and constant-pressure.

Gas flow increases when the flow valve control is turned counterclockwise – delivering the amount gas desired. It is worth mentioning that flow meters are calibrated for the gas they deliver and are **not** interchangeable. The oxygen flowmeter is **always downstream** from all other flowmeters (far right in the U.S.) to reduce the chances of delivering a hypoxic mixture should a leak occur within a flowmeters.

In order to prevent delivery of a hypoxic mixture of oxygen and nitrous oxide all machines include an oxygen/nitrous oxide **ratio controller** that links the nitrous oxide flow to the oxygen gas flow. This guarantees a minimum oxygen concentration of 21–25%.

Vaporizers

The main function of the vaporizer is to vaporize the volatile anesthetics before they reach the patient. All vaporizers are agent specific and have concentration-calibrated dials that tightly control the amount of anesthetic gas deliver to the patient.

There are in two types of vaporizers currently in use: variable-bypass and electronic vaporizers. The variable-bypass vaporizer divides the fresh gas flow into two streams. One stream contacts the volatile agent and picks it up, whereas the other stream leaves the vaporizer unchanged. The two streams then merge as they leave the vaporizer and enter into the breathing circuit.

Electronically controlled vaporizers are most commonly used for Desflurane (because its low boiling point of 23.5 C or 73.4 °F is very close to room temperature). They work by heating Desflurane to a temperature of 39 C in order to create a constant vapor pressure. For this vaporizer there is no fresh gas flow though it. Instead the vaporizer simply releases the amount desired and then mixes it with fresh gas. Of note is that these vaporizers do not compensate for changes in elevation.

All modern vaporizers (except for desflurane vaporizers) compensate for temperature and ambient pressure changes. This ensures that the same amount of agent will be delivered to the patient at all time.

Because vaporizers are agent specific, it is critically important to fill up the vaporizer with the correct agent – or else an unanticipated concentration of agent may be delivered. In order to prevent mis-filling, vaporizers are color coded and have agent-specific keyed filling ports that only accept the correct key or straw (Fig. 10.4).

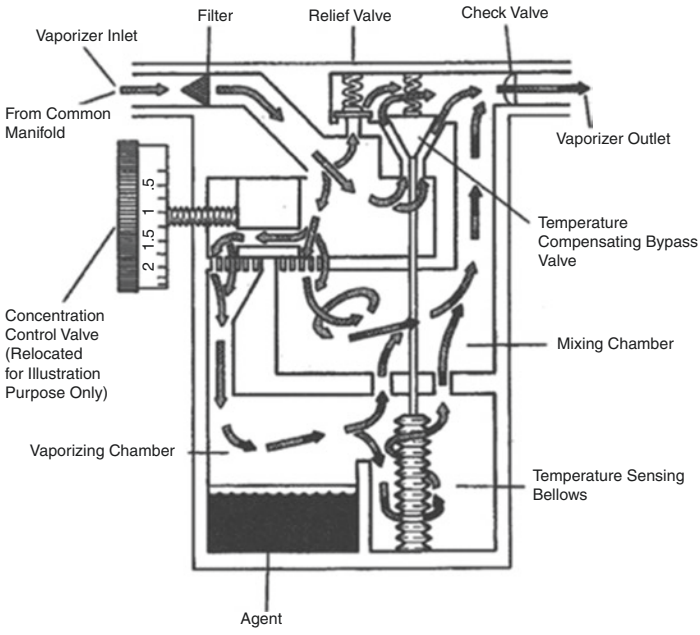


Fig. 10.4 Vaporizer schematic. (Reproduced with permission from Biomedical Engineering Handbook. Bronzino, J. Springer Press 2000. Fig. 84.2, page 86)

Gas Outlet

The gas outlet transports fresh gas carrying volatile agent from the machine to the breathing circuit.

Alarms

Anesthesia machines include a number of alarms. Each will have a **low pressure alarm** that goes off when a set airway pressure is not reached in the circuit. It is the **first** alarm to go off when a disconnection occurs in the circuit.

The **oxygen fail-safe** monitor checks for the presence of low oxygen pressure within the system. If the pressure drops below a certain limit, the monitor sounds an alarm and shuts off the inflow of other gases – until the oxygen pressure is reestablished.

The oxygen sensor in the inspiratory limb of the breathing circuit checks the concentration of oxygen delivered to the patient and will alarm if the delivered FiO_2 drops below a set threshold. This is *probably one of the most important monitors in the entire machine*.

Waste-Gas Scavengers

Waste-gas scavengers prevent the operating room personnel from unnecessary exposure to volatile agents. The National Institute of Occupational Safety and Health (NIOSH) recommends limiting the room concentration of nitrous oxide to 25 ppm (ppm) and halogenated volatile agents to 2 ppm. Each anesthesia machine has a port that connects to the hospital central suction and a vacuum control valve that should be adjusted to permit evacuation of 10–15 L of waste gas per minute. As with many systems there are some hazards that come with it. If the system becomes occluded, it may deliver excessive positive pressure to the patient increasing the risk of barotraumas. Conversely, if the system generates too much negative pressure, it may inadvertently suction out fresh gas from the patient and increase the amount of volatile agent needed.

Oxygen Flush Valve

The oxygen flush valve serves as safety device by allowing the anesthesiologist to deliver 100% oxygen, free of volatile agent and at a high flow (400–55 l/min), directly to the breathing circuit at any given time. Looking carefully at Fig. 10.1, one can see that there is a direct communication between the oxygen source (pipeline or cylinder) to the common gas outlet, which bypasses the pressure regulator. When the valve is activated (by pressing the button located on the front of the machine) it allows oxygen to

flow at the pressure delivered from the source, directly into the circuit and the patient's lungs. This action has the potential to cause barotrauma due to the high transmitted pressures.

Anesthesia Machine Checkout

As anesthesiologists, we rely heavily on our machine as a way of delivering fresh gases and anesthetic agents to our patients. In fact, machine failures can be potentially catastrophic or fatal. Because of this, it is critically important to perform a machine checkout at the start of each case. While many of the new machines do this checkout automatically, it is important to understand how each machine works and the potential steps one would take to troubleshoot a given problem should any kind of failure arise. For a set of sample machine specific checkout procedures, refer to the ASA web page http://www.asahq.org/clinical/checklist.htm.

Anesthesia Breathing Systems

It is important to realize that the breathing system is not a part of the anesthesia machine. The anesthesia machine ends at common gas outlet. In order to deliver the gases from the machine to the patient we need a breathing system. Multiple designs have been developed and they are classified as closed, semiclosed, open and semiopen. This classification is based on the presence or absence of unidirectional valves, a gas reservoir bag, rebreathing of exhaled gases and ways to chemically neutralize the exhaled carbon dioxide coming from the patient.

The most common system in use these days is the **circle system**. The circle system (see Fig. 10.5) is composed of an inhalation check valve, inspiratory limb, Y-piece, expiratory limb, exhalation check valve and APL valve, reservoir bag, bag/vent selector switch and a CO_2 absorber. This system itself can be classified as closed, semiclosed and semiopen depending on how much fresh gas flow is used.

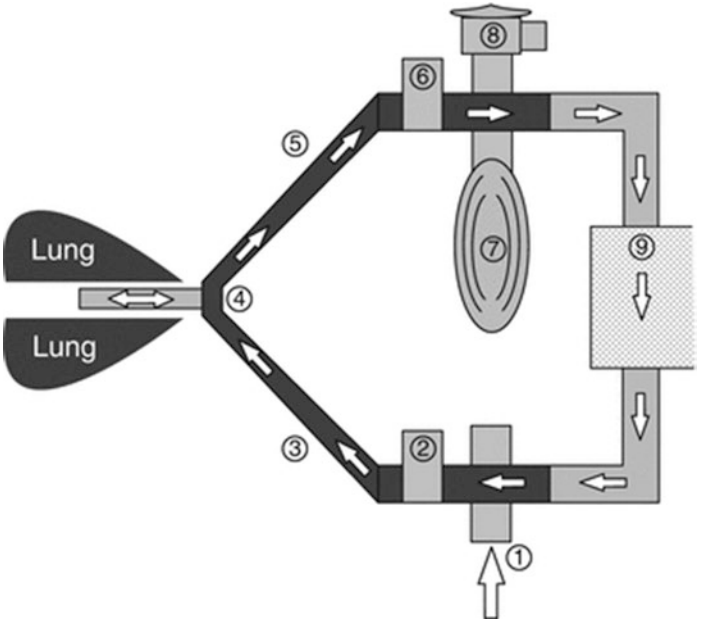


Fig. 10.5 Anesthesia machine circle system flow schematic. (Image courtesy J. Ehrenfeld)

The circle system takes the gas delivered from the anesthesia machine via the common gas outlet and delivers it to the patient. Depending on the volume of the gas flow delivered to the patient, rebreathing of exhaled gases may occur. In order to prevent rebreathing of CO_2, unidirectional valves and a CO_2 neutralizing system are in place. These devices prevent any CO_2 rebreathing and in many cases reduce the total amount of inhaled anesthetic that must be put into the system.

1. Fresh gas enters the circle system
2. Inspiratory limb one-way valve
3. Inspiratory tubing
4. Patient y-piece
5. Expiratory tubing

6. Expiratory limb one-way valve
7. Reservoir bag
8. Adjustable pressure limiting (APL) Valve
9. CO_2 absorbent

Humidifiers

Because fresh gas delivered to a patient by an anesthesia machine bypasses all of the natural mechanisms which humidify inspired gases (nasal vessels, oral secretions), steps must be taken to prevent desiccation of the respiratory mucosa. This is accomplished by the use of humidifiers. These devices may be active or passive.

Passive humidifiers (the most commonly used) trap water released on exhalation such that some water will be added back to the fresh gas flow during the next inspired cycle. Active humidifiers contain a water chamber and add vaporized water to the inspiratory gas flow. While active humidifiers do not any dead space to the circuit, passive humidifiers do.

The Mechanical Ventilator

The mechanical ventilator is a sophisticated and key piece of equipment that has evolved substantially in the last 20 years. There are two basic ventilatory modes, volume control ventilation (VCV) and pressure control ventilation (PCV). Other modes have been developed lately by taking advantage of sophisticated computer algorithms including pressure support ventilation (PSV), synchronized intermittent mandatory ventilation (SIMV), pressure controlled volume guaranteed ventilation (PC-VGV), etc.

In the VCVVolume control ventilation (VCV), the tidal volume to be delivered to the patient is set up by the anesthesia provider and the machine delivers the set tidal volume (TV) each breath, in this mode the pressure delivered by the machine can change with each tidal volume delivered depending on the patient's lung characteristics. Usually there is a high-pressure alarm that will go off if the machine reaches that pressure to

deliver the pre set tidal volume. For example let's say one wants to deliver a TV of 600 ml, with each breath the machine will deliver 600 ml of mix gases but the inspiratory pressure may change with each breath.

On the other hand in the PCV mode, the anesthesia provider presets a maximum pressure to be delivered by the machine to reach an approximate tidal volume. In this case each tidal volume delivered each breath will vary depending on the patient's lung characteristics. Usually there is an alarm that will go off if pre set pressure entered cannot be reached. For example let's say one wants to deliver a peak inspiratory pressure (PIP) of 20 cm H_2O, in this case with each breath the machine will deliver 20 cm H_2O of PIP but the tidal volumes will change with each breath.

Case Study

The Anesthesia Machine

You are working with your attending on a busy day. She tells you to go set up the room for your first case. You are familiar with the preparation of airway equipment and have previously discussed the drugs you will be using. As you walk towards the OR, your attending calls out to you to "remember to check the anesthesia machine." You walk into the OR and discover to your dismay that the machine is an older model that does not feature automatic machine check-out like the more modern ones that you have been using.

(Note that this case will be easier if you have read the supplemental Internet material referenced in the chapter).

You begin by inspecting the hoses attached to the machine from the gas outlets on the wall. How can you tell if they are properly connected and functional?

The gas lines are color coded, green for oxygen, yellow for air, and blue for nitrous oxide. You can check to make sure they are connected to the proper outlets on the wall and the machine, but it is extremely unlikely that they could be misconnected. This is because they are diameter indexed and cannot be attached to the wrong outlet or inlet. You can

inspect the pressure gauges on the anesthesia machine to ensure that there is adequate pressure in the lines (indicated by a green band).

How can you tell if you have adequate backup gas supplies should the hospital supply fail?

All anesthesia machines also have tanks of oxygen and usually nitrous oxide attached directly to the back of the machine to be used as backup supplies. You can open the valve on one of the oxygen tanks and inspect the pressure valve for tank pressure to ensure that you have an adequate supply. It is usually recommended that you have at least ½ a tank, which should register as 1100 PSI, compared to a full tank at 2200 PSI. This corresponds to a little more than 300 l of oxygen, enough for over an hour at 5 l per minute and much longer at low fresh gas flows.

How can you test to make sure the machine will prevent administration of a hypoxic gas mixture?

There are several safety mechanisms in the machine to ensure admnistration of adequate oxygen to prevent hypoxia. You can test the oxygen monitor's accuracy by running 100% oxygen through the circuit and ensuring that it reads 100%, and you can place the sensor outside the circuit exposed to room air an make sure it reads 21%. This monitor should alarm if the mixture is hypoxic. There is also an interlock on the gas flow controls that should prevent you from setting a flow of nitrous oxide that is too high relative to the oxygen flow. You can turn on both gases and then decrease the oxygen flow; at some point the nitrous oxide flow should automatically decrease. Finally, there is a "fail safe valve" that senses oxygen and nitrous oxide pressures and should turn off all other gases should oxygen pressure drop. You can test this valve by disconnecting the wall supply of oxygen while administering nitrous oxide (and with the oxygen tank turned off). The nitrous oxide flow should be turned off and an alarm should sound.

Later you are doing the case, which began uneventfully. The patient is intubated and being mechanically ventilated. You note on the capnograph that there appears to be inspired CO_2. Given your understanding of the anesthesia machine, why might this be occurring (see Fig. 10.2*)? Which of the causes should you have been able to pick up during the machine checkout?*

Inspired CO_2 implies that the circuit has either not successfully separated inspired and expired gas flows, or that the CO_2 absorber is not functioning properly. In particular, if the expiratory one-way valve is incompetent, then gas in the expiratory limb, which contains exhaled CO_2, could be inspired. Depending on fresh gas flow, the same phenomenon can occur if the inspiratory valve is incompetent. In this case, some of the exhaled gas can travel down the inspired limb rather than the expired limb, and if fresh gas does not "wash it out" before the next inspiration, the patient could breathe in some of this CO_2-containing gas. You should be able to detect malfunctioning valves on machine checkout. Different methods are suggested, but in essence one observes the functioning of the valves through their transparent covers during inspiration or expiration.

The other possibility is malfunctioning CO_2 absorbent. This canister contains granules that react chemically with exhaled CO_2 and remove it from the gas stream. The reaction turns a chemical indicator from white to purple, to indicate when the granules have become exhausted. Unfortunately, the granules will turn back to white after they dry out, so if an exhausted absorbent were left in place after the last case, you would not have detected this during checkout. You're off the hook!

Suggested Readings

1. ASA Machine Checklist. http://www.apsf.org/newsletters/html/2008/spring/05_new_guidelines.htm
2. Barash PG, Cullen BF, Stoelting RK (2006) Clinical anesthesia, 5th edn. Lippincott, Williams & Wilkins, Philadelphia
3. Dorsch JA, Dorsh SE (1999) Understanding anesthesia equipment, 4th edn. Lippincott, Williams & Wilkins, Philadelphia
4. Morgan, Mikhail's (2022) Clinical anesthesiology, 7th edn. McGraw Hill, New York
5. Stoelting RK, Miller RD (2000) Basics of anesthesia, 4th edn. Churchill Livingstone, New York

Anesthesia Equipment and Monitors

11

Basem Abdelmalak, D. John Doyle, and Daniel Presutti

For maximum impact, it is recommended that the case study and questions found on page xxii are reviewed before reading this chapter.

Key Learning Objectives

- Learn the indications for applying intraoperative monitors
- Understand the underlying principles behind the various monitors
- Know the limitations associated with various types of monitors

B. Abdelmalak · D. J. Doyle
Anesthesia Institute, Cleveland Clinic, Cleveland, OH, USA

D. Presutti (✉)
Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA
e-mail: dpresutt@wakehealth.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_11

Introduction

Patient monitoring and the equipment to support it are vital to caring for patients in operating rooms, intensive care units, emergency departments, and in acute care settings. Over the last few decades, technologies once considered luxury have become ubiquitious standards of patient care. Although the scope and spectrum of monitoring can be very case specific, at the core of monitoring, the process can be as simple as the periodic measurement of **routine vital signs (blood pressure, heart rate, respiratory rate, temperature)**. Diligent monitoring also entails the interpretation of available clinical information to help identify or predict problems with a patient. Patient monitoring, thus, not only involves quantitative physiological measurements (such as respiratory rate), but also involves qualitative observations (e.g., observation of signs of patient distress such as movement, agitation, or diaphoresis). The combined interpretation of both objective and subjective data followed by critical thinking and the subsequent inference of diagnoses is of paramount importance for the anesthesiologist. *For example, unilateral chest rise may imply endobronchial intubation or a pneumothorax.*

Visual and auditory surveillance is central to anesthesia monitoring, and involves many dimensions:

- Observing the patient's color, respiratory pattern, accessory muscle use, and looking for movements, grimaces or unsafe patient positioning
- Observing the patient's clinical data on all intraoperative monitors
- Observing bleeding and coagulation at the surgical site (e.g., are the surgeons using many sponges and/or are they doing a lot of suctioning?)
- Monitoring the functioning of all lines to ensure that IV catheters have not infiltrated
- Conducting an anesthesia machine and workspace checkout

The importance of patient monitoring during anesthesia has been emphasized by the following policy statements from the American Society of Anesthesiologists (ASA) (see Table 11.1).

Based on these principles, patients are monitored both by clinical observation ("look, listen, feel") as well as by using specialized monitoring equipment (see Table 11.2). Most importantly, monitoring information of this kind can be useful in detecting various clinical problems, frequently before they result in unnecessary harm. Some monitors (e.g., airway pressure) are usually built into the anesthesia machine. In addition, one should visually

Table 11.1 ASA monitoring standards

Standard 1: Qualified anesthesia personnel shall be present in the room throughout the conduct of all general anesthetics, regional anesthetics and monitored anesthesia care.
Standard 2: During all anesthetics, the patient's oxygenation, ventilation, circulation, and temperature shall be continually evaluated (where "continuous" means without interruption and "continually" means repeated regularly and frequently)

Table 11.2 Monitoring equipment typically employed in general anesthesia cases

Electrocardiogram (*provides information about rate, rhythm, ischemia (ST segments)*)
Blood pressure (*manual, automatic, inta-arterial catheter*)
Pulse oximeter (*usually on fingertip or ear lobe*)
Capnography (*standard of care in patients with an advanced airway such as an ETT or LMA*)
Oxygen analyzer (*part of anesthesia machine*)
Anesthetic agent concentration analyzer (*part of anesthesia machine*)
Temperature (*usually esophageal, nasopharyngeal or axillary*)
Precordial or esophageal stethoscope (*listen to heart sounds, breath sounds*)
Gas flows/spirometry (*part of anesthesia machine*)
Airway pressure monitor (*part of anesthesia machine*)
Airway disconnect alarm (*part of anesthesia machine*)
Peripheral nerve stimulator (*where muscle relaxants have been used*)
Urometer (*measure urine output – where appropriate*)

monitor the patient's breathing pattern and color, look for signs of distress, etc. The diligence of the anesthesiologist cannot be understated, as she is the primary patient advocate and guardian when the patient is anesthetized.

Blood Pressure Monitoring

Manual blood pressure monitoring is easily achieved via auscultation of Korotkoff sounds as learned by every medical student. However, automatic blood pressure monitoring is more practical and is generally achieved via a technique known as **oscillometry**. Here, the cuff is inflated to a high pressure, then deflated slowly. Oscillations in the cuff pressure begin to be detected when the cuff pressure first falls below systolic pressure. As deflation continues, the mean blood pressure is identified as the cuff pressure at which the amplitude of the oscillations is the greatest. The oscillations then vanish as the diastolic pressure is approached (see Fig. 11.1).

In most cases, automatic blood pressure monitoring is done at least every 5 min, or more frequently, as needed. Many automatic blood pressure machines also have a "stat" mode where measurements are done immediately one after the other. Occasionally, anesthesiologists also put a manually operated blood pressure cuff on a second arm, in case the automatic blood pressure monitor fails to provide reasonable numbers, or in the setting of cases where blood pressures may be different due to circulatory or anatomic reasons (e.g., vascular occlusion / obstruction).

In longer, complex cases (with expected large hemodynamic variations), or in very sick patients, invasive blood pressure monitoring via an arterial line can be utilized. Arterial lines are most often inserted into one of the radial arteries, although it may less commonly be placed in a brachial, femoral, ulnar, or dorsalis pedis artery. This method involves connecting 20–22 gauge arterial catheter to a pressure transducer via a narrow fluid-filled pressure tubing. The input from the transducer is converted to a

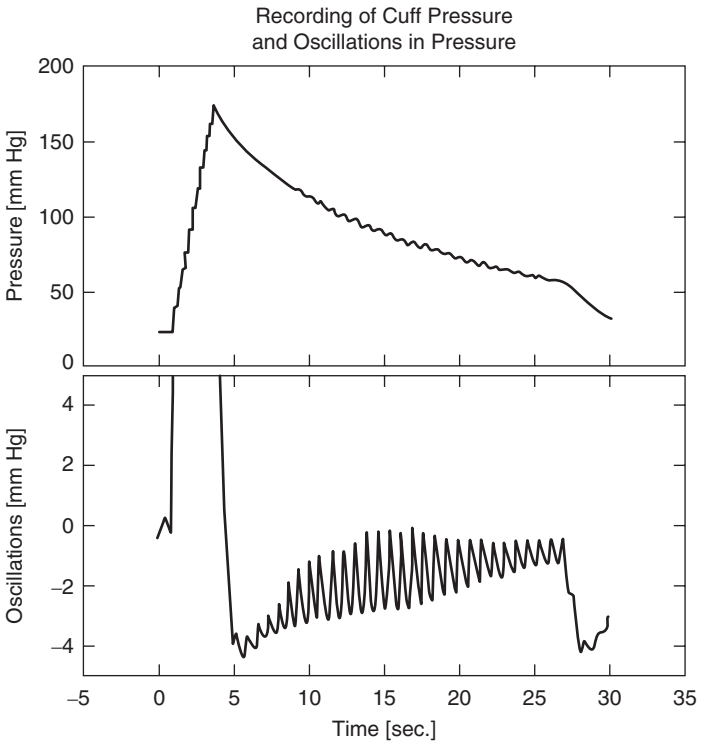


Fig. 11.1 Sample blood pressure measurement using oscillometry. The peak oscillation corresponds to the mean arterial pressure. (Reproduced with permission from Bronzino [4])

visual and numerical waveform (Fig. 11.2). This arrangement provides realtime pressure information that is helpful, for instance, in patients with poor ventricular function. In addition, since arterial blood gases are easily drawn from an arterial line, they can be particularly useful in patients with pulmonary disease or patients with acid–base disorders. Similarly, blood samples can be sent for hemoglobin, glucose, or a myriad of other tests to assist in critical intraoperative management for patients whose condition is changing rapidly or in which large blood losses are anticipated.

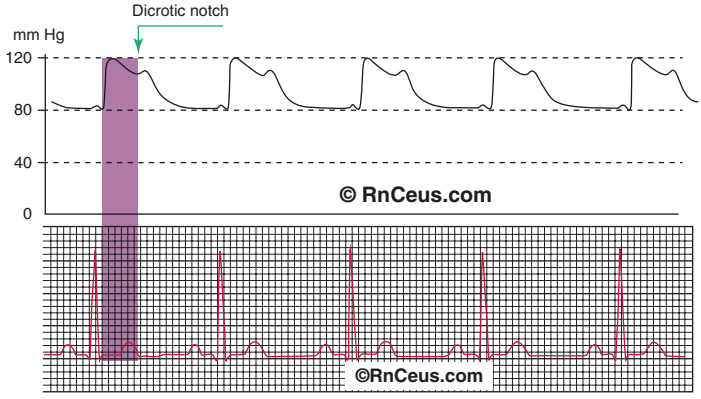


Fig. 11.2 Arterial line waveform and its relationship to cardiac cycle. (Reproduced with permission from www.rnceus.com/hemo/artline.htm)

Electrocardiographic Monitoring

All anesthetized patients undergo electrocardiographic monitoring. This provides the clinician with three types of information: (1) heart rate, (2) cardiac rhythm, and (3) information about possible myocardial ischemia (via ST segment analysis). In addition, ECG monitoring can help assess the function of a cardiac pacemaker.

The most common electrocardiographic system used during anesthesia is a five-electrode lead system. This arrangement (Fig. 11.3) allows for the recording of any of the six limb leads plus a single precordial (V) lead.

Frequently, the surgical field prohibits exact placement of the leads, so the anesthesiologist should anticipate this and create a printed reference strip at the start of the case. In doing this, the challenges of lead placement resulting in an ECG abnormality versus actual intraoperative ECG changes can be discerned quickly.

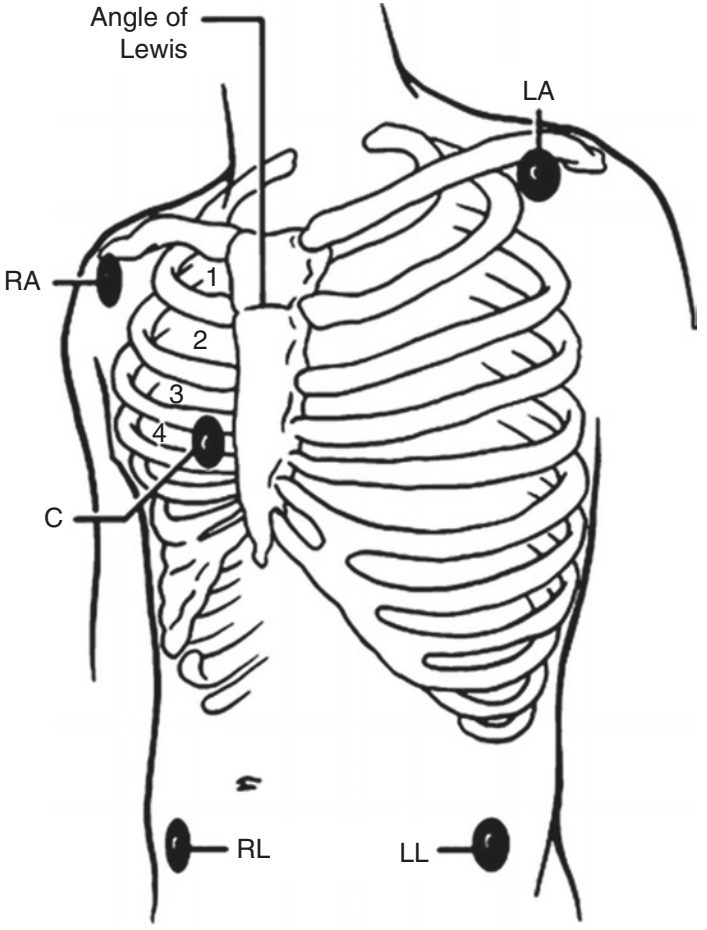


Fig. 11.3 Location of the five electrodes used in a typical intraoperative electrocardiographic monitoring setup. In this image the precordial lead would correlate to V1 but can be moved laterally to the left to monitor V5, for instance. (Reproduced with permission from American Heart Association [1])

Pulse Oximetry

Pulse oximetry is a simple noninvasive method of monitoring arterial oxygen saturation (the percentage of hemoglobin (Hb)

with oxygen molecules bound). The arterial saturation obtained in this manner is designated as SpO_2. A pulse oximeter consists of a probe attached to the patient's finger, toe, or ear lobe, which is in turn attached to the main unit (Fig. 11.4). It measures the red (e.g., 660-nm wavelength) and infrared light (e.g., 940-nm wavelength) transmitted through and/or reflected by a given tissue. It is usually associated with an audible tone which occurs with each heart beat and changes pitch with the actual saturation reading.

A patient is generally said to be hypoxemic when the SpO_2 falls below 90%, a point usually corresponding to an arterial PO_2 of 60 mmHg. An important advantage of using a pulse oximeter is that it can detect hypoxemia well before the patient becomes clinically cyanotic. Pulse oximetry is mandated in **all** patients undergoing anesthesia. However, it is important to realize that pulse

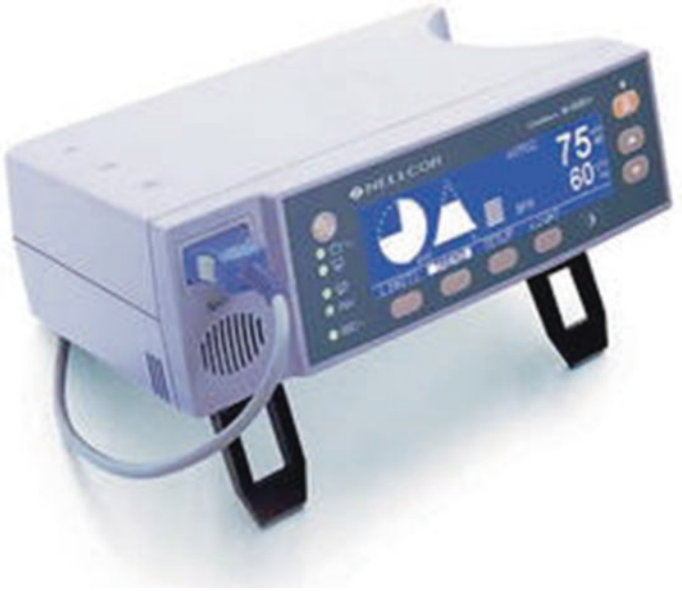


Fig. 11.4 A typical stand-alone pulse oximeter, showing a S_pO_2 of 75% and a heart rate of 60 beats/min. A waveform display allows one to ensure that a quality signal is present. Most new monitoring systems incorporate SpO2 as a portion on a multi-function display. (Image courtesy Covidien).

oximeters give no information about the level of arterial CO_2 and are useless in assessing adequacy of patent ventilation. Remember, oxygenation and ventilation are two different things! New oximetry designs even promise the capability of providing realtime hemoglobin concentration, a useful feature in surgical patients expected to undergo large blood losses.

Capnography and Ventilation Monitoring

Capnography (see Fig. 11.5a–e) is the continuous analysis and recording of carbon dioxide (CO_2) concentrations in respiratory gases. Commonly referred to as end-tidal CO_2 ($EtCO_2$), capnogra-

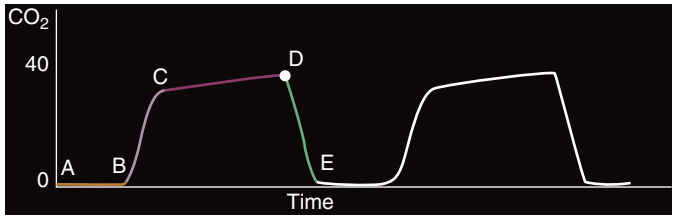


Fig. 11.5 (**a**) Normal capnogram. The CO_2 level at point D (end-tidal CO_2) is normally around 40 mmHg. As shown above, the capnogram has four segments that correspond to phases of the respiratory cycle. The first phase (*AB*) is a flat part due to exhalation of dead space. It should always fall to zero; otherwise rebreathing is occurring. The second phase (*BC*) is the ascending segment from exhalation of mixed dead space and alveolar air. The third phase (*CD*) is the plateau portion that represents exhaled CO_2 from the alveoli. The fourth phase (*DE*) represents the beginning of inspiration (Used with permission from Oridion Medical, Inc. www.oridion.com) (**b**) Hyperventilation. The end-tidal CO_2 here is substantially less than 40 mmHg. Hyperventilation is sometimes used as a means to reduce intracranial pressure in head-injured patients (Used with permission from Oridion Medical, Inc.) (**c**) Hypoventilation. The end-tidal CO_2 here is substantially greater than 40 mmHg. In this instance, this is due to a low respiratory rate, as might occur in a patient breathing spontaneously with opiate analgesics in use (Used with permission from Oridion Medical, Inc.) (**d**) Rebreathing. In this instance, the CO_2 concentration never falls to zero. A common cause of this is exhausted CO_2 absorbent (e.g., soda lime) in the anesthesia machine patient breathing circuit. This may be corrected by increasing the fresh-gas flow rate. (Used with permission from Oridion Medical, Inc.) (**e**) A notch in the plateau ("a curare cleft") is an indication of a spontaneous respiratory effort during mechanical ventilation

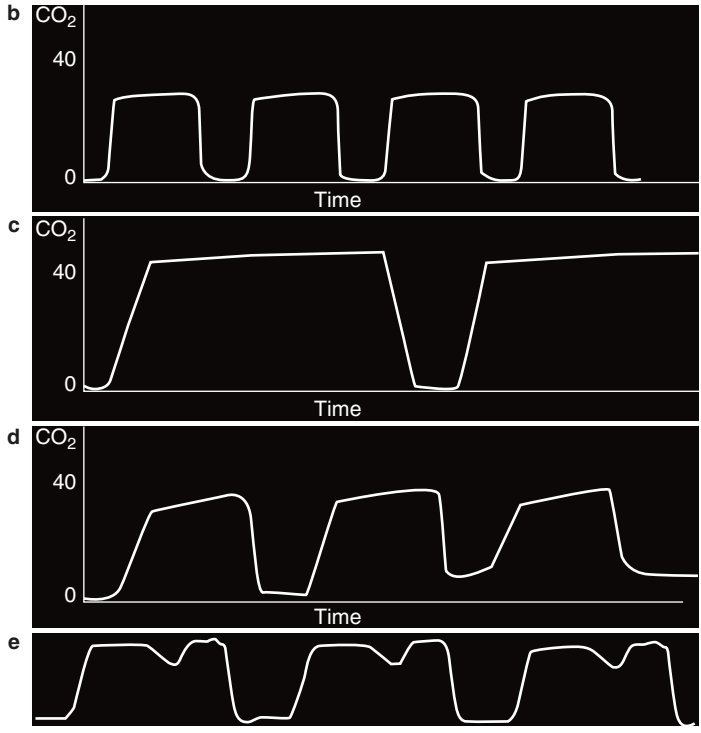


Fig. 11.5 (continued)

phy is an ASA mandated monitor for both general anesthesia as well as for moderate sedation. A capnograph uses one of two types of analyzers: mainstream or sidestream. Mainstream units insert a sampling window into the breathing circuit for gas measurement, while the much more common sidestream units aspirate gas from the circuit and the analysis occurs away from the circuit. Modern capnography typically utilizes infrared technology which passes in infrared beam of light over the sample and, as CO_2 absorbs the light, this information is displayed on the monitor as both a visual waveform and numeral. Other techniques such as mass spectroscopy, Raman scattering, or photoacoustic technology are infrequently used.

Capnography is useful in a number of important clinical situations:

- Detecting when an anesthetic breathing circuit disconnects
- Verification of endotracheal intubation (a sustained normal capnogram is not obtained when the endotracheal tube ends up in the esophagus)
- Verification of proper LMA placement with adequate ventilation
- Assisting in the detection of hypoventilation (raised end-tidal CO_2 is often present) and hyperventilation (low end-tidal CO_2 is often present)
- Detecting rebreathing of CO_2 (in which case the inspiratory CO_2 level is nonzero)
- Detecting capnograph tracings suggestive of COPD (where no plateau is present in the capnogram)
- Monitoring CO_2 elimination during cardiac arrest and CPR (the capnogram "improves" as pulmonary blood flow improves with adequate circulation/chest compressions)

Most importantly and simply stated, capnography is used a monitor and measure of ventilation. In sedated or anesthetized patients, the mere observation of chest movement and (especially) skin color can often be deceiving. Reliably estimating the degree of chest excursion by visual means is often difficult, and observation of cyanosis (dusky, bluish skin coloration) provides only a late warning of the presence of hypoxemia. By contrast, the use of capnography usually provides clinicians with **reliable respiratory data** and helps with the early detection of obstructed ventilation, hypoventilation, or apnea. Another point to remember is that since capnography measures ventilation, it will alert the caregiver to adverse ventilatory events well before a pulse oximeter signals an alarm. This is particularly true since patients receiving oxygen can have arterial saturation levels that are completely acceptable despite the patient having significant hypercarbia.

Information acquired from end-tidal CO_2 is invaluable and can serve as the first indicator to a catastrophic cardiorespiratory event

such as circulatory arrest, a large pulmonary embolus, or severe hypotension (such as from extreme blood loss or compression of the inferior vena cava).

Mechanical ventilation must also be assessed through vigilant monitoring of tidal volumes (V_T), airway pressures, minute ventilation, and inspired gas concentrations. Recall that with mechanical ventilation, simply speaking, the anesthesiologist selects for either volume control **or** pressure control modes to achieve the desired minute ventilation. Tidal volumes (generally initiated at 5–6 cc/kg using ideal body weight) may change as the patient's condition changes. For example, when pressure-controlled ventilation mode is used, the V_T is inversely related to total chest compliance. Chest compliance is a broad term which encompasses intraparenchymal lung conditions, chest wall/anatomic constraints, external compression, and surgically induced causes such as pneumoperitoneum during laparoscopy. It is important to also have the insight to realize that nonpatient factors, such as circuit leaks and partially inflated tube cuff, can also cause a decrease in V_T being delivered.

Airway pressures (peak and plateau) can change secondary to patient factors such as the aforementioned chest wall compliance. For example, when volume controlled ventilation is used, the airway pressures are inversely related to the total chest compliance. Nonpatient factors such as tube kinks, narrow ETT sizes, and mucous plugs can cause an increase in airway pressures by increasing the resistance to gas flow.

Another component of mechanical ventilation is the delivery of inspired gases. At the most basic level, the concentration of oxygen is selected. Within the practice of anesthesia, the anesthesiologist selects the fractions of inspired gases to create the appropriate inspired concentrations of air, oxygen, and other anesthetic gases/agents. The balances and ratios are both case and patient specific and should be tailored on an individual basis.

Monitoring Muscle Relaxation

Muscle relaxation, or paralysis using neuromuscular blocking agents such as rocuronium, is often required during surgery. For instance, muscle relaxation may be needed to facilitate tracheal intubation, to allow abdominal closure, or to ensure that no move-

ment occurs during neurosurgery. In such settings, neuromuscular blockade monitoring or **"twitch monitoring"** is employed.

This involves electrode placement along the known anatomic path of a nerve, frequently the ulnar, tibial, or facial nerve, with use of a peripheral nerve stimulator (see Fig. 11.6). Nerve stimulators have several modes, the most common being the "train of four" (TOF). This electrical stimulation uses four electrical pulses over 2 seconds to determine the degree of the neuromuscular block. The

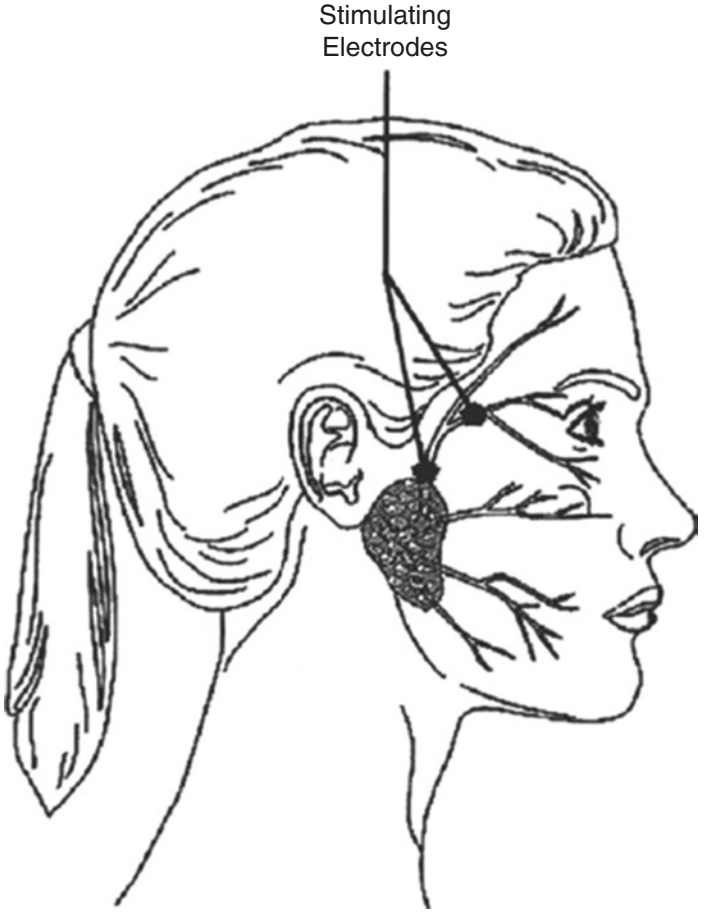


Fig. 11.6 Proper electrode placement for stimulating the facial nerve. (From O'Donnell and Nácul [11]. Used with permission)

observed "twitch" response to either stimulus sequence allows the anesthesiologist to determine the degree of muscle paralysis, which is rated in the perceived number of twitches (0/4 through 4/4). The stimulus should result in a predictable motor response related to the nerve being stimulated (e.g., tibial nerve stimulation results in plantar flexion of the foot). Newer technologies have also recently evolved which include acceleromyography and electromyography (EMG) in an effort to more accurately quantify the return of neuromuscular function. The goal is to provide a measured numerical value to demonstrate the return of function. A TOF ratio is employed and numerical values show the return of neuromuscular function as a ratio to the measured baseline measurements (the baseline level is checked prior to the administration of neuromuscular blockade). This evolution of neuromuscular blockade monitoring is becoming more commonplace as there is high variability of anesthesia providers being able to consistently quantify the return to baseline after reversal of the neuromuscular blockade.

In addition to intraoperative monitoring to assure patient akinesis, neuromuscular blockade monitoring is used at the end of the surgical procedure to assess both the suitability of the patient for reversal of muscle relaxation utilizing reversal agents such as neostigmine or sugammadex. Once a reversal agent has been given, a few minutes later the stimulation is repeated to assess the degree to which reversal has been successful.

Monitoring the Depth of Anesthesia

While monitoring muscle relaxation is fairly straightforward using "twitch" monitors, measuring the *degree of unconsciousness* during general anesthesia is not. Some clinical techniques that anesthesiologists use to help gauge the depth of anesthesia include noting patient movements, response to various stimuli, measuring the end-tidal anesthetic gas concentration, and following the blood pressure and heart rate trends. In addition to these classical methods, several electronic indices of brain function are available. Among these are the Bispectral Index, EEG Entropy, Patient State Index, and others. Among these, the Bispectral Index (BIS) (Fig. 11.7) is by far the best validated and most commonly used technique to monitor patient unconsciousness.

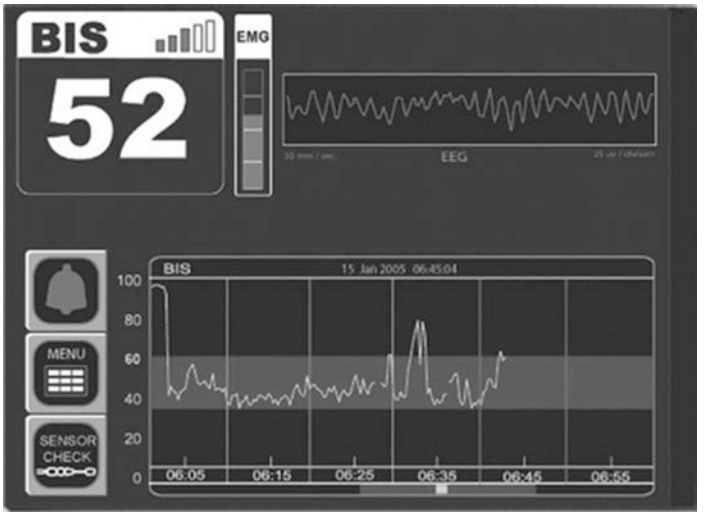


Fig. 11.7 Bispectral index (BIS) monitoring system. *Left*: electrode assembly. *Right*: monitor showing a BIS score of 52 with the raw electroencephalogram shown on the *upper right* and the processed signal shown on the *bottom*

BIS is a processed EEG (electroencephalogram) parameter, a measure of electrical activity in the brain. BIS provides a quantifiable measure of the effects of anesthetic agents on the central nervous system, and can be related to the hypnotic component of the anesthetic state. A dimensionless number is used, ranging from 0 to 100, with 0 being complete brain electrical silence and 100 representing a fully awake EEG. A BIS index between 40 and 60 is usually regarded as corresponding to adequate surgical anesthesia. It is important to realize, that the BIS value must be taken into consideration with the other measures of depth of anesthesia as mentioned above, and not as a sole measure.

Temperature Monitoring

Normal core temperature in humans usually varies between 36.5 and 37.5 °C and typically decreases 0.5–1.5 °C following the induction of general anesthesia. Heat loss is due to impairment of

thermoregulatory control by anesthetic agents and vasodilation combined with exposure to the cold operating room environment. When the temperature drop is large, hypothermia may occur. Hypothermia is defined as a core body temperature of less than 35 °C and may be classified as mild (32–35 °C), moderate (28–32 °C), or severe (<28 °C). Although mild hypothermia is sometimes desirable in head-injured patients, under other conditions the adverse effects of hypothermia (e.g., impaired cardiac contractility, impaired cardiac conduction, impaired blood clotting, increased postoperative infection rate) may present undesirable clinical problems. Reductions in core temperature are particularly likely in patients undergoing abdominal or thoracic surgery, and interventions such as forced-air warming or underbody water warmers should be used.

Core temperature can be measured with sensors in the nasopharynx, esophagus, pulmonary artery, tympanic membrane, or even in the rectum or urinary bladder. Skin-surface temperature tends to run much lower than core temperature, but follows core temperature trends fairly well. The ASA standards for patient monitoring require that every patient receiving anesthesia have temperature monitoring "when clinically significant changes in body temperature are intended, anticipated, or suspected."

Finally, a rare but life threatening complication known as malignant hyperthermia (see Appendix B) remains a theoretical risk in all patients undergoing general anesthesia. While a rise in core temperature is not typically the first sign, it occurs due to a hypermetabolic state associated with malignant hyperthermia and may serve as another indicator within the clinical picture. Malignant hyperthermia be treated quickly and decisively when occurring, as it has an extremely high mortality rate otherwise.

Central Venous Pressure (CVP) and Pulse Pressure Variability (PPV) Monitoring

Central venous catheters are commonly placed percutaneously into the right internal jugular vein as well as via a number of other sites that lead to the superior vena cava and right atrium. These catheters are generally inserted for one of three reasons: (1) to

establish large vascular access for cases likely to involve a high degree of blood loss (2) to allow the determination of central venous pressure (right-sided cardiac preload) and (3) to establish definitive intravenous access to ensure the delivery of vasoactive substances. In certain high risk procedures, specialty multi-orifice catheters can also be placed to remove entrapped air from the heart in a case of air embolus. In addition to providing an overall measure of central venous pressure, the pressure waveforms provided by a central venous catheter yield a great deal of information and are shown in Fig. 11.8.

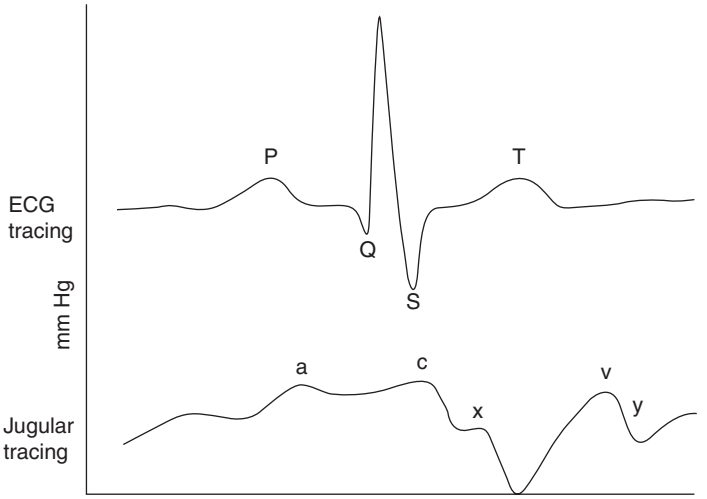


Fig. 11.8 The central venous pressure waveform. +a wave: this wave is due to the increased atrial pressure during right atrial contraction. It correlates with the P wave on an ECG. +c wave: This wave is caused by a slight elevation of the tricuspid valve into the right atrium during early ventricular contraction. It correlates with the end of the QRS segment on an ECG. −x descent: this wave is probably caused by the downward movement of the ventricle during systolic contraction. It occurs before the T wave on an ECG. +v wave: this wave arises from the pressure produced when the blood filling the right atrium comes up against a closed tricuspid valve. It occurs as the T wave is ending on an ECG. −y descent: this wave is produced by the tricuspid valve opening in diastole with blood flowing into the right ventricle. It occurs before the P wave on an ECG. (Used with permission. From Norton et al. [10])

It should be mentioned that absolute CVP measurements have not been as helpful as was originally hoped in identifying which hypotensive patients respond favorably to a fluid bolus.

It is now recognized that in patients on mechanical positive pressure ventilation, the more variable the systolic blood pressure across the respiratory cycle, the more likely the patient is to have a favorable increase in hemodynamics following a fluid bolus. This concept is known as pulse pressure variation (PPV). Another way to interpret this is that stroke volume varies more when hypovolemia is present due to decreased cardiac filling (as a function of mechanically generated intrathoracic pressures from ventilation). This is then reflected as increased variability in the arterial waveform pulse pressure. As you can imagine, changes in preload and volume status can have a profound impact on the filling of the ventricles. In order for clinical decisions to be soundly based, certain criteria must be achieved when utilizing PPV:

1. Mechanical ventilation on a paralyzed patient with an endotracheal tube
2. Absence of cardiac arrhythmias
3. Tidal volumes of at least 8 cc/kg
4. Absence of significant alterations to the chest wall (e.g., open chest)

If the above criteria are met and PPV is elevated, a fluid bolus and challenge are frequently administered while monitoring for adequacy of the response. By utilizing objective measures of volume status, patient specific goal directed fluid therapy is possible.

Pulmonary Artery Pressure Monitoring

Pulmonary artery catheters (see Fig. 11.9) are passed into the pulmonary artery via the right atrium, right ventricle and pulmonary valve. Often called a **"Swan-Ganz" or "Swan" catheter** after the device's inventors, it is equipped with an inflatable balloon at the tip which "floats" along with the catheter as it ultimately "wedges" into position in a small pulmonary vessel. The device has at least

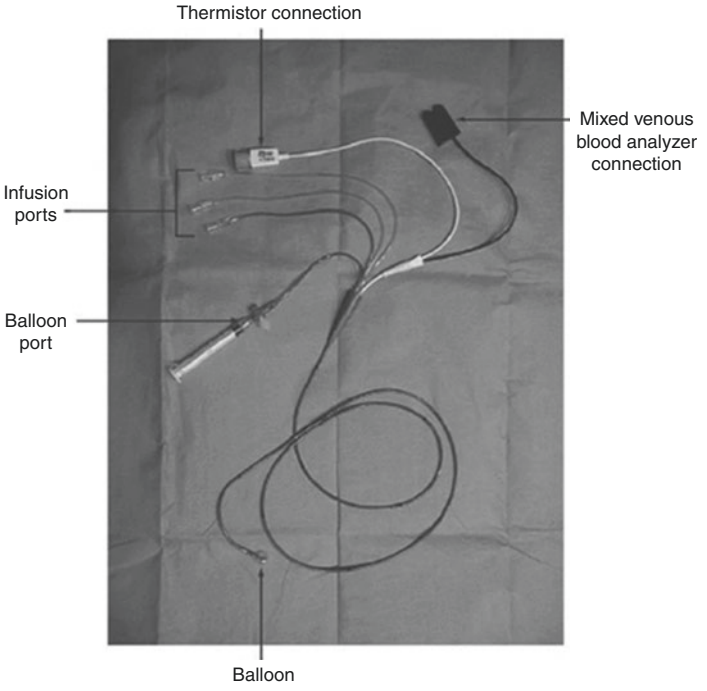


Fig. 11.9 A typical pulmonary artery catheter

two lumens: one for CVP measurements and one for PA pressure measurements. In addition, while all have a means to measure cardiac output via thermodilution, some can also be used for cardiac pacing, for mixed venous oximetry or for other specialized purposes. Table 11.3 shows the data typically obtainable using a PA catheter. Table 11.4 shows hemodynamic profiles of common clinical diagnoses depending mainly on data obtained from the PA catheter.

CO is the cardiac output, the blood ejected per minute from the heart. BSA is the body surface area, typically around 2 m^2 for adults. CI is the cardiac index. Systemic vascular resistance (SVR) is the vascular resistance (afterload) that the left ventricle works against. Pulmonary vascular resistance (PVR) is the resistance

Table 11.3 Data typically obtained using a PA catheter

	Formula	Typical values
CO	SV × HR	4–8 l/min
CI	CO/BSA	2–5 l/min/m^2
SV	[CO/HR] × 1000	60–90 ml/beat
SI	CI/HR	40–60 ml/beat/m^2
LVSW	[MAP−PCWP] × SV × 0.0136	60–80 g m/beat
RVSW	[MPAP−CVP] × SV × 0.0136	10–15 g m/beat
SVR	[[MAP−CVP]/CO] × 80	800–1500 dyn s/cm^5
PVR	[[MPAP−PCWP]/CO] × 80	100–250 dyn s/cm^5

Table 11.4 The utility of hemodynamic parameters derived from the systemic blood pressure, and the pulmonary artery catheter in making clinical diagnoses

Diagnosis	Blood pressure	CVP	CO	CI	PCWP	Pulmonary artery diastolic pressure	SVR
Hypovolemia	⇓	⇓	⇓	⇓	⇓	⇓	⇑
Cardiogenic shock	⇓	⇑	⇓	⇓	⇑	⇑	⇑
Septic shock	⇓	⇓	⇓ ⇒ ⇑	⇓	⇓	⇓	⇓
Neurogenic shock	⇓	⇓	⇓	⇓	⇓	⇓	⇓
Tamponade	⇓	⇑	⇓	⇓	⇑	⇑	⇑

ß Low; *Ý* High, *Þ* No change
CVP central venous pressure, *CO* cardiac output, *CI* cardiac index, *PCWP* pulmonary capillary wedge pressure, *SVR* systemic vascular resistance

that the right ventricle works against. Left ventricular stroke work (LVSW) is the amount of work that the left ventricle does with each beat, and is a rough indicator of left ventricular contractility. Right ventricular stroke work (RVSW) is the amount of work that the right ventricle does with each beat. Stroke volume (SV) is the amount of blood ejected with each heart beat.

Other Special Patient Monitors

In addition to the patient monitors discussed above, special clinical situations often require specialized monitors. Examples include spinal cord function monitoring during spinal surgery (both sensory and motor evoked potential types), specialized coagulation monitoring during cardiac surgery, liver transplant surgery, or major resuscitations (traumas) involving the administration of blood products (e.g., via thromboelastography), transesophageal echocardiography (TEE) / transthoracic echocardiography (TTE) to assess heart function, and so on. In recent years TEE has become increasingly popular as a means to sort out hemodynamic concerns, as it can provide real-time information about ventricular filling, cardiac contractility, valvular function, volume status and more.

Other Anesthesia Equipment

While a good deal of anesthesia equipment is related to patient monitoring, some is used for other purposes. This includes the anesthesia machine (discussed in Chap. 10), equipment for airway management (discussed in Chap. 9), and equipment used to warm patients (e.g., forced air warmers and fluid warmers).

Standards for Basic Anesthetic Monitoring

Committee of Origin: Standards and Practice Parameters

(Standards for Basic Anesthetic Monitoring, approved by the ASA House of Delegates on October 21, 1986, and last amended on October 28, 2015, is reprinted with permission of the American Society of Anesthesiologists, 520N. Northwest Highway, Park Ridge, IL 60068–2573).

These standards apply to all anesthesia care although, in emergency circumstances, appropriate life support measures take pre-

cedence. These standards may be exceeded at any time based on the judgment of the responsible anesthesiologist. They are intended to encourage quality patient care, but observing them cannot guarantee any specific patient outcome. They are subject to revision from time to time, as warranted by the evolution of technology and practice. They apply to all general anesthetics, regional anesthetics and monitored anesthesia care. This set of standards addresses only the issue of basic anesthetic monitoring, which is one component of anesthesia care. In certain rare or unusual circumstances, (1) some of these methods of monitoring may be clinically impractical, and (2) appropriate use of the described monitoring methods may fail to detect untoward clinical developments. Brief interruptions of continual† monitoring may be unavoidable. These standards are not intended for application to the care of the obstetrical patient in labor or in the conduct of pain management.

Standard I

Qualified anesthesia personnel shall be present in the room throughout the conduct of all general anesthetics, regional anesthetics and monitored anesthesia care.

Objective

Because of the rapid changes in patient status during anesthesia, qualified anesthesia personnel shall be continuously present to monitor the patient and provide anesthesia care. In the event there is a direct known hazard, e.g., radiation, to the anesthesia personnel which might require intermittent remote observation of the patient, some provision for monitoring the patient must be made. In the event that an emergency requires the temporary absence of the person primarily responsible for the anesthetic, the best judgment of the anesthesiologist will be exercised in comparing the emergency with the anesthetized patient's condition and in the selection of the person left responsible for the anesthetic during the temporary absence.

Standard II

During all anesthetics, the patient's oxygenation, ventilation, circulation and temperature shall be continually evaluated.

Oxygenation

Objective

To ensure adequate oxygen concentration in the inspired gas and the blood during all anesthetics.

Methods

1. Inspired gas: During every administration of general anesthesia using an anesthesia machine, the concentration of oxygen in the patient breathing system shall be measured by an oxygen analyzer with a low oxygen concentration limit alarm in use.*
2. Blood oxygenation: During all anesthetics, a quantitative method of assessing oxygenation such as pulse oximetry shall be employed.* When the pulse oximeter is utilized, the variable pitch pulse tone and the low threshold alarm shall be audible to the anesthesiologist or the anesthesia care team personnel.* Adequate illumination and exposure of the patient are necessary to assess color.*

Ventilation

Objective

To ensure adequate ventilation of the patient during all anesthetics.

Methods

1. Every patient receiving general anesthesia shall have the adequacy of ventilation continually evaluated. Qualitative clinical signs, such as chest excursion, observation of the reservoir breathing bag, and auscultation of breath sounds, are useful.

Continual monitoring for the presence of expired carbon dioxide shall be performed unless invalidated by the nature of the patient, procedure, or equipment. Quantitative monitoring of the volume of expired gas is strongly encouraged.*

2. When an endotracheal tube or laryngeal mask is inserted, its correct positioning must be verified by clinical assessment and by identification of carbon dioxide in the expired gas. Continual end-tidal carbon dioxide analysis, in use from the time of endotracheal tube/laryngeal mask placement, until extubation/removal or initiating transfer to a postoperative care location, shall be performed using a quantitative method such as capnography, capnometry or mass spectroscopy.* When capnography or capnometry is utilized, the end tidal CO_2 alarm shall be audible to the anesthesiologist or the anesthesia care team personnel.*
3. When ventilation is controlled by a mechanical ventilator, there shall be in continuous use a device that is capable of detecting disconnection of components of the breathing system. The device must give an audible signal when its alarm threshold is exceeded.
4. During regional anesthesia (with no sedation) and monitored anesthesia care (with no sedation), the adequacy of ventilation shall be evaluated by continual observation of qualitative clinical signs. During moderate or deep sedation the adequacy of ventilation shall be evaluated by continual observation of qualitative clinical signs and monitoring for the presence of exhaled carbon dioxide unless precluded or invalidated by the nature of the patient, procedure, or equipment.

Circulation

Objective

To ensure the adequacy of the patient's circulatory function during all anesthetics.

Methods

1. Every patient receiving anesthesia shall have the electrocardiogram continuously displayed from the beginning of anesthesia until preparing to leave the anesthetizing location.*
2. Every patient receiving anesthesia shall have arterial blood pressure and heart rate determined and evaluated at least every 5 min.*
3. Every patient receiving general anesthesia shall have, in addition to the above, circulatory function continually evaluated by at least one of the following: palpation of a pulse, auscultation of heart sounds, monitoring of a tracing of intra-arterial pressure, ultrasound peripheral pulse monitoring, or pulse plethysmography or oximetry.

Body Temperature

Objective

To aid in the maintenance of appropriate body temperature during all anesthetics.

Methods

Every patient receiving anesthesia shall have temperature monitored when clinically significant changes in body temperature are intended, anticipated, or suspected.

* Under extenuating circumstances, the responsible anesthesiologist may waive the requirements marked with an asterisk (*); it is recommended that when this is done, it should be so stated (including the reasons) in a note in the patient's medical record.

† Note that "continual" is defined as "repeated regularly and frequently in steady rapid succession," whereas "continuous" means "prolonged without any interruption at any time."

Case Study

[Editor's note: this case is primarily about monitoring, though figuring out the entire scenario will require your knowledge from other chapters].

You are providing anesthesia for a healthy young woman having a laparoscopic tubal ligation, your last case of a busy day of short gynecology cases. You induced anesthesia with propofol and succinylcholine and artfully intubated the woman's trachea. You have maintained anesthesia with sevoflurane and fentanyl. The case is now over and you are preparing to wake the patient up. You have discontinued sevoflurane, increased oxygen flows, and have expected to see the patient open her eyes by now. She remains apneic (ventilator dependent, no spontaneous respirations), unresponsive to verbal stimuli, and does not react when you suction her mouth. Your attending asks why we are not already on our way to the PACU.

How do you know she is apneic? Which monitors can verify this for you?

Several monitors and physical examination techniques are helpful in assessing ventilation. First, do not forget good old-fashioned auscultation! A stethoscope, placed either over the lung fields externally, or with a weighted bell precordially, or in the esophagus, can detect breath sounds, among other things. Second, you can turn off the ventilator, turn the selector to the reservoir bag, and observe the bag for motion. Third, you can check the capnogram during this same time, watching for exhaled carbon dioxide indicative of spontaneous respiration. Fourth, you can check the expired tidal volume monitor. Finally, the airway pressure monitor can detect changes in the circuit pressure indicative of respiratory movements. If all of these demonstrate no flow, you can be certain that the patient is apneic. You should still observe the chest to make certain that the patient is not making respiratory efforts against an obstructed airway!

You conclude that the patient is indeed apneic. Two minutes into your examination, the pulse oximeter shows the saturation to be 99%. How is this possible? Do you suspect a malfunction?

The pulse oximeter is ***not a ventilation monitor***! Desaturation during apnea takes some time, particularly if the patient has been breathing 100% oxygen for some time. In fact, this is exactly the principle behind "preoxygenation" or "denitrogenation" prior to induction of anesthesia. A well-oxygenated patient will remain saturated for 4 or more minutes in the absence of cardiopulmonary disease or other physiologic abnormalities affecting oxygen consumption or functional residual capacity (pregnancy, obesity). It is likely that the monitor is not malfunctioning. You can verify that it is picking up an arterial pulse signal (waveform) by inspecting the display and comparing the pulse rate to the ECG rate.

How can you tell if you have allowed enough time for the anesthetics to be eliminated?

You can check the end-tidal agent monitor. Most modern operating rooms have such a monitor, most commonly one based on infrared absorption of light by inhaled anesthetics. If the concentration of expired sevoflurane has decreased to 0.1–0.3 MAC (the "MAC awake," about 0.2–0.5% for sevoflurane), it is likely that you have washed most of this anesthetic out. It is more difficult to assess the presence or absence of fentanyl. In spontaneously breathing patients, you can assess opioid effect by measuring respiratory rate, which will be slow in a "narcotized" patient. You can inspect the pupils, who will generally be pinpoint in a patient with substantial opioid concentrations, but this sign can be unreliable in the presence of inhaled agents.

Although you believe that enough time has indeed elapsed, you would like to confirm whether or not she is "asleep." What other monitors can help you?

First, do not forget to use your own eyes! ***Look at the patient*** for signs of arousal: grimacing, tearing, patient movement, rapid-shallow breathing. Next, you can interpret basic hemodynamic data in comparison to the patient's preoperative and intraoperative vital signs. A deeply anesthetized patient should have blood pressure and heart rate similar to the period during the operation at times of light or no surgical stimulation. A "light" patient will often show increasing heart rate and blood pressure, signs of sympathetic activation. Of course, patients taking beta blockers or who have received heavy doses of opioids may not demonstrate these signs. Finally, you can use a consciousness monitor analyzing the processed EEG, such as the bispectral index (BIS), to measure the degree of brain sedation.

On the basis of these investigations, you are convinced that the patient's anesthetics have been eliminated, and that she is not anesthetized. What else might explain her failure to awaken? What monitor could help you verify the diagnosis?

The remaining drug class that you have not explored is the neuromuscular blocking agents. You intubated this patient using succinylcholine and did not use other relaxants. Normally this drug is eliminated by plasma cholinesterase in 5–8 min, but in rare individuals with an atypical or absent enzyme, the effect can be vastly prolonged. In this case, the patient would exhibit signs of a shallow depth of anesthesia (hemodynamic stimulation, tearing, absence of end-tidal anesthetic, brain activity compatible with consciousness on EEG) but not move. You can verify the diagnosis by placing a neuromuscular blockade ("twitch") monitor and demonstrating absence of twitch in response to train-of-four stimulation. Be cautious about using tetanic stimulation, which is painful, in this potentially "awake" but immobile patient. If you find her to be paralyzed but potentially conscious, you should immediately reassure her and explain that she will need to stay intubated until the drug wears off. You should sedate her with a short acting drug, such as propofol, to keep her comfortable until the succinylcholine wears off, which may take several hours.

Suggested Further Reading

1. American Heart Association, Drew BJ et al (2004) Practice standards for electrocardiographic monitoring in hospital settings. Circulation 110:2721–2746
2. Bigatello LM, George E (2002) Hemodynamic monitoring. Minerva Anestesiol 68:219–225
3. Bigatello LM, Schmidt U (2003) Arterial blood pressure monitoring. Minerva Anestesiol 69:201–209
4. Bronzino JD (2000) The biomedical engineering handbook, 2nd edn. Springer, New York
5. Hemmerling TM, Le N (2007) Brief review: neuromuscular monitoring: an update for the clinician. Can J Anaesth 54:58–72
6. Iacobelli L, Lucchini A, Asnaghi E, Nesci M (2002) Oxygen saturation monitoring. Minerva Anestesiol 68:488–491
7. Kneeshaw JD (2006) Transoesophageal echocardiography (TOE) in the operating room. Br J Anaesth 97:77–84
8. McGuire NM (2006) Monitoring in the field. Br J Anaesth 97:46–56
9. Monk TG, Weldon BC (2011) Does depth of anesthesia monitoring improve postoperative outcomes? Curr Opin Anaesthesiol 24:665–669
10. Norton JA et al (2008) Surgery: basic science and clinical evidence. Springer, New York
11. O'Donnell JM, Nácul FE (eds) (2001) Surgical intensive care medicine. Springer, New York
12. Orser BA, Mazer CD, Baker AJ (2008) Awareness during anesthesia. CMAJ 178:185–188
13. Pajewski TN, Arlet V, Phillips LH (2007) Current approach on spinal cord monitoring: the point of view of the neurologist, the anesthesiologist and the spine surgeon. Eur Spine J 16:S115–S129
14. Palanca BJ, Mashour GA, Avidan MS (2009) Processed electroencephalogram in depth of anesthesia monitoring. Curr Opin Anaesthesiol 22:553–559
15. Sanderson PM, Watson MO, Russell WJ (2005) Advanced patient monitoring displays: tools for continuous informing. Anesth Analg 101:161–168
16. Shah A, Shelley KH (2013) Is pulse oximetry an essential tool or just another distraction? The role of the pulse oximeter in modern anesthesia care. J Clin Monit Comput 27:235–242
17. Steiner LA, Andrews PJ (2006) Monitoring the injured brain: ICP and CBF. Br J Anaesth 97:26–38
18. Young D, Griffiths J (2006) Clinical trials of monitoring in anaesthesia, critical care and acute ward care: a review. Br J Anaesth 97:39–45

Part IV

Intraoperative Considerations

Anesthetic Techniques: General, Sedation, MAC

12

Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xxiii are reviewed before reading this chapter.

Key Learning Objectives

- Learn how to prepare for the different phases of an anesthetic
- Understand the continuum of sedation
- Discuss the advantages and disadvantages of different anesthetic techniques

The Anesthesiologist and the Airline Pilot

A common analogy compares the job of an anesthesiologist to that of an airline pilot. This analogy is fitting in that each professional is charged with peoples' lives – failure to perform the job appropriately and consistently can result in death or injury of

J. M. Ehrenfeld (✉)
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: jehrenfeld@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_12

those in their care. This analogy is also fitting because in doing their job, each professional must faithfully perform a set of key steps.

Preflight Check

The preflight check is performed prior to the pilot allowing any passengers onto the plane. This preflight check is analogous to the preanesthetic setup and machine check. Both the pilot and anesthesiologist must ensure that their equipment is ready and in optimal operating conditions – before patients or passengers are allowed to board or enter into the operating room.

Our preflight check starts at the beginning of the day with our initial room setup. In preparing a room, most anesthesiologists will use the mnemonic **M.S.M.A.I.D.S.** (Table 12.1) just as a pilot will use a written checklist to make sure that nothing is missed. The 7 individual components of the mnemonic are outlined in the discussion below.

The first "**M**" stands for the anesthesia **M**achine. In performing a machine check, one should use a written check list in order to ensure that nothing is overlooked. A typical machine check will include:

1. Assure an adequate source of gases is coming from the wall
2. Ensure an alternative source of oxygen (E-cylinder) is attached to the back of the anesthesia machine and that it is full
3. Calibrate the oxygen sensor

Table 12.1 M.S.M.A.I.D.S. mnemonic

M → machine
S → suction
M → monitors
A → airway
I → **I**V
D → drugs
S → special

4. Make sure fail-safe alarms are working
5. Check the level of volatile agent in the machine vaporizers
6. Perform a high pressure test
7. Perform a low pressure test
8. Make sure ventilator bellows are working

Suction is a vital part of any room setup. It is imperative that suction be present and powerful enough to quickly evacuate any secretions in the oropharynx if they are present on induction – as this can improve the anesthesia provider's view of the airway structures and help avoid aspiration of gastric contents. Prior to bringing a patient into the operating room, the anesthesiologist should ensure that there is an adequate source of suction available and that it will reach the patient.

The second "**M"** of the mnemonic reminds an anesthesia provider to prepare the standard American Society of Anesthesiologists recommended monitors as well as to consider if additional or invasive monitoring is necessary. Minimum monitoring requirements (see Chap. 11) include pulse oximetry, blood pressure, ECG, and capnography.

The **A**irway part of the mnemonic is vital to ensure that the necessary airway equipment is present and in good working order. If there is a possibility that the patient may have a difficult airway, emergency airway equipment or a difficult airway cart should be readily available. The minimum airway set up should include a working laryngoscope with at least 2 types and sizes of blades. An endotracheal tube of appropriate size should also be available and the endotracheal cuff should be tested to ensure that it is patent.

The **"I**V" portion of the mnemonic is a cue to consider how much intravenous access will be necessary for a given case. The degree of access required is determined by the expected blood loss and intraoperative fluid requirements. For patients, you may also need fluid warmers, pressure bags, rapid infusers, or even central venous access. Again, ideally these considerations should be made before the case begins.

The anesthesiologist must have an adequate supply of **D**rugs. This includes medications necessary to induce and maintain anesthesia, as well as emergency medications should the patient

require vasoactive, inotropic, or chronotropic support. Typically, succinycholine, atropine, ephedrine, and phenylephrine are drawn up and available in addition to standard induction drugs (propofol, fentanyl).

The final "**S"** of the mnemonic encompasses all other considerations about the case such as padding, positioning, or other **S**pecial equipment.

As a part of this "pre-flight checklist," the anesthesia provider should also carefully consider the preoperative assessment of the patient and administer any preoperative medications that might be appropriate given the patient's comorbidities. Typical preoperative medications might include antibiotics, sedatives for anxiolysis, antiemetics for patients at risk of post-operative nausea, and antacids for patients at high risk of gastric aspiration.

Takeoff

The two most difficult and dangerous times for a pilot come during takeoff and landing – this corresponds to induction and emergence during anesthesia. Both the pilot and the anesthesiologist work hard to ensure a safe and smooth takeoff and landing.

Prior to induction, the anesthesiologist will apply monitors to the patient. After confirming that the patient is appropriate for anesthesia and that all of the monitors are working, the anesthesiologist will preoxygenate the patient by having them inhale 100% oxygen through a sealed mask. The purpose of preoxygenation is to replace the nitrogen that is in the patient's lungs with oxygen – as well as to maximally oxygenate all of the patient's vital organs prior to induction. This essential step is a safety measure, which will help ensure that the patient is best able to tolerate any period of apnea from the time of anesthetic induction to the time when the airway is secured.

After the patient is maximally oxygenated, the anesthesiologist will induce anesthesia in the patient, usually with a combination of sedative hypnotics and analgesic drugs. After medications are given, the anesthesiologist will check for a lid-lash reflex by brushing a finger gently across the eye lashes. If no blink reflex is

elicited, a mask airway will then be established by applying gentle positive pressure to the breathing circuit. **Only after a mask airway has been established** will paralytic agents then be administered to allow further manipulation of the airway. With the airway secured, the patient can then be properly positioned for surgery, prepped, and draped. Prior to surgical incision, a "time-out" or "hard stop" should be performed to verify that the correct procedure is about to be undertaken on the correct patient.

Cruising Altitude

Once a plane has reached altitude, many people think that the pilot can just turn on the auto-pilot and take a nap – but this is simply not true. The pilot and co-pilot must remain vigilant, constantly check the instruments, and communicate with the air traffic controllers to avoid a mishap. Similarly, during the maintenance phase of anesthesia, although on the surface it may appear that nothing is happening, the anesthesiologist must remain as vigilant as ever. The needs of a patient during the maintenance portion of an anesthetic may include fluid resuscitation, adjustment of the anesthetic and analgesic agents, monitoring of the patient's blood pressure, heart rate and temperature, and paying attention to what is going on in the surgical field.

Landing

Landing a plane safely is the goal of every pilot just as a safe wake up and extubation is the goal of every anesthesiologist. Occasionally passengers on a plane will clap after a successful touchdown; similarly, our patients expect us to land them safely and comfortably. Depending on the patient, the anesthesiologist can choose to remove the endotracheal tube while the patient is still deeply asleep (Stage 3) or fully awake (Stage 1). Patients who have their airways manipulated during the intermediate Stage 2 of anesthesia are much more likely to suffer from laryngospasm and agitation than patients in either Stage 1 or Stage 3. There are mul-

Table 12.2 Stages of general anesthesia

Stage 1 – Amnesia	Patients should follow commands; respiration pattern typically regular
Stage 2 – Delirium	Period of uninhibited excitation; patients at risk for laryngospasm; pupils often divergent; respirations often irregular
Stage 3 – Surgical anesthesia	Target depth for anesthesia during surgery; respiration pattern typically regular
Stage 4 – Overdosage	Patients at risk for hypotension and cardiovascular collapse

tiple numerical endpoints that anesthesia providers use to ensure that a patient is ready for extubation. If a patient is going to be extubated awake, he/she should be following commands, able to oxygenate and ventilate without assistance, and able to protect his/her airway. The 4 stages of general anesthesia are outlined in the Table 12.2.

Taxi to the Terminal

The taxi to the terminal and the post flight check list is analogous to the trip from the operating room to the post anesthesia recovery area (PACU). The anesthesia provider should be at the head of the bed continuously evaluating the patient and ready to support the airway if necessary. Once in the PACU, the anesthesiologist will give a report to the PACU nurse and turn the care of the patient over to the PACU staff. Orders should be written to prepare for potential postoperative problems, such as pain, post operative nausea and vomiting, hypoxia, and blood pressure and heart rate perturbations (see Chap. 27, Postoperative Care Unit and Common Postoperative Problems) (Table 12.3).

Table 12.3 Action sequence of a general anesthetic

Air plane analogy	Anesthesia tasks	Important points
Preflight check	Operating room setup Preoperative patient evaluation Preoperative medications	M.S.M.A.I.D.S Assessment of medical history Confirm NPO status Obtain informed consent Obtain I.V. access Administer appropriate preoperative medications and/or anxiolysis
Takeoff	Patient monitoring Induction of anesthesia Airway management	Place and confirm appropriate monitors Position patient and pad pressure points Preoxygenate Administer induction agent Place endotracheal tube or other advanced airway device
Cruising altitude	Maintenance of anesthesia Maintenance of homeostasis	Protect patient eyes Monitor vital signs and maintain appropriate blood pressure Ensure amnesia and anesthesia Monitor blood loss and administer appropriate fluids
Landing	Antagonism of neuromuscular blockade Emergence/ extubation	"Reversal" of neuromuscular blockade Turn off anesthetic agents Ensure patient is awake, following commands, protecting airway and can ventilate and oxygenate adequately prior to extubation Confirm stable vital signs
Taxi to the terminal	Safe transfer to PACU PACU orders and discharge	Monitor airway Maintain oxygenation Confirm stable vital signs Write appropriate order to treat pain, nausea, vomiting and hyper or hypotension Give report to PACU staff

Anesthetic Techniques

Having outlined the basic sequence of a general anesthetic (Table 12.3), we will now turn to the different types of anesthetic techniques available to take a patient safely through surgery (also see Chap. 13, Regional Anesthesia). Keep in mind that there is no absolutely correct technique for any given procedure. The type of anesthesia administered will depend on the anesthesia provider, surgeon, and patient's preferences and may be dictated by the type of surgery and/or patient co-morbidities. Some surgeries are minimally invasive and cause the patients little pain or psychological discomfort. In such cases, a surgeon may request to have an anesthesia provider present to monitor the patient and administer sedation while the procedure is being performed. This is called Monitored Anesthetic Care (MAC).

Monitored Anesthesia Care (MAC)/Anesthesia Sedation

Monitored Anesthesia Care or MAC is not a technique of anesthesia but rather a descriptive term for an anesthetic service in which an anesthesiologist is requested to be present at a surgical or diagnostic procedure to monitor the patient and administer medications for anxiolysis, analgesia, or sedation. It may or may not involve sedation of the patient. It is appropriate here to discuss the continuum of depth of sedation from minimal sedation to general anesthesia, as outlined in Table 12.4. The main point here is that **the depth of sedation is a continuum**, and sometimes it is difficult to categorize exactly what type of anesthesia the patient is getting. During the course of the procedure, the patient can easily slip from one type to the other.

All anesthetic techniques fall on a continuum and many are combined. On one side of the continuum is "sedation" (which progresses from minimal to deep) that is delivered during a typical MAC case. On the other end is "general anesthesia" during which patients are completely unarousable and are often, but not always, intubated.

Table 12.4 ASA continuum of depth of sedation

	Minimal sedation (anxiolysis and analgesia)	Moderate sedation or "Conscious Sedation"	Deep sedation	General anesthesia
Responsiveness	Normal response to verbal stimulation	Purposeful response to verbal or tactile stimulation	Purposeful response following repeated or painful stimulation	Unarousable even with painful stimulation
Airway	Unaffected	No intervention required	Intervention may be required	Intervention often required
Spontaneous ventilation	Unaffected	Adequate	May be inadequate	Frequently inadequate
Cardiovascular function	Unaffected	Usually maintained	Usually maintained	May be impaired

Different anesthetic techniques can be combined and the anesthetic technique can be changed during the case. For example, an anesthesiologist may provide IV sedatives and hypnotics during a MAC case if the patient begins to have discomfort or pain. In addition, the anesthesia provider must always be prepared to convert to a general anesthetic if the patient cannot tolerate sedation alone – or becomes oversedated and requires ventilatory support. Also, some patients can have a regional anesthetic alone, while others may need a regional anesthetic (epidural, regional block) as well as a general anesthetic.

Anesthetic agents used to sedate patients are rapid-acting and can affect different patients in profoundly different ways based on the patient's pharmacogenetics, age, sex, co-morbidities, and home medication regimen. An anesthesiologist must be prepared to rescue a patient who was intended to have minimal sedation, but ends up being deeply sedated. Similarly, the anesthesiologist must be able to convert from sedation to general anesthesia. Drugs commonly used during anesthesia sedation may include

midazolam, propofol (sedation dose: 30–100 μg/kg/min), ketamine, fentanyl, remifentanil, and dexmedetomidine (see Chap. 4, Table 4.7).

Choice of Anesthetic Technique

In choosing an appropriate level of sedation and anesthetic technique, the anesthesiologist evaluates:

1. the type of procedure
2. patient comorbidities/health status
3. the preference of the surgeon
4. the preference of the patient

The primary concerns when considering whether or not a patient can tolerate deep sedation and general anesthesia are the airway and cardiovascular status. For a patient with severely depressed cardiovascular function who is scheduled to undergo a procedure on a distal extremity, it may be wiser to choose an anesthetic technique other than general anesthesia which could further depress their cardiac function. Similarly, an anesthesiologist may choose general anesthesia for a healthy patient who is undergoing a procedure that normally only requires conscious sedation but has a full stomach or severe gastrointestinal reflux, in which case protection from aspiration of gastric contents is important.

The goal of an anesthetic is to allow a patient to tolerate a procedure with the least degree of discomfort and the greatest degree of safety. For minor procedures, this may mean injecting local anesthetic to block the transmission of pain and administering a benzodiazepine for anxiolysis. However, for major procedures that require patients to be completely immobile, their level of consciousness deeply depressed, and their muscles paralyzed, it will usually mean inducing general anesthesia.

General Anesthesia

General anesthesia implies the loss of consciousness and protective airway reflexes. A patient under general anesthesia will not respond purposefully to noxious stimuli. The main goals of general anesthesia are to provide adequate hypnosis, relaxation, amnesia, immobility, and analgesia. General anesthesia can be induced and maintained with either intravenous medications or the inhalation of volatile anesthetics. Table 12.5 depicts the major components of a typical general anesthetic. Table 12.6 lists the common drug classes employed to achieve these components.

Physiology of General Anesthetics

Sedative-hypnotic medications such as propofol, etomidate, barbituates, and benzodiazepines all appear to have similar mechanisms of actions. These medications can be used for light sedation if given slowly and in small doses or can be used to induce general anesthesia if given in large bolus doses. Sedative-hypnotic agents act by binding to and activating $GABA_A$ receptor chloride channels in neuron transmembrane proteins. Activation of these receptors causes an influx of ions, results in cell hyperpolarization, and prevents depolarization. If a neuronal cell cannot depolarize, it is said to be inhibited and cannot send information. This is the neurobiological basis for the effect of these drugs. Sedative-hypnotics can cause sedation, loss of consciousness and amnesia, but in general are not effective at providing analgesia or inhibiting movement.

Table 12.5 Important components of a general anesthetic

Hypnosis	Rendering the patient unconscious
Analgesia	Removal of the sensation of pain
Amnesia	Prevention of memory formation
Paralysis	Prevention of movement
Reflex blunting	Prevention of exaggerated autonomic response

In contrast to sedative-hypnotic medications, **volatile anesthetics** can produce both loss of consciousness and inhibit movement. We still do not have a complete understanding of the mechanism of action of volatile anesthetics (also see Chap. 5, Pharmacology of Inhalational Anesthetics). There is no unified theory to explain how and why all volatile anesthetics work, but it is felt that they must act on the central nervous system as well as at the level of the spinal cord in order to produce amnesia,

Table 12.6 Common drugs used during a basic general anesthetic

Time of administration	Purpose	Example
Preoperative medications	Anxiolysis	Benzodiazepines Midazolam (versed) Diazepam (valium)
	Antacid	Nonparticulate Sodium citrate (Bicitra) Histamine blockers Ranitidine (Zantac)
	Beta blockade	Beta blockers Metoprolol
	Analgesia	Opioids Fentanyl Morphine, hydromorphone
Induction	Induction of anesthesia	GABA receptor agonists Propofol (Diprivan) Etomidate (Amidate) Thiopental (pentothal) NMDA receptor antagonists Ketamine
	Neuromuscular blockade	Neuromuscular blockers Succinylcholine Vecuronium, cisatracurium Rocuronium, pancuronium

Table 12.6 (continued)

Time of administration	Purpose	Example
Maintenance of anesthesia	Volatile anesthetics	Volatile anesthetics Sevoflurane Desflurane Isoflurane Nitrous oxide
	Intravenous anesthetics	IV anesthetics Propofol Ketamine
	Antihypotensives	Sympathomimetics Ephedrine Phenylephrine
	Analgesics	Opioids Morphine, hydromorphone Fentanyl, remifentanil Sufentanil, alfentanil Other Ketamine
Emergence	"Reversal" of neuromuscular blockade	Acetylcholineseterase inhibitors Neostigmine Edrophonium Anticholinergics Atropine Glycopyrolate Cyclodextrins Sugammadex
Recovery in the PACU	Antiemetics	5HT3 blocker Ondansetron (Zofran) Granesitron (Kytril) Dopamine agonists Metoclopramide (Reglan) Corticosteroids Decadron Histamine blockers Promethazine (Phenergan)

sedation, and inhibition of movement to noxious stimuli. Unlike neuromuscular blocking agents which bind to receptors at the neuromuscular endplates to prevent movement, volatile anesthetics are thought to work at the level of the spinal cord to inhibit purposeful and reflexive movement.

A common misconception is that general anesthesia requires a patient to have an endotracheal tube and artificial respiration. Patients that are not at risk for gastroesophageal reflux (GERD) and can maintain adequate oxygenation and ventilation while under anesthesia can be allowed to spontaneously breathe during an anesthetic, even while rendered unconscious by anesthetic drugs. Another common misconception is that general anesthesia is always maintained with a volatile gas anesthetic. General anesthesia can be induced and maintained with a variety of different medications. **Total Intravenous Anesthesia** (TIVA) has become increasingly popular as a general anesthetic technique. TIVA avoids the use of inhalational agents by utilizing i.v. agents to induce and maintain anesthesia. The main advantage of this technique is avoidance of the side effects of the inhalational agents such as nausea and vomiting. Additionally, this technique is an important option for patients who may be susceptible to malignant hyperthermia (see Appendix B) as the inhalational agents are known triggering agents for this condition. Medication infusions commonly used to provide a TIVA anesthetic include propofol, remifentanil, sufentanil, and dexmedetomidine.

Case Study

A 78-year-old ASA III male with a Mallampati class III airway presents for a cerebral angiogram due to a recent episode of severe headache and transient neurological deficit. He has a history of stable coronary artery disease, poorly controlled hypertension, hyperlipidemia, and type II diabetes mellitus. He is a former heavy drinker and smoker but quit both last year. He has no known drug allergies and takes atorvastatin, lisinopril, metoprolol, and roziglitazone (Avandia). You plan monitored anesthesia care (MAC).

The case will be done in theangiographysuite, not the OR, and you plan MAC, not general anesthesia. How will this alter your anesthetic equipment set up?

The short answer is, it won't! In any anesthetizing location, you should have all of your usual tools, drugs, and equipment. Any case planned for monitored anesthesia care could potentially require advanced airway management or conversion to general anesthesia. The remote location of an increasing fraction of anesthesia cases poses a challenge and requires flexibility, since the geometry of the radiology, endoscopy, and cardiac catheterization laboratory suites will differ from the operating room. But the basic elements should always be present.

What drugs will you select for the case?

Midazolam and fentanyl are often used for light sedation, but they can produce respiratory depression and may have a greater effect in the elderly or those with cardiopulmonary disease. You might consider instead the use of shorter acting drugs with predictably short offset, such as a low-dose propofol infusion (25–75 μg/kg/min) or a dexmedetomidine infusion (0.2–0.5 μg/kg/h).

After imaging the patient, the radiologist discovers an aneurism and small intracerebral hemorrhage and wishes to coil embolize it to prevent further bleeding. She requests that you alter conditions to completely immobilize the patient for the procedure. What are your options?

You could deepen the sedation but given his comorbidities and age you might prefer to induce general anesthesia instead. This also lets you use neuromuscular blocking drugs to provide immobility without the fear that oversedation would lead to apnea. Moreover, in some neuroradiology procedures, immobility also includes periods of deliberate apnea, so in this case, general anesthesia with a controlled airway is the only option.

Suppose you select general anesthesia. How will you induce and maintain anesthesia? Do you need to intubate the patient and control ventilation?

This case does not involve much surgical stimulation. In fact, the case will not be any more painful than it has already been. Therefore, you do not need a particularly deep anesthetic plane. You may wish, therefore, to use NMB drugs with light general anesthesia, to avoid the use of deep general anesthesia with its attendant cardiovascular depression. This will also allow you to provide the immobility and periods of apnea that may be required. You will also generally choose short acting drugs, to allow for a neurological examination shortly after emergence from anesthesia. A reasonable combination would be propofol for induction, a nondepolarizing neuromuscular blocking drug such as vecuronium, and maintenance with a low dose volatile anesthetic such as sevoflurane. If you had been using propofol or dexmedetomidine for sedation, you could consider continuing these drugs with a TIVA technique, but higher doses will be required to keep the patient comfortable for endotracheal intubation and controlled ventilation, as well as to prevent awareness under anesthesia when paralyzed.

How will you monitor the patient after you induce general anesthesia? Will your plan change, relative to the monitored anesthesia care phase of the case?

You will already have been using ASA standard monitors as you do for any anesthetic. You may consider adding an arterial line, as careful control of blood pressure may be needed in this neurovascular case. You may be asked to raise or lower blood pressure with intravenous agents. Although there will be a femoral arterial sheath in place for access to the cerebral vasculature, the catheters threaded in the sheath may not allow high fidelity recording of pressure, so some radiologists will ask you to have your own arterial catheter. You will be using a light general anesthetic and may be concerned about awareness. However, it may not be possible to use a consciousness monitor like BIS because the electrodes may obscure the cerebral images. You will probably use an end-tidal gas monitor to assess the concen-

tration of inhaled agent in the patient's brain. You will also add a neuromuscular blockade (twitch) monitor, continuous capnography, tidal volume, and airway pressure monitors, and may consider continuous temperature monitoring.

How do your recovery (PACU) plans change with the decision to change to general anesthesia?

They do not change markedly. All patients recovering from anesthesia, be it regional, general, or monitored anesthesia care, require postoperative observation in an area with careful nursing care and availability of cardiovascular monitoring and resuscitation. However, the nature of the anesthetic does influence the intensity of care, the length of stay in recovery, and the particular details to be monitored. You may choose to take the patient to the main PACU rather than the recovery area used for conscious sedation or MAC cases, which may be part of the radiology suite. Since you have administered a general anesthetic with paralysis, you will make this known to the PACU or post-procedure recovery area. Because this is a neurological case, you will assess the patient's neurological exam immediately after emergence. This is often done cooperatively with the radiologist.

Suggested Further Reading

1. Barash PG, Cullen BF, Stoelting RK (2001) Monitored anesthesia care. In: Clinical anesthesia, 4th edn. Philadelphia, PA: Lippincott, Williams, and Wilkins
2. Longnecker DE, Brown DL, Newman MF, Zapol WM (2008) Total intravenous anesthesia. In: Anesthesiology, 1st edn. New York, NY: McGraw Hill
3. Urman RD, Ehrenfeld JM (2009) Anesthesia techniques. In: Pocket anesthesia, 1st edn. Philadelphia, PA: Lippincott, Williams, and Wilkins

Anesthetic Techniques: Regional

13

Ryan J. Traudt and Christina M. Spofford

Introduction

Regional anesthesia includes a variety of anesthetic approaches such as **neuraxial** (epidural and spinal anesthesia), **peripheral**, and **intravenous** techniques. Regional anesthesia plays an important role both inside and outside of the operating room. In addition to its use for surgical anesthesia, it is also gaining widespread use for perioperative pain control, especially as a key contributor to many opioid-sparing pain management regimens. In this chapter, we will review the basic tenets of neuraxial, peripheral, and intravenous regional anesthesia.

Special thanks to Brian C. McLean, Anthony R. Plunkett and Jesse M. Ehrenfeld for their contribtions as authors of the previous chapter edition.

R. J. Traudt
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: rtraudt@mcw.edu

C. M. Spofford (✉)
Department of Anesthesiology, Marshfield Medical Center, Beaver Dam, WI, USA
e-mail: spofford.christina@marshfieldclinic.org

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_13

Neuraxial Anesthesia

Neuraxial Anatomy

The vertebral column extends from the foramen magnum to the sacral hiatus. The spinal cord is contained within this bony framework. There are 24 vertebrae (7 cervical, 12 thoracic, 5 lumbar, and 5 fused vertebrae forming the sacrum). Each vertebrae is identified via palpation of the lateral transverse processes and a posterior spinous process. The spinous process and transverse process are connected via bilateral lamina, while the transverse process is connected to the vertebral body via the pedicles (see Fig. 13.1).

The spinal cord is contained within the spinal canal and covered by three layers called the meninges. The **pia mater** is closely adherent to the spinal cord and is the deepest layer, while the **arachnoid mater** is more closely adherent to the outermost **dura mater**. Cerebral spinal fluid (CSF) is contained within the space between the pia mater and arachnoid mater, called the **subarachnoid space**. This is the site of injection when performing spinal anesthetic. The spinal cord normally extends from the foramen

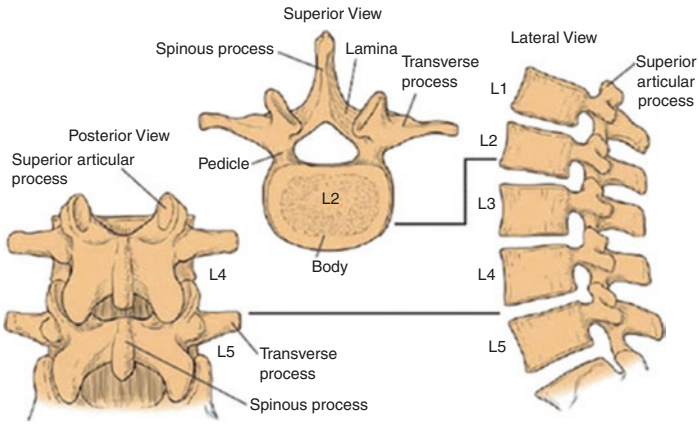


Fig. 13.1 Vertebral anatomy. (Reproduced with permission from Mathias [5])

magnum to the level of L1 in adults and L3 in children, at which point it terminates as the conus medullaris and forms the cauda equina. As a result, performing a spinal (subarachnoid block) or epidural below the level of L3 avoids potential trauma to the spinal cord. An important surface landmark when performing neuraxial anesthesia is the level of the iliac crest, which most commonly corresponds to the level of L4–L5, and additional bony landmarks are illustrated in Fig. 13.2 below.

The spinal cord has a rich vascular supply from a single anterior spinal artery and paired posterior spinal arteries. The anterior spinal artery supplies approximately 2/3 of the spinal cord, while the paired posterior spinal arteries provide the remaining 1/3. There is a prominent feeder artery called the artery of Adamkiewicz or *Radicularis Magna* that provides blood supply to the anterior, lower 2/3 of the spinal cord. Trauma or ischemia of this artery can lead to **anterior spinal artery syndrome**, resulting in bilateral lower extremity paralysis with preservation of proprioception and vibration (as the posterior/dorsal column function is typically preserved).

The spinal nerve roots exit the spinal canal via intervertebral foramen. The nerves arise above their respective vertebrae, but starting at T1, they exit below their vertebrae. As a result, there are eight cervical nerve roots, one more than the number of cervical vertebrae. Each spinal nerve innervates an area of skin referred to as a dermatome (see Fig. 13.3). Keep in mind, these dermatomes

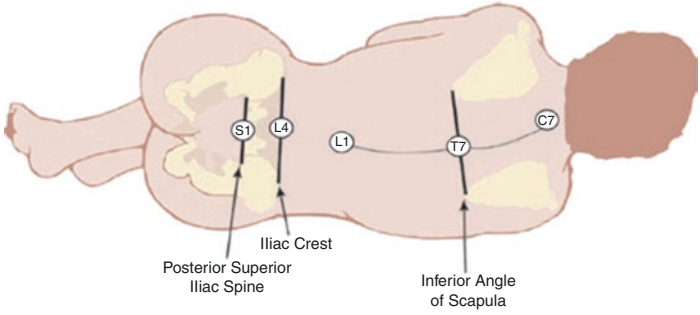


Fig. 13.2 Surface anatomy for neuraxial anesthesia

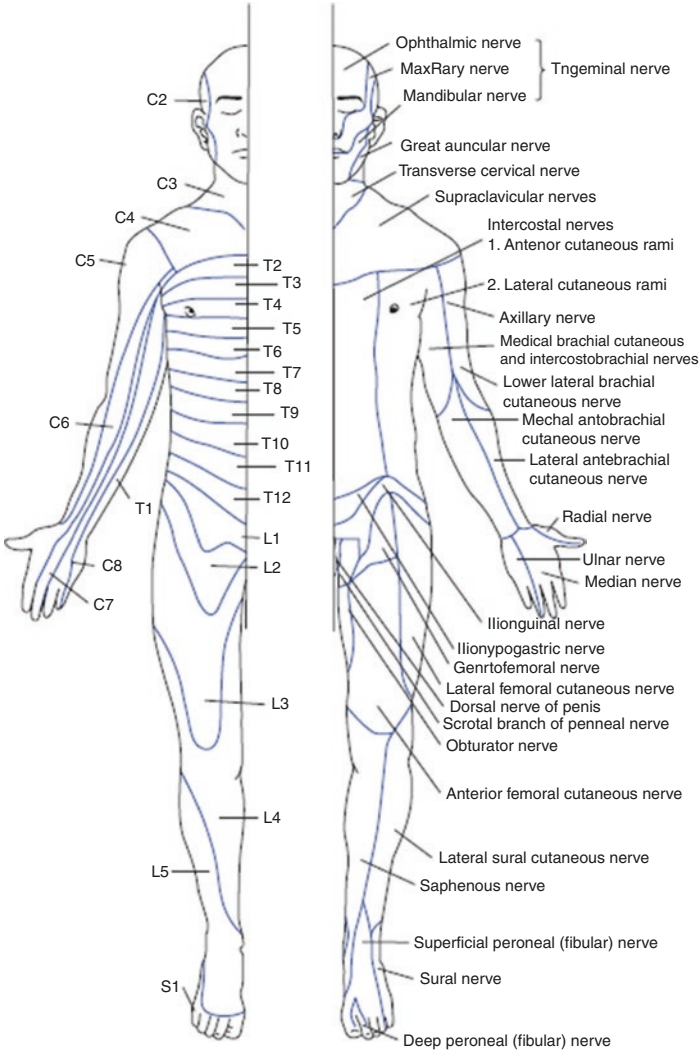


Fig. 13.3 Dermatomes. (Reproduced with permission from Stewart [6])

do not completely match the nerve root innervation of different muscle groups or bones, known as myotomes and osteotomes, respectively.

Indications and Contraindications

As with any anesthetic procedure, the risks and benefits of neuraxial regional anesthesia must be discussed with the patient. Potential risks are shown in Table 13.1.

Spinal anesthesia is primarily indicated for lower abdominal surgery, the perineum, and lower extremities. Epidural anesthesia is primarily indicated for lower abdominal surgery, thoracic surgery, surgery on the lower extremities, and labor. Epidurals can have sacral nerve root "sparing" and may not be optimal for surgery involving this area. Contraindications to neuraxial anesthesia are listed in Table 13.2.

Mechanism of Action

The most common medication given for neuraxial anesthesia is a local anesthetic. Local anesthetic that has been injected directly into the subarachnoid space (spinal) or that bathes the nerve roots and perhaps also diffused into the subarachnoid space from the

Table 13.1 Risks of neuraxial anesthesia

Bleeding
Infection
Nerve injury
Post-dural puncture headache
Urinary retention
Failure of block to provide adequate anesthesia
Hypotension/hemodynamic changes/cardiac arrest
Total spinal
Transient neurological symptoms
Drug toxicity/LAST (Local Anesthetic Systemic Toxicity)

Table 13.2 Contraindications to neuraxial anesthesia

Absolute contraindications	Relative contraindications
Patient refusal	Bacteremia
Infection in the area of needle puncture	Pre-existing neurologic disease (e.g. multiple sclerosis)
Elevated intracranial pressure	Severe spinal deformity
Severe hypovolemia	Stenotic valvular heart disease
Coagulopathy or bleeding diathesis	LV outflow obstruction (hypertrophic obstructive cardiomyopathy/HOCM)

epidural space (epidural) will inhibit synaptic transmission of action potentials. The effect of local anesthetics on nerve fibers varies according to the size of the nerve fiber, myelination and the concentration of the local anesthetic (also see Chap. 6, Pharmacology of Local Anesthetics). Epidural anesthesia has slower onset (10–20 minutes) compared to spinal anesthesia (typically onset within 60 seconds). Differential blockade (the order of effects among the different nerve types) typically results in sympathetic blockade (often accompanied by change in temperature sensitivity), followed by sensory blockade (pain, light touch), and finally motor blockade (paralysis). A well-placed neuraxial anesthetic can provide total anesthesia for a variety of surgical procedures.

There are a number of other medications that can be used for both spinal and epidural anesthesia. Opioids (e.g., morphine, fentanyl, hydromorphone), alpha-2-receptor agonists (e.g., clonidine), and vasoconstrictors (e.g. epinephrine) have all been given with the effect of enhancing the quality or the duration of the block. Epinephrine can prolong the duration of spinal anesthesia by decreasing the rate of absorption of the local anesthetic.

Epidural Anesthesia

Epidural anesthesia allows the delivery of medication either continuously or intermittently into the epidural space for up to several days after the surgical procedure. Sitting is the most common position in which an epidural is performed. Benefits of the sitting position include better identification of the midline and more

flexion of the vertebral column. As the spine is flexed, it helps to open the space between spinous processes, allowing more room for the epidural needle to enter. An epidural may also be performed with the patient in the lateral position. This may increase patient comfort, especially for pregnant patients in active labor. However, the midline may be more difficult to identify, or may be malaligned.

The risks and benefits must be discussed with the patient and informed consent obtained. Standard monitors should be applied including blood pressure, ECG, and pulse oximetry, with end-tidal CO2 and supplemental oxygen if sedation is to be provided.

Technique

A midline or paramedian approach can be used. After infiltration of skin with local anesthetic, the epidural needle is advanced through the skin, subcutaneous tissue, the supraspinous ligament, the interspinous ligament (mostly avoided with paramedian approach, but paraspinal muscles are traversed), and finally into the ligamentum flavum. Identification of the epidural space may be found with a loss of resistance technique or a hanging-drop technique.

With the loss of resistance technique , a syringe containing saline or air or combination of both is attached to the epidural needle. As the needle is slowly advanced, the anesthesiologist places pressure on the syringe. The positive pressure encountered in the supraspinous ligament, interspinous ligament and ligamentum flavum prevents the plunger of the syringe from depressing (see Fig. 13.4). As the needle advances past the ligamentum flavum, a distinct loss of positive pressure is felt, as the plunger gives way and the saline or air or both is injected into the epidural space. A small catheter can then be threaded into the epidural space, usually 3–5 cm past the needle tip. Once the catheter is placed, the catheter is aspirated to ensure no blood or cerebrospinal fluid (CSF) is withdrawn (indicative of an intravascular or intrathecal catheter, respectively), and then a syringe containing a "test dose" of lidocaine with epinephrine 1:200,000 is attached. The test dose, typically 3 mL, is injected through the epidural

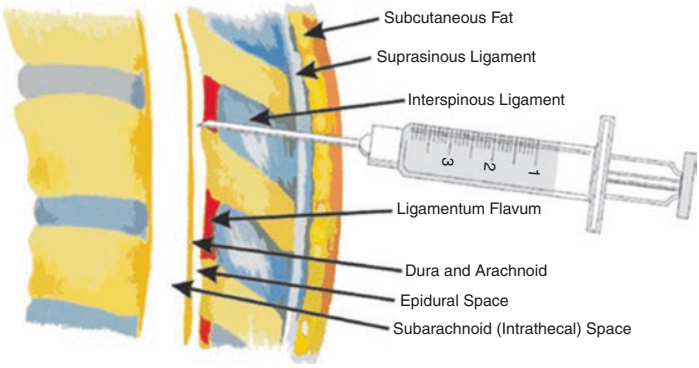


Fig. 13.4 Trajectory of epidural anesthesia. (Image courtesy J. Ehrenfeld, M. D)

catheter. The epinephrine serves as a surrogate marker to ensure the catheter has not threaded into a blood vessel (if positive, one would expect to see an increase in heart rate). The test dose also helps to determine if the catheter is in the subarachnoid space (spinal), which would typically result in rapid onset of sensory or motor changes within 3 min. If negative, the catheter is most likely not in the subarachnoid space.

With the hanging-drop technique, a small drop of saline is placed at the hub of the needle. As the needle passes through the positive pressure structures stated above, the drop of saline will remain at the hub of the needle. Once the needle contacts and passes through the ligamentum flavum, the drop of saline is retracted back into the needle as the negative pressure of the epidural space is encountered. The catheter is then placed, as above.

Pharmacology of Epidural Anesthesia

Similar local anestheticscan be used for both epidural and spinal anesthesia. Chloroprocaine, lidocaine, and mepivacaine are fast onset medications with a short duration of action, while bupivacaine and ropivacaine have a slower onset and longer duration.

Unlike spinal anesthesia, the level of anesthesia in an epidural is not influenced by baricity or position of the patient immediately after injection (see below), but, rather, injectate volume (typically 1–2 ml per segment to be blocked). Concentration of local anesthetic used also affects density of block, and can be chosen based on the epidural indication (eg., surgical anesthetic versus analgesic block). Only preservative-free local anesthetic solutions and medications are used.

The amount of local anesthetic required to produce surgical anesthesia with an epidural is significantly more than with a spinal, as the local anesthetic must traverse more layers to act on the nerve roots. The addition of epinephrine can prolong the effect of local anesthetic by decreasing vascular uptake, allowing more time for the medication to act on the nerve roots. Opioids, such as morphine or fentanyl, can also be added to an epidural. They help to enhance the quality of the epidural as well as provide postoperative pain control.

Spinal Anesthesia

As with general anesthesia, prior to starting a spinal anesthetic, standard patient monitors should be applied (blood pressure, pulse oximeter, and ECG). Supplemental oxygen is often administered, with EtCO2 monitoring. Intravenous access also must be established. In some situations, the patient may be sedated as patient comfort will help in both positioning and anxiolysis while performing the spinal. As with an epidural, a spinal may be placed in either the sitting or lateral position.

The spinal cord typically ends at the level of L1 in adults and L3 in children. Placing the spinal needle below the level of L3 provides an additional margin of safety by decreasing the likelihood of any spinal cord penetration. The iliac crest has been traditionally used as an anatomic landmark corresponding with an L4–L5 interspace (see Fig. 13.2).

Technique

There are two main techniques for performing a spinal anesthetic, midline and paramedian, similar to that of an epidural anesthetic as outlined above. As with epidural anesthetic, the patient is positioned and interspace identified, skin cleaned and prepared with antiseptic solution, local anesthesia is infiltrated in the skin and subcutaneous tissues. With the **midline approach**, the spinal needle is first introduced into the skin between the upper and lower spinous processes at the desired interspace. After passing through the skin, the needle continues to pass through subcutaneous tissue, the supraspinous ligament, the interspinous ligament, the ligamentum flavum, and finally advancing through the epidural space into the subarachnoid space (Fig. 13.4). Often a distinct "pop" is felt by the anesthesiologist as the needle penetrates the ligamentum flavum. Correct identification of the subarachnoid space is confirmed by free flow of CSF out of the hub of the needle.

The **paramedian approach** is used in patients where the midline may be difficult to identify (e.g., scoliosis) or the interspace may be challenging to pass a needle through (e.g., thoracic level for epidural placement, elderly patients with calcified ligaments or loss of disc space). Needle insertion is typically 1 cm from the midline. After the transverse process is contacted, and the needle is redirected cephalad and medial to pass through the interlaminar space. One of the main differences between the paramedian and midline approach is that the ligamentum flavum is the first resistance encountered with the paramedian approach. Again, correct identification of the subarachnoid space is confirmed by free flow of CSF out of the hub of the needle.

Assuming there is no blood exiting the needle and the patient has not experienced a paresthesia, administration of the local anesthetic can proceed, and the specific local anesthetic is chosen based upon characteristics which affect onset, duration, and potential for toxicity (see Chap. 6, Pharmacology of Local Anesthetics). Before injection of the local anesthetic, one confirms intrathecal position via aspiration of a small amount of CSF,

visualized as a CSF "swirl" when mixing with the local anesthetic in the syringe. The local anesthetic is injected slowly over 3–5 seconds. CSF can be aspirated in the middle and at the end of the injection as well to confirm the needle has not moved from the spinal space while injecting.

Factors Effecting Level and Duration of Local Anesthesia

Two of the most important factors determining the distribution of local anesthetic in the subarachnoid space are the **baricity** of the solution (density compared to CSF) and the **position** of the patient immediately after injection of the solution. Addition of a vasoconstrictor (e.g., epinephrine) and the type of local anesthetic selected may influence the onset and duration of the spinal block.

Hyperbaric solutions usually contain glucose/dextrose. They allow for a more controlled spread of the local anesthetic. If a higher dermatomal level is needed, the patient may be placed in a head-down (Trendelenburg) position, allowing the hyperbaric solution to migrate cephalad. Likewise, if the surgery requires dense lumbosacral anesthesia (such as for a perineal procedure), the patient may be left in a sitting position for several minutes after completion of the spinal (commonly referred to as a "saddle block"). Hyperbaric solutions can also be administered in a lateral position, which results in a unilateral block of the dependent side.

Hypobaric solutions are used less commonly in clinical practice. A patient undergoing hip arthroplasty may benefit from having the hypobaric solution "float up" to the operative side. Hypobaric solutions can be made by mixing the local anesthetic with sterile water, or normal saline.

Isobaric solutions tend to have limited spread within the subarachnoid space and are thought to produce a more profound motor block and longer duration of action. Isobaric solutions can be prepared by mixing the local anesthetic with normal saline or the patient's CSF.

Addition of epinephrine (0.1–0.2 mg) or phenylephrine (2–5 mg) to the local anesthetic solution increases the duration of the spinal block. The resultant decrease in spinal cord blood flow and uptake of the local anesthetic prolongs the exposure to the nerve roots of the local anesthetic.

Caudal Anesthesia

This type of regional anesthetic is most commonly performed in pediatric patients. After induction of general anesthesia the child is placed in the lateral position. The sacral cornu are identified as well as the sacral hiatus. The skin is prepared in sterile fashion. A needle is introduced perpendicular to the skin through the sacrococcygeal ligament (beneath the sacral hiatus), advanced slightly, then the angle is dropped and the needle is advanced slightly further into the epidural caudal canal. Confirmation of proper needle position can be obtained by rapidly injecting 3–5 mL of air or saline while the anesthesiologist's fingers are palpating the skin directly over the needle. Skin swelling or crepitus indicates the needle has not penetrated the epidural space. Once proper position is confirmed, a syringe is connected to the end of the needle and aspirated to ensure no blood or CSF is obtained. Local anesthetic is then injected in slow 3–5 mL aliquots. Dosing is typically 0.5–1.0 ml/kg of 0.125% or 0.25% bupivacaine or ropivacaine, and may include epinephrine, opioids, or alpha-2-agonists, as discussed previously.

Combined Spinal–Epidural

The last technique for neuraxial anesthesia combines the advantageous qualities of both a spinal (fast, dense onset of anesthesia) and an epidural (placement of a catheter for continuous medication infusion). A special combined spinal–epidural kit is often used that contains an epidural needle with a small hole at the tip to allow passage of a spinal needle. An epidural technique is performed. Once the needle has reached the epidural space, the spi-

nal needle is then introduced through the epidural needle until it pierces the dura, allowing free flow of CSF back through the needle. Local anesthetic is injected into the spinal space, the spinal needle is withdrawn, and the epidural catheter is then threaded through the epidural needle. Catheter placement should be confirmed with aspiration and a test dose, as above. While this technique combines advantages of both spinal and epidural anesthesia, it also exposes a patient to the risks of both. Combined spinal–epidural anesthesia is often used in obstetrics.

Complications and Side Effects: Spinal and Epidural Anesthesia

Cauda Equina Syndrome (CES)

There have been some reports of permanent neurologic injury when using lidocaine for spinal anesthesia. This was first associated with high doses of medication being administered through a continuous spinal catheter, but has also been reported with single-dose injections. It is reported more commonly with higher-concentration local anesthetic injection. The patient develops bowel and bladder dysfunction as well as lower extremity paralysis.

Transient Neurologic Syndrome (TNS)

TNS (or transient radicular irritation) results in pain in the back, buttocks, and lower extremities without motor or sensory deficit, occurring after resolution of spinal anesthesia and resolving within several days. Most reported cases involved high dose lidocaine, but has also been reported with other local anesthetics and has even been reported with epidural anesthesia. The incidence is increased when patients are placed in the lithotomy position and when large doses of local anesthetic are used.

Cardiovascular Changes

As a result of sympathetic nervous system blockade, spinal anesthesia and epidural anesthesia can cause hypotension. Treatment centers around volume replacement to restore adequate venous return and cardiac output. The anesthesiologist may also need to administer vasoconstrictor medications (e.g., ephedrine, phenylephrine) to raise blood pressure.

As the level of blockade rises, there is an increased risk of bradycardia. The **cardioaccelerator fibers** originate at the T1–T4 level and may be blocked by neuraxial anesthesia approaching this level. Again, treatment centers around volume replacement to restore preload, but may also require atropine or ephedrine. There is a risk of cardiac arrest following spinal anesthetic, and this is usually preceeded by bradycardia and/or hypotension, thus these symptoms should be promptly treated.

Post-dural Puncture Headache (PDPH)

When the dura mater is violated (as with spinal anesthesia and unintentionally during epidural anesthesia), CSF is allowed to leak through the dural defect faster than it is being produced. This causes traction on the structures supporting the brain, including the meninges, dura, and tentorium, and may result in a headache. Dural puncture with a larger needle (smaller gauge number) leads to higher rates of PDPH, as the result of a larger defect resulting in greater rate of CSF flow. The pathognomonic feature of PDPH is a headache that worsens with sitting or standing and is relieved by lying flat (postural component). Patients may also experience nausea, vomiting, and vision changes. Children and elderly patients have the lowest risk of PDPH, while risk increases with needle size, certain needle types (cutting needles greater risk than pencip point), female sex, young age, and pregnancy. Conservative treatment focuses on bed rest, fluid replacement, caffeine, analgesics, and recumbent positioning. Additional treatment includes sphenopalatine ganglion block, occipital nerve block, and epi-

dural blood patch. Epidural blood patch involves injection of approximately 20 mL of the patient's blood into the epidural space at the same level or one interspace below the level of dural puncture, resulting in near immediate relief.

High/Total Spinal Anesthesia

Total spinal anesthesia refers to excessive sensory and motor anesthesia associated with loss of consciousness, severe hypotension, bradycardia, and loss of respiratory drive. This may occur due to accidental intrathecal injection or overdose of medication. Apnea results from severe sustained hypotension and medullary hypoperfusion, and occasionally through blockade of C3-C5 nerve roots (which contain the phrenic nerve innervation). Treatment focuses on the "ABCs" (Airway, Breathing, Circulation) and tracheal intubation is often necessary until block resolves.

Urinary Retention

Blockade of S2–S4 nerve roots can decrease bladder tone and inhibit the voiding reflex. Most patients that have neuraxial anesthesia require a catheter in the bladder to avoid bladder distention, but this can be avoided with block distribution above the level of sacral nerve roots (such as mid to high thoracic epidural anesthesia for rib fracture analgesia).

Intravascular Injection/LAST (Local Anesthetic Systemic Toxicity)

Since the total dosage of drug administered in a spinal is relatively small, complications resulting from intravascular injection typically occur with epidural anesthesia where volumes are much higher. Local anesthetic may be injected via the needle or a catheter that has been inadvertently threaded into a vessel. Frequent aspiration, administration of a "test dose" (addition of epineph-

rine), and slow, incremental injections of local anesthetic all help to minimize the chance of intravascular injection. Accidental intravascular injection may result in toxic blood levels of local anesthetic. This can result in effects on the central nervous system (unconsciousness, seizure) and cardiovascular system (hypotension, reduced contractility, arrhythmias). Early signs include tinnitus, metallic taste in the mouth, and ear ringing. Mainstay of treatment is cessation of further local anesthetic injection and administration of a 20% lipid emulsion given via bolus followed by infusion.

Spinal/Epidural Hematoma

The incidence of hematoma after an epidural is commonly cited as approximately 1/150,000 and 1/200,000 after a spinal. Most cases occurr in patients that have abnormal coagulation profiles, including thrombocytopenia, platelet dysfunction, or administration of anti-platelet and anti-coagulant medications. The mass effect of the evolving hematoma causes injury via direct pressure and ischemia. Immediate recognition is paramount to avoid permanent neurologic insult. Symptoms usually include sharp back pain with progression to sensory and motor deficit. An MRI and a neurosurgical consult should be obtained as soon as possible. Emergent surgical decompression of the spine is required and can prevent permanent neurologic damage if performed early.

Epidural Abscess

Abscess formation is a potentially devastating complication of an epidural. The average time frame for the development of symptoms is 5–14 days after catheter placement. There is a progression of symptoms that typically result in back pain exacerbated by percussion over the epidural insertion site, followed by the development of radicular pain, then motor or sensory deficit, and finally paraplegia. As with spinal hematoma, an imaging study and a neurosurgical consultation should be obtained as soon as possible.

Peripheral Nerve Blocks

Peripheral nerve blocks (PNB) and peripheral nerve catheters are common. PNBs are effective for postoperative analgesia and can allow earlier, more intense participation in rehabilitation. Furthermore, regional anesthesia can contribute to reductions in the stress response of a patient associated with surgery or acute pain/trauma, potentially decrease systemic analgesic needs (especially opioid analgesics and their associated side effects), general anesthesia requirements, and even serve as primary anesthetic techniques, providing an alternative to general anesthesia in many cases. The placement of a peripheral nerve catheter can also allow the continued administration of local anesthetic, thus allowing for prolonged blockade well beyond the duration that a "single shot" block would allow. Novel medications utilizing liposomal formulations of local anesthetics have been developed with the potential benefit of prolonged single shot block duration. As with neuraxial anesthesia, the patient must be made aware of the risks and benefits of PNB. Patient refusal, infection at the insertion site, lack of patient cooperation, and coagulopathy are relative or absolute contraindications. As with neuraxial anesthesia, regional anesthetic techniques should only be administered where standard monitors, supplemental oxygen, and resuscitative equipment and medications are available, including those required to treat LAST. While there are many types of PNBs, and many more novel techniques that are increasingly described in the literature, we will focus on a few of the most commonly performed for both upper and lower extremity surgery.

Identification of the Target Nerve

There are four major techniques used to identify the desired neural structure: **paresthesias**, **nerve stimulation**, **field block**, and **ultrasound**. Paresthesias are radiating electric shock-like sensations that can occur as a needle contacts or comes very close to a nerve. Due to potential for nerve injury, this is rarely done in current practice. Nerve stimulation (Fig. 13.5) elicits a motor

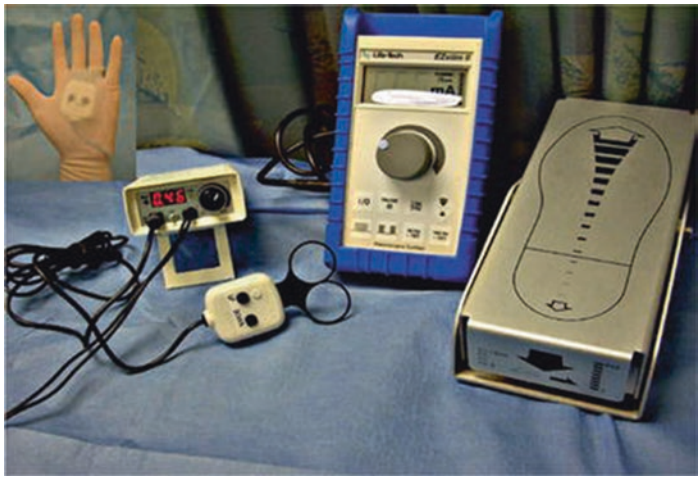


Fig. 13.5 Nerve stimulation setup for peripheral nerve block. (Reproduced with permission from Tsui [7])

response from a peripheral nerve as the stimulating needle approaches closer to the nerve. A motor response maintained at a current of less than 0.4 mA is thought to indicate close enough proximity to the target nerve to produce anesthesia. Motor response at a current of 0.2 mA or less may indicate needle placement directly in the nerve (intraneural) and injection should only proceed following repositioning of the needle to elicit a less sensitive response. Field block involves injection of local anesthetic targeting cutaneous nerves, and is frequently utilized for minor procedures. Finally, ultrasound uses high-frequency sound waves which are reflected back when they encounter different types of tissue. Different tissues have different degrees of echogenicity and thus reflect the sound waves at different speeds. The resulting image provides varying shades that helps distinguish the tissue types. Nerves can be seen as round, oval, or triangular shaped structures and can be hyperechoic (light) or hypoechoic (dark). For example, nerves visualized above the clavicle tend to be hypoechoic, while those below tend to be hyperechoic. Color flow Doppler can be applied to distinguish blood vessels from other

structures. This allows the provider to directly visualize peripheral nerves, adjacent structures, and the needle itself. This allows the provider the ability to both avoid structures that would potentially cause serious harm if punctured (such as lung pleura, peritoneum, and blood vessels), as well as directly visualize spread of local anesthetic to ensure deposition of drug at the desired location for highest rate of block success (and potentially reduce the required volume of administered drug).

Brachial Plexus and Upper Extremity Blocks

The brachial plexus is formed from the anterior rami of cervical nerves C5–C8 and T1 (Figs. 13.6 and 13.7). The brachial plexus runs through the groove formed by the middle and anterior scalene muscles. The plexus initially emerges as the cervical roots, then forms three trunks, six divisions, three cords, and finally the terminal branches that innervate almost all of the upper extremity. A mnemonic sometimes used is "**R**andy **T**ravis **D**rinks **C**old **B**eer" with the first letters of each word standing for **r**oots, **t**runks, **d**ivisions, **c**ords, and terminal **b**ranches.

Interscalene Block

Interscalene block is performed for procedures involving the shoulder and upper arm, as it primarily targets roots C5–7. The block is performed under nerve stimulation by identifying the interscalene groove. To do so, a line is drawn laterally from the cricoid cartilage (the level of the transverse process of C6). The interscalene groove (between the anterior and middle scalene muscle) is palpated (see Fig. 13.8). The brachial plexus is superficial at this level and a nerve block needle is typically inserted only 1–2 cm. Optimal motor response should involve deltoid or biceps, with diaphragm or trapezius response indicationg a position too anterior or posterior, respectively.

Ultrasound guided interscalene block (Fig. 13.9) involves identification of the brachial plexus between the scalene muscles

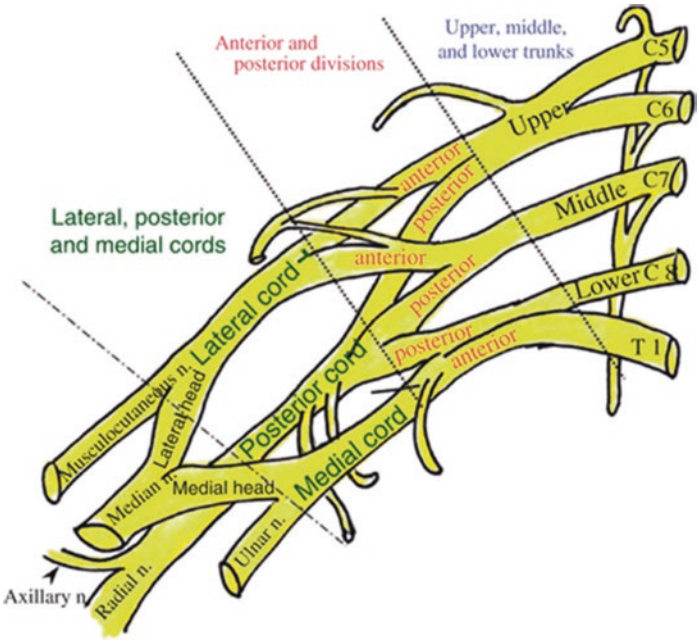


Fig. 13.6 Brachial plexus anatomy. (Reproduced with permission from Tsui [7])

at the level of approximately C6, visualized as a "stop-light sign" as shown in the image above, with the "lights" comprised of three to five hypoechoic circles that are the target roots of the brachial plexus.

An interscalene PNB will often miss the inferior trunk (C8 and T1) and is thus not appropriate for lower arm and hand surgery. Hemidiaphragmatic paralysis via blockade of the ipsilateral phrenic nerve is a side effect in nearly 100% of patients. In a patient with normal respiratory function, this hemidiaphragmatic paralysis is not a concern. Blockade of sympathetic nerves can also produce an ipsilateral Horner's syndrome (ptosis, anhidrosis, miosis, enophthamos, and nasal congestion). Other risks include, vertebral or carotid artery puncture and neuraxial injection.

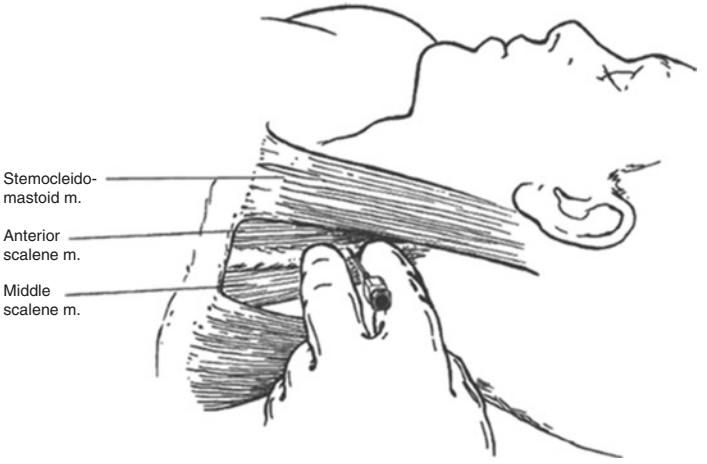


Fig. 13.7 Interscalene nerve block. (Reproduced with permission from Twersky and Philip [8])

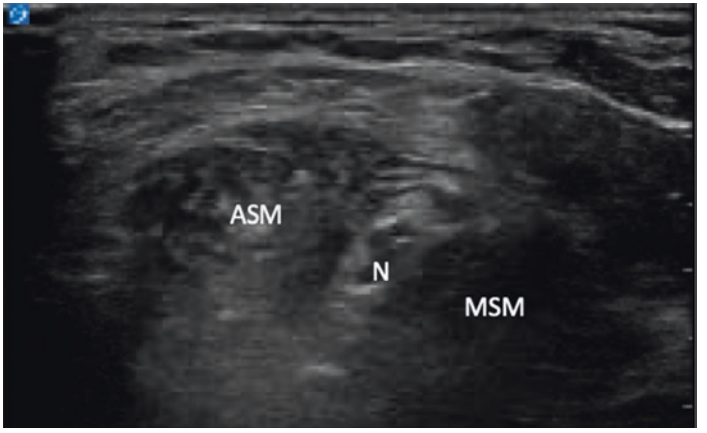


Fig. 13.8 Interscalene block, ultrasound image. ASM anterior scalene muscle, MSM middle scalene muscle, N brachial plexus nerve roots

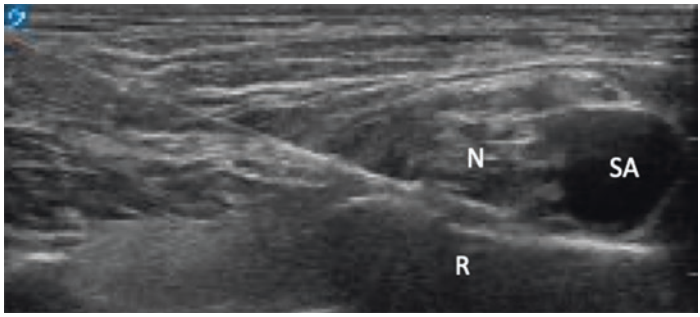


Fig. 13.9 Supraclavicular block, ultrasound image. SA subclavian artery, N brachial plexus nerves, R rib

Supraclavicular Block

A supraclavicular PNB is an excellent choice for surgery of the arm or hand (but is not reliable for shoulder surgery given frequent sparing of axillary and suprascapular nerves), and is often referred to as the "spinal of the arm" given its rapid onset and predictability. Once the interscalene groove is palpated, the groove is followed down the neck to the clavicle. Approximately 1 cm above the clavicle is the insertion point for the block needle. Under ultrasound guidance, the brachial plexus appears as a "cluster of grapes" lateral to the subclavian artery (Fig. 13.10), and use of ultrasound can reduce risk of pneumothorax and subclavian artery puncture. The most common serious complication is pneumothroax, which can occur in 1% of cases.

Infraclavicular Block

An infraclavicular PNB is a good block for surgery of the lower arm and hand (again sparing the shoulder). As the brachial plexus passes under the clavicle, the plexus forms three cords (lateral, posterior, and medial) surrounding the axillary artery. The nerve block needle is further removed from the pleura and the neuraxis and the risk of pneumothorax or neuraxial anesthesia is low. There

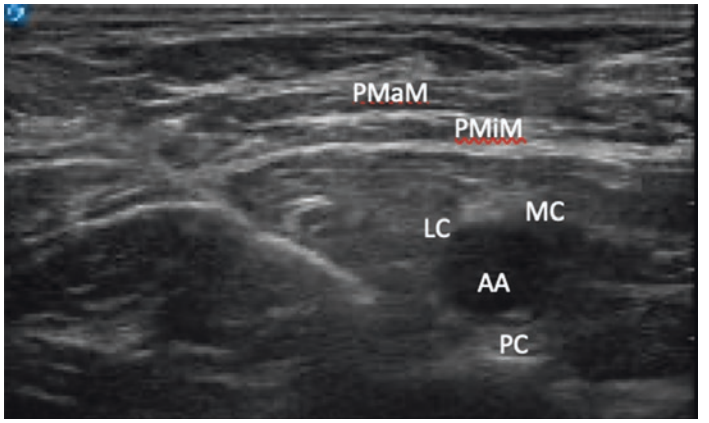


Fig. 13.10 Infraclavicular block, ultrasound image. Brachial plexus surrounding axillary artery at the level of cords. AA axillary artery, MC medial cord, PC posterior cord, LC lateral cord, PMaM pectoralis major muscle, PMiM pectoralis minor muscle

are several approaches to the infraclavicular PNB. The most common approach is ultrasound guided where the probe is placed parasagittaly and allows identification of the three cords and axillary artery to be seen. The block is completed with injection of local anesthetic surrounding the axillary artery and three surrounding cords. If using nerve stimulation, the approach is 2 cm below and 2 cm medial of the acromion. A motor response is usually sought in the hand (finger flexion or extension) with a current <0.4 mA.

Axillary Block

Axillary PNBs are used for surgery involving the lower arm and hand. It offers the advantage of being performed off the chest with minimal risk of phrenic nerve blockade or pneumothorax. As the brachial plexus enters the axilla, the three cords become the terminal branches surrounding the axillary artery. Under ultrasound guidance, the brachial plexus (as the three terminal branches,

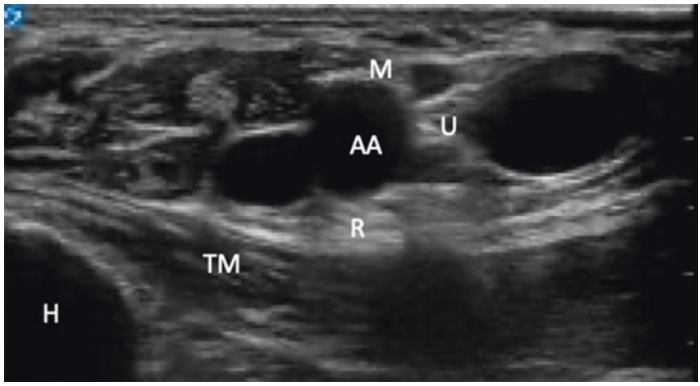


Fig. 13.11 Axillary block, ultrasound image. Brachial plexus surrounding axillary artery at the level of the branches. AA, axillary artery. M median nerve, U ulnar nerve, R radial nerve, TM triceps muscle, H humerus

referred to as the radial, ulnar, and median nerves) is visualized surrounding the axillary artery (Figs. 13.11 and 13.12) Approximately 10 ml of local anesthetic is injected around each nerve. The musculocutaneous nerve is a terminal branch that exits very proximal from the brachial plexus and must be blocked separately. This nerve can be visualized directly under ultrasound and injected, if required for the procedure. As the brachial plexus runs more distal from the roots, the time to onset increases. The axillary PNB takes the longest time to set up of all the upper extremity blocks. Table 13.3 provides a summary of upper extremity peripheral nerve blocks.

Lower Extremity Peripheral Nerve Block

The lumbosacral plexus, comprised of the lumbar plexus (typically L1-L4) and sacral plexus (L4–5 and S1–4), provides lower extremity innervation, and many unique approaches allow for targeted anesthesia of the lower extremity. Figures 13.12 and 13.13 illustrate the sensory distributions of lower extremity nerves. Understanding of these distrubutions is critical to choosing the

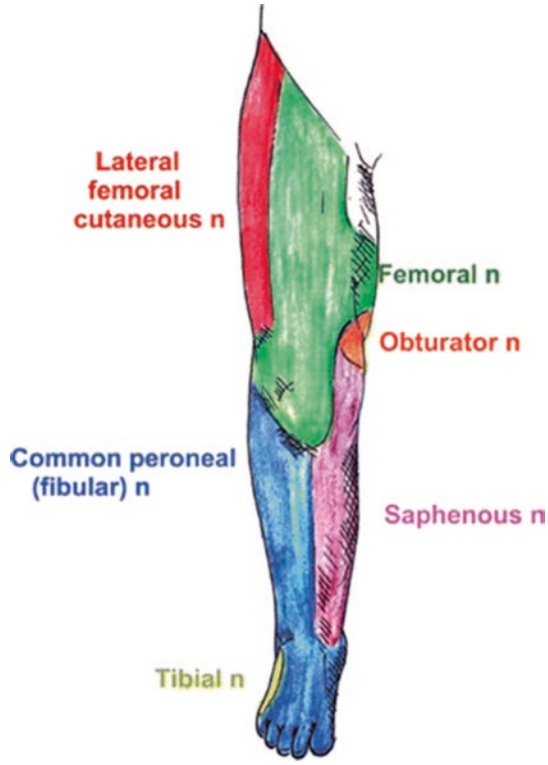


Fig. 13.12 Cutaneous distribution of peripheral nerves. (Reproduced with permission from Tsui [7])

correct peripheral block for a desired analgesic effect. Only a select few will be discussed below.

Femoral Nerve Block

To perform a femoral nerve block, indicated for anesthesia of the hip, thigh, and distribution of the saphenous nerve (medial leg and ankle joint), the patient is placed in the supine position. A line drawn from the anterior superior iliac spine to the pubic tubercle

Table 13.3 Summary of upper extremity nerve blocks

Type of nerve block	Indications	Anatomical landmarks	Potential complications
Interscalene	Shoulder; distal clavicle, upper arm	Between middle and anterior scalene muscles at the level of C6 (cricoid cartilage)	Hemi-diaphragmatic paralysis; Horner's syndrome; epidural spread; intravascular injection; ulnar nerve sparing
Supraclavicular	Upper and lower arm; hand	Between the middle and anterior scalene muscles, 1 cm above the clavicle	Pneumothorax (1% incidence); intravascular injection, may still get hemidiaphragmatic paralysis
Infraclavicular	Upper and lower arm; hand	2–3 cm caudad from the midpoint of the clavicle	Pneumothorax,intravascular injection
Axillary	Lower arm; hand	Brachial artery pulsation	Intravascular injection; prolonged set-up time; miss the musculocutaneous nerve

represents the inguinal ligament. The femoral artery is then palpated along this line and marked. The block needle is inserted 1–2 cm lateral to the femoral artery pulse. The desired motor response is a quadriceps twitch. Under ultrasound guidance, the femoral nerve is visualized over the inguinal crease, just lateral to the femoral artery and deep to the fascia iliaca. Femoral nerve PNB can be used for surgery involving the knee, anterior thigh, and medial portion of the lower leg. Since the femoral nerve is located in close proximity to the femoral artery, careful aspiration is important to avoid intravascular injection of local anesthetic.

The femoral nerve and its branches can be blocked at more distal locations to preferentially provide analgesia of more distal portions of the leg with sparing of quadriceps muscle weakness.

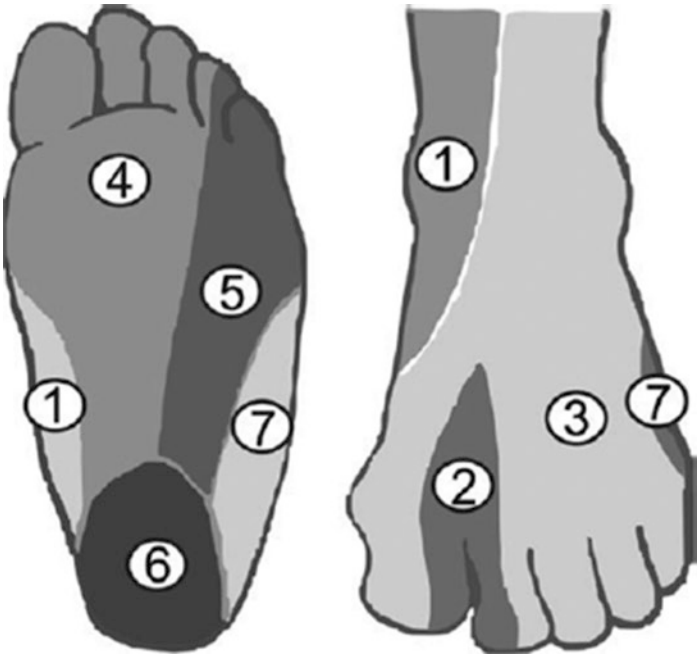


Fig. 13.13 Innervation of the foot. *Plantar surface*: 1 Saphenous nerve; 2 Deep peroneal nerve; 3 Superficial peroneal nerve; 4 Medial planar nerve. *Dorsal surface*; 5 Lateral plantar nerve; 6 Tibial nerve (calcaneal branch); 7 Sural nerve. (Image courtesy J. Ehrenfeld)

The adductor canal block is an option for analgesia of the knee and medial leg, and saphenous nerve block can provide analgesia of the medial leg and ankle joint.

Sciatic Nerve Block

The sciatic nerve is formed from the L4–L5 and S1–S3 nerve roots, and can be blocked anywhere along its course (including posterior, subgluteal, and popliteal approaches). For a posterior (or classical) approach, the patient is placed in the lateral position with the operative side up. The operative leg is flexed at the knee,

while the nonoperative leg remains straight. A line is drawn between the greater trochanter and the posterior superior iliac spine. A second line can be drawn from the greater trochanter to the sacral hiatus. A third line is drawn from the mid-point of the first line, intersecting the second line. This is the point of needle entry. The needle is inserted perpendicular to all planes with the desired motor response of plantar or dorsiflexion of the foot. Using ultrasound guidance, the subgluteal approach is usually chosen, and and positioning of the probe is identified using the landmarks of the greater trochanter and ischial tuberosity. The nerve, triangular in appearance, is often visible deep to the gluteal muscles and allows for injection of local anesthetic surrounding the nerve, although nerve stimulation is frequently used in conjunction with ultrasound to confirm proper placement of local anesthetic (see image below). A sciatic nerve block can be used for surgery below the knee (with the exception of the medial portion of the lower leg innervated by a branch of the femoral nerve), although it is also used commonly in addition to femoral blockade for anesthesia of the hip, thigh, and knee. When combined with a lumbar plexus block, it can provide complete anesthesia to the entire leg.

Ankle Block

Five nerves supply sensation to the foot (Fig. 13.10). Four of the five nerves are branches of the sciatic nerve, while one is a branch of the femoral nerve. The **saphenous nerve** (branch of the femoral nerve) provides sensation to the anteromedial aspect of the foot. It can be blocked by infiltrating local anesthetic just anterior to the medial malleolus. The **deep peroneal nerve** provides sensation to the webspace between the first two digits. It can be blocked by infiltrating local anesthetic lateral to the dorsalis pedis artery, and by ultrasound identification of the nerve or the adjacent artery. The **superficial peroneal nerve** provides sensation to the dorsum of the foot and all five digits. It can be blocked by administering local anesthetic from the anterior border of the tibia to the lateral malleolus. The **sural nerve** provides sensation to the

lateral aspect of the foot. It can be blocked by injection of local anesthetic just lateral to the Achilles tendon, toward the lateral malleolus. Finally, the **posterior tibial nerve** provides sensation to the heel. The nerve can be blocked by injection of local anesthetic posterior to the medial malleolus, and can again be identified under ultrasound. Approximately 5–8 mL of local anesthetic is injected for each nerve.

Peripheral Nerve Catheters

Placement of a peripheral nerve catheter, or continuous peripheral nerve block, involves identification of a peripheral nerve, placement of a percutaneous catheter adjacent to the nerve, and allows continuous administration of local anesthetic to the area surrounding the nerve. This technique allows for prolonged analgesia from a single procedure, including the possibility of discharging a patient to the home with a continuous infusion of medication. Administration via a continuous nerve block has been shown to potentially decrease rates of chronic postsurgical pain. Potential complications include LAST, nerve injury, infection, hematoma, and intervascular placement of catheter, although these are relatively rare.

Intravenous Regional Anesthesia (Bier Block)

A Bier block is a fairly simple block to perform and can produce profound anesthesia and analgesia. It is often used for short surgical procedures of the hand or forearm (e.g., carpal tunnel), although it is decreasing in popularity with the increasing use of ultrasound guided brachial plexus blocks. To perform the block, a peripheral intravenous line is started and a double pneumatic tourniquet is placed on the arm. The arm is exsanguinated and the proximal cuff on the double tourniquet is inflated. Approximately 25–50 mL of 0.5% lidocaine is injected into the IV and the IV is removed.

If the patient begins to complain about tourniquet pain, the distal cuff can be inflated and the proximal cuff deflated. If the surgical procedure is extremely short, the tourniquet must still be left in place for at least 20 min to avoid rapid systemic absorption of a high concentration of local anesthetic. Due to concern of inadvertent early tourniquet deflation and systemic absorption, long-acting local anesthetics, such as bupivacaine, are not recommended for intravenous regional blocks.

Case Study

A 58-year-old man is to undergo right total knee replacement (TKR/TKA). After a thorough H&P and consultation, he elects to have the procedure under regional anesthesia. He is otherwise healthy, though he smokes a pack of cigarettes a day and does not exercise regularly due to his arthritic knee. He takes an NSAID daily for pain and lately has been taking oxycodone and acetaminophen for worsening pain.

Which dermatomes or nerves will you need to block to perform a total knee replacement comfortably?

The anterior portion of the thigh and leg are innervated by the L3, L4, and L5 dermatomes. The back of the knee, though not in the incision, is stimulated nonetheless in TKR, and is innervated by S2. In addition, a thigh tourniquet is usually employed to prevent blood loss, so L2 and possibly L1 should be blocked. In practice, the femoral, lateral femoral cutaneous, obturator, and portions of the sciatic nerve need to be blocked.

Which regional anesthetic techniques are suitable for total knee replacement? Which will you choose?

In theory, several techniques are possible. Spinal anesthesia will reliably block all the involved nerve roots, whether a plain solution or hyperbaric solution containing glucose is used. Hyperbaric solutions may produce higher levels than are necessary, so plain solutions may be favored

for the lower incidence of hypotension. Epidural anesthesia can be used for TKR and allows titration of local anesthetic to the desired level. Disadvantages include a 5–10% incidence of failed or inadequate block (asymmetric anesthesia or incomplete sacral nerve blockade). An additional advantage is the ability to extend the block for either prolonged surgery or for postoperative analgesia. Peripheral nerve blocks may also be used. Individual nerve blocks can provide surgical anesthesia. It is more practical to perform a lumbar plexus or three-in-one block (which will cover the femoral, lateral femoral cutaneous, and obturator nerves with a single injection or catheter). A separate sciatic block, or a spinal or general anesthetic may then be added to complete the anesthetic.

If you choose spinal analgesia, how will you locate the intrathecal space?

Standard monitors are placed and an IV is inserted. The patient can be seated or lying on his side; many find the sitting position easier to locate the midline. The back is sterilely prepped and draped and local anesthetic is infiltrated in a lumbar interspace, typically L3–L4 or L2–L3. With the **midline approach**, the spinal needle is passed through the skin, subcutaneous tissue, the supraspinous ligament, the interspinous ligament, the ligamentum flavum, and finally advancing through the epidural space into the subarachnoid space (Fig. 13.4). Often a distinct "pop" is felt by the anesthesiologist as the needle penetrates the ligamentum flavum. Correct identification of the subarachnoid space is confirmed by free flow of CSF out of the hub of the needle.

If choosing spinal anesthesia, what are the potential benefits, when compared to general anesthesia? Which of the available regional blocks should be considered to help provide post-operative analgesia? What are potential negative implications of choosing these blocks?

The use of neuraxial anesthesia has been associated with improved outcomes following TKA, with potential benefits

including decreased hospital length of stay (LOS), decreased OR times, improved 30-day mortality rates, and decreased blood loss. Regional anesthesia techniques provide the opportunity for improved post-operative pain relief, and may reduced pain scores and opioid requirements, as well as shorten hospital LOS. Consideration should be given to single-shot or continuous adductor canal/saphenous block, femoral nerve block, or sciatic nerve block. Adductor canal block attempts to block the sensory branch of the saphenous nerve and provide analgesia to the medial and anterolateral knee below the patella while avoiding motor weakness, but will not provide anesthesia to the posterior aspect of the knee. Femoral nerve block can provide analgesia to the anterior knee, and sciatic block can be used in conjunction to adequately anesthetize the posterior knee, but both will result in likely motor weakness that can potentially result in falls, or delayed participation in rehabilitation exercises.

Suggested Further Reading

1. Basques BA, Toy JO, Bohl DD, Golinvaux NS, Grauer JN (2015) General compared with spinal anesthesia for total hip arthroplasty. J Bone Joint Surg. 97(6):455–461
2. Bernards CM (2006) Epidural and spinal anesthesia. In: Barash P, Cullen B, Stoelting R (eds) Clinical anesthesia, 5th edn. Lippincott Williams & Wilkins, Philadelphia, pp 691–717
3. Drasner K, Larson MD (2007) Spinal and epidural anesthesia. In: Stoelting R, Miller R (eds) Basics of anesthesia. Churchill Livingstone, Philadelphia, pp 241–290. Gray AT, Collins AB, Eilers H (eds) Peripheral nerve blocks
4. Franco CD, Clark LL, Robards C, Hadzik A (2007) In: Hadzic A (ed) Textbook of regional anesthesia and acute pain management, 1st edn. McGraw-Hill Companies, Inc., New York, pp 419–440, 481–488
5. Mathias J (2006) Percutaneous vertebroplasty and kyphoplasty, 2nd edn. Springer, New York
6. Stewart O (2000) Functional neuroscience. Springer Press, New York

7. Tsui B (2007) Atlas of ultrasound and nerve stimulation-guided regional anesthesia. Springer, New York
8. Twersky R, Philip B (2008) Handbook of ambulatory anesthesia. Springer, New York
9. Wedel DJ (2002) Upper extremity blocks. Lower extremity blocks. In: Faust R, Cucchiara R, Rose S, Spackman T, Wedel DJ, Wass CT (eds) Anesthesiology review, 3rd edn. Churchill Livingstone, Philadelphia, pp 311–315

Electrolytes and Acid-Base Balance

14

Bryan Marchant, Adam Kingeter, and Matthew D. McEvoy

Educational Objectives

1. Understand physiologic regulation of serum electrolytes and describe common abnormalities
2. Understand the importance of acid base regulation in clinical practice
3. Describe the determinants of pH according to both the Stewart and traditional approach
4. Understand physiologic regulation of pH
5. Understand the causes of both metabolic and respiratory acid base disturbances
6. Understand risks and benefits of treatment options available for metabolic acidosis

B. Marchant (✉)
Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA
e-mail: bmarchan@wakehealth.edu

A. Kingeter · M. D. McEvoy
Department of Anesthesiology, Vanderbilt University Medical Center, Nashville, TN, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_14

Introduction to Serum Osmolality

When not influenced by transporters and channels fluids separated by a permeable or semipermeable membrane will follow a concentration gradient of solute from least to greatest until equalization occurs and the separate fluids spaces are termed isotonic. The property of fluids that allows for this is called osmotic activity and the pressure that drives this fluid migration is known as osmotic pressure. Osmotic activity is determined entirely by number of particles of solute in the fluid and not influenced by size of the particle or that particle's electrical charge. Fluids with a large number of particles tend to draw additional water to them and are termed hypertonic, those with less particles tend to allow water to flow away and are called hypotonic.

Although osmolarity and osmolality are often used interchangeably they have distinct definitions. The former refers to osmotic activity per volume of any solution while the latter is specific to that of water. As plasma is primarily composed of water serum osmolality is usually used in physiologic discussion.

In the human body serum osmolality is tightly regulated between 275 and 290 mOsm/kg.

Serum osmolality is estimated by the following equation:

$$\text{Serum Osmolality} = \left(\text{Serum } Na^{+} \times 2\right) + \left(\text{Serum glucose} / 18\right) + \left(\text{Serum BUN} / 2.8\right)$$

Sodium is multiplied by 2 to account for the osmotic activity of chloride (this of course assumes that sodium and chloride are balanced in serum, a look at a normal basic metabolic panel will show this is not exactly the case). The absolute value of glucose and BUN are divided by their molecular weights to express them in terms of osmolality.

While sodium, chloride, glucose and BUN are the primary solutes in serum there are others present in much smaller concentrations. Despite their small concentration when added up these

additional solutes will lead to a discrepancy between the measured and calculated osmolality. This difference is known as the osmolar gap and is usually less than 10.

The hypothalamic-pituitary-adrenal (HPA) axis plays a major role in the regulation of serum osmolality. Serum osmolality is sensed by osmoreceptors in the organum vasculosum of the lamina terminalis (OVLT), located in the portion of the hypothalamus outside of the blood-brain barrier. Changes in osmolality of as little as 1% are sensed by the osmoreceptors, which send projections to the supra-optic (SON) and para-ventricular (PVN) hypothalamic nuclei. The SON and PVN synthesize anti-diuretic hormone (ADH) and send projections to the posterior pituitary. These projections in the posterior pituitary release ADH into systemic circulation. ADH acts on the medullary collecting duct of the nephron, and causes increased water absorption. This increase in water absorption leads to a subsequent decrease in serum sodium concentration, thus driving down serum osmolality.

Introduction to Serum Electrolyte Composition

Electrolytes are defined as compounds that contain an electrical charge when dissolved in a solution such as water and as such are able to conduct electricity. These charged compounds are referred to as ions, and their charge may be either positive (cations) or negative (anions). Tight regulation of electrolytes in both the intracellular and extracellular spaces is essential for normal cellular function in every organ system. The body will seek to maintain serum electrochemical neutrality; that is, a balance of all positive and negative charges. In addition to this, the body seeks to maintain acid-base regulation within a very narrow range. These two forces, electrochemical neutrality and acid-base balance, are tightly coupled in order to maintain normal homeostasis. Disruption of this balance leads to cellular dysfunction and can cause fatal pathologic processes such as renal dysfunction, dysrhythmias, seizures and coma.

Physiologic Regulation of Electrolytes

The major serum cations are sodium and potassium, with calcium and magnesium present in much lower concentrations. The major serum anions are chloride and bicarbonate. Phosphate and lactate are present as well albeit in lower concentrations. Intracellular concentration of these ions is determined by active transmembrane pumps and to a lesser extent by passive ion-specific channels. Extracellular – including serum – concentration of electrolytes is regulated primarily by the renal system with significant input from the hypothalamic-pituitary-adrenal (HPA) axis.

Sodium

Sodium is the most abundant serum cation, and is a major determinant of serum osmolality. The HPA axis as described above plays a major role in the regulation of sodium balance as driven by serum osmolality. The other major system regulating sodium balance is the renin-angiotensin system (RAS). Decreased sodium delivery to the macula densa triggers the synthesis and release of renin from the juxtaglomerular apparatus. Renin converts angiotensinogen to angiotensin I, which is then rapidly converted into angiotensin II by angiotensin converting enzyme (ACE). Angiotensin II acts directly on the vasculature to increase systemic vascular resistance (SVR), increase ADH release, and stimulate the release of aldosterone from the zona glomerulosa of the adrenal cortex. Aldosterone acts on the distal tubules and collecting ducts of the nephron to increase the reabsorption of water and sodium as well as increase the secretion of potassium. Abnormalities in either of these systems can lead to disorders of sodium homeostasis.

Given that sodium and serum osmolality are tightly linked, and that osmolality is influenced by relative volume status, disorders of sodium homeostasis are categorized by intravascular volume status. Hyponatremia may occur in the context of any intravascular volume state although for very different reasons. Thus an evaluation of intravascular volume status is critical to understanding the etiology of hyponatremia.

Hypovolemic causes are due to the loss of both sodium and total body water as occurs with profuse sweating, prolonged vomiting or diuretic use. A rare cause of hypovolemic hyponatremia is cerebral salt wasting syndrome (CSW). CSW is typically seen in the context of head trauma or, less commonly, an intracranial lesion. This syndrome is characterized by decreased renal sodium retention, polyuria, and dysautonomia. Treatment of hypovolemic hyponatremia is mainly supportive and aimed at fluid and electrolyte replacement. A mineralocorticoid such as fludrocortisone may be used to increase renal sodium reabsorption. Most cases typically resolve spontaneously within 2–4 weeks, although a few persist longer.

An increase in total body water will lead to hypervolemic hyponatremia which typically occurs in the context of decreased effective serum osmolality and is often associated with peripheral edema. Common etiologies include heart failure, nephrotic syndrome, and liver disease with associated ascites. In these states, plasma osmolality is decreased and oncotic pressure is unable to retain volume in the intravascular space. Water accumulates in the interstitial space leading to both decreased effective circulating volume and edema. The kidneys, sensing a decrease in circulating volume, increase water reabsorption which maladaptively further decreases serum osmolality. Treatment involves fluid restriction as well as treating or optimizing the underlying etiology. Vaptans are a class of medications that act as antidiuretic hormone antagonists at renal V2 receptors effectively preventing water reabsorption in the distal nephron and for this reason may be useful as well.

Euvolemic hyponatremia is typically caused by either the presence of osmotically active molecules (pseduohyponatremia) or excess secretion of ADH. Pseudohyponatremia occurs when hyperosmolarity from non-sodium osmotically active agents (glucose, triglycerides, immunoglobulins) draws water from the intracellular compartment into the intravascular space with subsequent dilution of sodium content. Syndrome of Inappropriate Anti-Diuretic Hormone (SIADH) is the paradigm for euvolemic hyponatremia, and is seen in a wide array of clinical conditions ranging from intracranial abnormalities to various tumors. SIADH

is characterized by inappropriately elevated levels of ADH in the absence of a physiologically appropriate stimulus (i.e. hypotension or hypotonicity). The hallmark of SIADH is inappropriately concentrated urine relative to plasma osmolality. As discussed, one of the physiologic effects of ADH is water retention and these patients develop a pure water excess. Water is not confined to one fluid compartment, it distributes equally throughout all of them, thus these patients appear clinically euvolemic. Classically, water restriction has been the mainstay of SIADH treatment. In cases where water restriction is poorly tolerated, a vaptan or demeclocycline has been used. Demeclocycline is a tetracycline analogue that inhibits vasopressin mediated water reabsorption in the collecting duct.

The deleterious physiologic effects of hyponatremia develop when sodium levels drop enough to significantly lower plasma tonicity, leading to a shift of water into the intracellular space. This leads to cellular dysfunction, particularly in the CNS and accounts for the clinical manifestations of confusion, coma and seizures. In cases of symptomatic hyponatremia, sodium repletion maybe given either orally or in the form of intravenous fluids. 0.9% normal saline is usually sufficient however in extreme cases concentrated 3% saline may be considered. Regardless of method used for correction this must be done gradually to avoid Central Pontine Myelinolysis, the most feared complication of hyponatremia correction. Central Pontine myelinolysis may be neurologically devastating due to a rapid shift of water out of the intracellular space in the CNS and neuron shrinkage and desiccation. In order to avoid this complication plasma sodium concentration should not be raised by a rate of more than 0.5 mmol/L/h, and an absolute repletion of no more than 10 mmol/L in a 24 hour period.

Hypernatremia leads to an increase in serum osmolality, with a subsequent shift of water out of the intracellular compartment and cellular dysfunction. As with hyponatremia, the CNS is particularly sensitive to these shifts and patients with symptomatic hypernatremia typically present with weakness, confusion and lethargy. In contrast to hyponatremia, hypernatremia is almost always a result of water loss in excess of sodium loss rather than

excess sodium intake relative to water intake. As such, these patients are typically hypovolemic.

Most commonly, hypernatremia occurs via either evaporative losses or by excretion of large volumes of very dilute urine. Evaporative, or insensible losses result from evaporation of pure water from the respiratory tract or other exposed mucosal surfaces. These losses are highly variable and are increased by patients who are febrile, tachypnic, or in warm environments. Surgical procedures that expose large body cavities to room air greatly increase the surface area for evaporative loss. Under these conditions evaporative losses may be significantly higher than that which they would be under normal environmental conditions. The loss of large volumes of dilute urine is characteristic of diabetes insipidus (DI). DI results from either a lack of vasopressin release from the posterior pituitary (termed central DI) or lack of renal response to circulating vasopressin (known as nephrogenic DI). Patients with DI who are able to regulate their water intake typically do not develop hypernatremia as their input matches their output. However, in cases where there is an imbalance between intake and output hypernatremia and dehydration may develop rapidly.

Treatment of hypernatremia depends on the underlying cause. In patients with central DI, a synthetic vasopressin analogue, desmopressin or DDAVP, is the treatment of choice. DDAVP lacks the hypertensive effects of vasopressin and can be given nasally, intravenously, or orally. In patients with nephrogenic DI, thiazide diuretics have a paradoxical anti-diuretic effect and are utilized if the underlying cause cannot be reversed. In patients who are hypernatremic secondary to free water loss, the correction of the free water deficit results in correction of the hypernatremia. Free water deficit can be calculated from the following equation:

$$\text{Deficit} = \text{TBW}\left(1-\left[140/\text{Plasma Na}+\right]\right) \text{where TBW is total body water (L) estimated at } 0.5\times \text{lean body weight for women and } 0.6\times \text{lean body weight for men.}$$

Rapid correction of hypernatremia can lead to cerebral edema, therefore no more than half of the deficit should be replaced in the first 24 hours of treatment. The remainder can be corrected in the following 24–48 hours. Chronic hypernatremia is remarkably well tolerated secondary to compensatory changes which occur at the cellular level. These changes involve intracellular production of osmotically active substances to offset the extracellular hypertonicity.

Potassium

Potassium is the second most common cation in the body following sodium. Ninety-eight percent of the total body potassium content is contained intracellularly. The significant gradient in potassium concentration across the cell membrane leads to a negative electric charge in the intracellular space. This charge, known as a resting membrane potential, is necessary for the proper functioning of excitable tissues such as muscle and nerve. Active ion transport pumps located in the cellular membrane are necessary to maintain this gradient, which can account for up to 60% of a cell's total energy expenditure. Small changes in extracellular potassium concentration can lead to dysfunction of excitable tissue with potentially catastrophic consequences. Maintenance of potassium homeostasis is accomplished at both the cellular and organ system level; shifts of potassium into and out of cells buffers against acute changes in extracellular potassium, while the renal system maintains a balance between potassium intake and excretion. Multiple disease states affect these systems and can lead to disorders of potassium regulation.

Hyperkalemia may be classified by duration as either acute (<48 hours) or chronic. Acute hyperkalemia is almost always caused by a shift of potassium out of cells although in some rare circumstances may be caused by an excessive intake of potassium. A transcellular shift of only 2 percent of intracellular K^+ would cause serum K^+ levels to double. Dramatic transcellular shifts of potassium are often associated with cell death, such as tumor lysis syndrome or rhabdomyolysis. A metabolic acidosis

also results in a transcellular shift of potassium, as H^+ displaces K^+ from the intracellular compartment. Certain medications such as digitalis and succinylcholine are associated with transcellular shifts of potassium as well. Under normal circumstances, succhinycholine induced fasciculations cause a small amount of K^+ to leak from muscle. This small leak causes a transient increase in serum K^+ by about 0.5 mmol/L. However, in patients with upregulation of acetylcholine receptors such as those with prolonged immobilization or paralysis, severe burns, or muscle inflammation, the amount of K^+ released can be significantly larger with potentially fatal consequences. Excessive potassium intake is often iatrogenic such as may occur with overly aggressive oral or IV potassium replacement therapy. Banked blood contains a small amount of potassium due to breakdown of stored red blood cells. While this is usually not enough to be of significance with a singular blood transfusion, massive resuscitative efforts may lead to accumulation of large amounts of potassium and cause symptomatic hyperkalemia.

Causes of chronic hyperkalemia include renal failure, Addison's disease, and both aldosterone deficiency and renal tubular unresponsiveness to aldosterone. Hyperkalemia causes aberrant depolarization of cardiac myocytes resulting in dysrhythmias and impaired conduction disorders. Classic EKG changes associated with progressive hyperkalemia include (in order of their appearance as K^+ levels rise): peaked T waves, prolongation of the PR interval, widening of the QRS complex, loss of P wave, "sine wave" appearing ventricular fibrillation, and finally asystole. Hyperkalemia is also associated with paresthesias and skeletal muscle weakness progressing to a flaccid paralysis. Therapy for hyperkalemia is aimed initially at stabilizing the cell membranes of excitable tissues. Once this has been achieved, therapy is guided towards redistribution of K^+ into cells and enhanced elimination of K^+ from the body. Calcium directly antagonizes the myocardial effects of hyperkalemia and in so doing leads to membrane stabilization. This should always be the first step in treatment of hyperkalemia, however it is important to remember that while this protects the patient from cardiac dysrhythmias it does not address the hyperkalemia itself. For this to occur potassium

must initially be redistributed into the intracellular space and then ultimately excreted. Redistribution of potassium into cells can be accomplished by both insulin and albuterol. A dextrose infusion should be started to counteract the hypoglycemic effects of insulin therapy in these patients. Increased elimination of potassium from the body can occur via either the renal or GI route. Renal elimination of potassium is increased by increased flow through the distal nephron, typically accomplished by administration of IV fluid, typically normal saline due to its lack of K^+, and is enhanced by loop diuretics. GI losses of potassium are increased by the administration of sodium polystyrene sulfonate (SPS). SPS is a cation exchange resin that exchanges sodium for secreted potassium in the colon. SPS causes constipation and should be given with a cathartic. Caution should be used with this elimination modality as cases of colonic necrosis have been reported following administration of SPS. In extreme circumstances or when patients are aneuric hemodialysis can be used to quickly remove potassium.

As with hyperkalemia, hypokalemia may be classified according to duration as either acute (<48 hours) or chronic. Acute changes are almost always caused by transcellular shifts of potassium into cells. This inward shift is often seen with treatment of DKA secondary to insulin therapy, and can also be seen in refeeding syndrome due to increased endogenous insulin production. Other medications, such as β2-agonists, also cause a shift of potassium into cells and can cause acute hypokalemia. Chronic hypokalemia is usually the result of either decreased intake or increased elimination be it GI or renal. Renal losses of potassium are increased by diuretics, various antibiotics and mineralocorticoids. Various inborn tubular transport abnormalities, such as Barter and Gitelman's syndromes are also associated with increased renal losses of K^+ and hypokalemia. Hypokalemia leads to cell membrane hyperpolarization, and can cause cardiac arrhythmias and conduction defects. Non specific EKG changes include ST segment depression, T wave flattening and prominent U waves. Neuromuscular signs include weakness, muscle fatigue and myalgias. Treatment of hypokalemia involves replacement of the body deficit and correction of underlying cause when able.

Potassium may be given either orally or IV. Serum potassium levels peak immediately following an infusion and over the next 2–3 hours decrease to the new steady state. Repeat measurements of serum potassium should be taken after the new steady state has been achieved to further guide therapy.

Chloride

Chloride is the predominant anion in the extracellular fluid. As mentioned above, electroneutrality is maintained at all times; that is, the concentration of cations and anions is equal and charges offset. As such, changes in chloride concentration significantly effect the concentration of other anions such as bicarbonate, lactate and other organic acids. Many of these other anions take part in the buffering of serum H^+ concentration and help determine plasma pH. Due to the interplay of chloride and other serum anions, chloride physiology and acid base balance are closely related and interdependent.

An example of this sort of interdependence can be seen in patients who have been resuscitated with large volumes of normal saline. 0.9% normal saline contains 154 meq of sodium and 154 meq of chloride compared to a normal serum chloride concentration of approximately 100 meq. This increase in serum chloride causes a reciprocal decrease in other serum anions, notably bicarbonate. As serum bicarbonate levels decrease, there is a concomitant increase in unbuffered serum H^+ concentration and serum pH decreases resulting in an acidosis. The role of chloride physiology and acid-base balance will be further discussed in the next section.

Calcium

Calcium has several roles in the human body beyond being the primary composite of bone. It is necessary for cardiac function, muscle (both skeletal and smooth) contraction, and coagulation.

While the human body has abundant stores of calcium, with some references noting an average of approximately 500 g the

majority of this comprises bone and as such is not immediately available for physiologic use. The remaining calcium in serum exists in three forms; bound to albumin or other proteins and free ionized calcium account for the majority with a very minor contribution of calcium complexed with anions such as bicarbonate, citrate, lactate, or phosphate. Of these the free ionized calcium is the only form of the electrolyte that is biologically active.

A standard calcium assay will measure all three forms of calcium, however, as almost half of serum calcium is bound to albumin in cases of hypoalbuminemia less calcium is measured, although the biologically active ionized calcium is unaffected. For this reason it is imperative to take into account albumin when interpreting a calcium result. For every 1 g/dL decrease in albumin below normal (4.0 g/dL) a drop in serum calcium of 0.8 mg/dL may be expected. Conversely ionized calcium studies can be run. Ionized calcium can be interpreted off of a blood gas, but, since the sample has strict handling criteria, it is more difficult (and more expensive) to run as part of standard labs. The normal range for ionized calcium is 1.15–1.25 mmol/L.

Hypocalcemia can manifest itself initially with neuromuscular symptoms such as paresthesias, spasms and tetany. Here, the often referenced Chvostek's or Trousseau's signs may be apparent. With worsening hypocalcemia one may expect seizures and cardiac symptoms such as bradycardia, impaired contractility and prolongation of the QT interval. Magnesium and calcium regulation by the parathyroid are linked and decreased magnesium will invariably lead to hypocalcemia. Although incompletely understood, septic patients are also frequently found to be hypocalcemic. Hepatic and renal insufficiency, alkalosis, pancreatitis and certain drugs round out common causes of hypocalcemia. Additionally blood transfusions commonly lead to hypocalcemia in a dose dependent manner as citrate used as an anticoagulant in stored blood chelates serum calcium. It is thus imperative that calcium be supplemented when transfusing multiple units of banked blood.

IV replacement of calcium exists in two forms, 10% Calcium Gluconate and 10% Calcium Chloride. The latter contains three times as much elemental calcium however at the cost of a solution

with significantly higher osmolarity. For this reason calcium chloride should only be administered through a central line (or at minimum a large deep peripheral line). Caution should be used administering either of these medications IV and they should be given slowly as rapid administration may lead to hypertension.

Hypercalcemia is less commonly encountered in the critically ill population and is most commonly seen in patients with hyperparathyroidism or some malignancies. Signs and symptoms run the gamut from GI symptoms including nausea and vomiting, to musculoskeletal symptoms such as weakness, progressing to cardiac symptoms such as hypotension and shortened QT interval and finally neurologic symptoms such as confusion and somnolence. These symptoms are often seen at a total serum calcium of greater than 3.5 mmol/L and worsen with rising calcium level, especially if this rise is rapid. Initial management involves fluid hydration with normal saline as hypercalcemic patients are often volume depleted. Next, definitive control is obtained with calcitonin, which increases renal calcium excretion and impairs osteoclast function leading to decreased bone resorption, and bisphosphonates which also decrease bone resorption. Steroids may play a more long term role by inhibiting calcitriol and thus calcium absorption. In extreme cases hemodialysis is an effective method of rapidly removing calcium.

Magnesium

Magnesium serves a number of roles as an important cofactor. It is required for ATP hydrolysis, thus making it necessary for the expenditure of energy in all cells. It has a role in maintaining neuron membrane potential via its influence on the sodium potassium exchange pump. Further it regulates calcium movement into muscle cells making it critical for skeletal, smooth and cardiac muscle. Like calcium, magnesium exists primarily in bone although a large reserve is also found in muscle. Also like calcium, serum magnesium exits in three states, ionized, bound to anions or bound to serum proteins.

Hypomagnesemia is quite common, but as a cofactor it rarely exists in a vacuum. Instead symptomatic hypomagnesemia is usually associated with additional electrolyte imbalances such as hypokalemia and hypocalcemia. Neuromuscular symptoms are characterized by hyper-excitability including tetany, seizures and involuntary movements. Cardiovascular symptoms include such EKG changes as widened QRS and peaked T waves as well as increased PR intervals and finally atrial and ventricular arrhythmias. Neurologic symptoms may also be present and involve hyperreflexia and seizures as well as altered mental status. IV and oral preparations are available for magnesium replacement, however as it often exists with other electrolyte derangements, investigation for and replacement of these elements should be undertaken.

Hypermagnesemia is uncommon except for in cases of renal failure and iatrogenic magnesium overload (such as may occur when magnesium is given to preeclampsia patients). At lower levels hypermagnesemia is asymptomatic but when concentrations become higher then 4 mEq/L patients may experience neuromuscular and cardiovascular effects. Neuromuscular effects occur first, usually at a serum magnesium concentration of 4–6 mEq/L. The first sign is decreased alertness followed by decreased reflexes and muscle paralysis. As serum levels increase beyond 6 mEq/L cardiovascular effects are seen including hypotension, bradycardia and prolongation of PR, QRS and QT intervals. In the direst of circumstances complete heart block and cardiovascular collapse may be experienced. For mild hypermagnesemia stopping administration of magnesium or encouraging secretion with diuretics may be sufficient, however, if life threating symptoms are observed hemodialysis will likely be required.

Phosphate

Inorganic phosphate exists as a single phosphorus element bound to four oxygen atoms (PO_4) and is primarily found intracellularly. Phosphate plays a role in cellular energy regulation as the crucial component of ATP. ATP depletion may lead to neurologic symptoms such as paresthesias and seizures as well as cardiac symp-

toms such as decreased cardiac function and hypotension. Skeletal muscle is affected, leading to myopathy. Further, smooth muscle function can negatively be impacted, which may manifest as diaphragmatic weakness and decreased respiratory effort. Additionally phosphate has a role in oxygen disassociation with hemoglobin as a component of 2,3-Bisphosphogylceric acid. Due to its role in ATP one would think that depletion of the body's stores of phosphate would be devastating, however, surprisingly hypophosphatemia is rarely symptomatic unless it becomes extreme (less than 1 mg/dL). Hypophosphatemia is seen usually in starvation and extremely nutritionally depleted patients as well as in chronic alcoholism. Substantial use of antacids may also lead to hypophosphatemia. It is important to note that when glucose moves into cells PO_4 is moved in concurrently which can lead to a functional hypophosphatemia. This is of critical importance in debilitated patients who are for the first time receiving adequate nutritional support as it leads to a condition known as refeeding syndrome. Phosphate may be replaced either with parenteral or enteral supplementation.

Hyperphosphatemia is rare as renal regulation of phosphate is exceedingly efficient. That said it may be experienced in situations where there is more phosphate then the kidneys are able to handle, such as is seen with tumor lysis syndrome and rhabdomyolysis or in situations of renal failure or increased tubular reabsorption due to medications, hypoparathyroidism or some other rare endocrine disorders. Symptoms are often silent and evidence is primarily found on laboratory examination. Treatment revolves around fluid administration and if severe, hemodialysis.

Introduction to Acid Base Physiology

The tight control of extracellular hydrogen ion concentration is of paramount importance to the function of trans-membrane ion transport pumps and intracellular biochemical reactions. As such the body has developed numerous weak acid buffer systems to maintain a homeostatic pH between 7.35 and 7.45. Deviations in pH beyond this zone are termed acidemia (pH <7.35) and alkale-

mia (pH >7.45). The presence of acidemia or alkalemia indicates gross metabolic or respiratory abnormalities, which, if uncorrected, may lead to end organ dysfunction and death. Acid-base balance is a complex physiochemical process. Two different approaches can be used to explain acid-base interaction: anion gap/base excess and strong ion difference (Stewart approach).

The Stewart approach introduced by Peter Stewart in 1981 emphasizes two important elements of physical chemistry as the driving forces for acid base balance: electroneutrality and conservation of mass. The primary tenant of Stewart's approach is that serum bicarbonate does not alter blood pH. According to Stewart's theory, pH is the result of the interplay of three variables: Strong Ion Difference (SID), $PaCO_2$, and plasma concentration of weak non-volatile acids such as albumin and phosphate (Atot). The SID equals the difference between completely dissociated cations and anions in plasma. The equation for SID consists of the most abundant ions in plasma and is calculated as such:

$$\begin{aligned} \mathrm{SID} = &\left(\left[\mathrm{Na}^+\right] + \left[\mathrm{K}^+\right] + \left[\mathrm{Ca}^{2+}\right] + \left[\mathrm{Mg}^{2+}\right]\right) \\ &- \left(\left[\mathrm{Cl}^-\right] + \left[\mathrm{Lactate}^-\right]\right) = 40 - 44 \ \mathrm{mEq} \end{aligned}$$

Processes that increase the SID cause an alkalemia, whereas processes that reduce it cause acidemia. For example, the loss of gastric fluid, which has a high concentration of Cl^-, increases the SID and thus leads to alkalemia; by comparison, infusion of sodium chloride, a solution with equal parts Na^+ and Cl^- thus an SID of zero, reduces the SID and causes an acidemia. There is much emerging evidence of the likely clinical utility of the Stewart approach and so understanding this approach is important. That said, the anion gap approach benefits from being simpler to use and as such enjoys widespread use. As such it will be the approach favored for the remainder of this chapter.

The anion gap approach is based on the Bronsted–Lowry definition of an acid in which the primary extracellular buffer system is the equilibrium of carbonic acid and bicarbonate represented by the equation below.

$$H_2 0 + CO_2 <\longrightarrow> H_2CO_3 <\longrightarrow> H^+ + HCO3^-$$

The Henderson–Hasselbach equation describes the relationship between this equilibrium equation and pH as such:

$$pH = pK + \log_{10} \left(HCO_3^- / \alpha_{CO2} \times pCO_2 \right)$$

In this equation α_{CO2} represents the solubility coefficient of CO_2 (0.03) and pK represents the equilibrium constant (6.1). A derivative of this equation, known as the Henderson equation, simplifies matters as such:

$$H^+ = 24 \times pCO_2 / HCO_{3^-}$$

From this equation, it is evident that changes in pH may be either the result of a change in pCO_2 (referred to as respiratory) or HCO_3^- (referred to as metabolic).

Maintenance of homeostatic concentrations of CO_2 and HCO_3^-, including compensatory responses to insult, is a result of the interplay of the pulmonary and renal systems. Consequently, metabolic disturbances are accompanied by a respiratory compensation and vice versa. Compensation results in normalization of pH and can give some indication as to the duration of the insult, with chronic processes being better compensated. Attention must be paid to compensation, as multiple acid-base abnormalities can co-exist in the same patient, which are diagnosed by comparison of anticipated and actual compensatory changes. More than one metabolic abnormality may be present in a patient at one time, however, only one respiratory disturbance is possible at any given moment.

The introduction of blood-gas analysis in the 1950s allowed for the diagnosis and categorization of acid-base derangements and their subsequent treatment. The relatively low cost and ease of collection have led to the use of blood gas analysis in everyday anesthetic practice. Typical blood gas values include pH, pO_2, pCO_2, HCO_3^-, and base excess. Base excess is defined as the amount of strong acid (if BE >0) or strong base (if BE <0) which is required to return 1 L of whole blood at a pCO_2 of 40 mmHg to

Table 14.1 Acid-base disturbances and the expected compensation

Primary disorder	Primary change	Compensatory change	Expected compensation
Metabolic acidosis	↓ HCO_3	↓ $PaCO_2$	$\Delta PaCO_2 = 1.2 * \Delta HCO_3$
Metabolic alkalosis	↑ HCO_3	↑ $PaCO_2$	$\Delta PaCO_2 = 0.9 * \Delta HCO_3$
Respiratory acidosis	↑ $PaCO_2$	↑ HCO_3	**Acute:** $\Delta HCO_3 = 0.1 * \Delta PaCO_2$ **Chronic:** $\Delta HCO_3 = 0.35 * \Delta PaCO_2$
Respiratory alkalosis	↓ $PaCO_2$	↓ HCO_3	**Acute:** $\Delta HCO_3 = 0.2 * \Delta PaCO_2$ **Chronic:** $\Delta HCO_3 = 0.5 * \Delta PaCO_2$

a pH of 7.4. In theory, the base excess represents the metabolic component of an acid base disorder with positive values indicative of a metabolic alkalosis and negative values indicative of a metabolic acidosis. The deviation of BE from 0 can be used as a surrogate measure of severity of the metabolic derangement, with more severe disturbances resulting in values further from zero. Classical blood gas measurements allow for diagnosis of acidemia and alkalemia with levels of compensation as seen in Table 14.1. Further diagnosis and classification necessitates serum electrolytes, hemoglobin and serum lactate concentrations, which are available on most modern blood gas machines.

Metabolic Abnormalities

Metabolic Acidosis

Any process that causes a reduction in the extracellular bicarbonate concentration, via increased loss of bicarbonate or via accumulation of excess acid, is termed a metabolic acidosis. Multiple abnormalities can lead to a metabolic acidosis, and these are grouped according to whether or not they lead to an associated

increase in the serum anion gap. The serum anion gap is calculated by the following equation:

$$AG = \left(\text{Serum } Na^{+} + \text{Serum } K^{+}\right) - \left(\text{Serum } HCO_{3^{-}} + \text{Serum } Cl^{-}\right)$$

A normal value for anion gap is between 8 and 12 mmol/L and represents the concentration of anions normally unmeasured by a basic metabolic panel such as albumin, phosphates, sulfates and organic anions. Due to the large contribution of albumin, the anion gap varies significantly with serum concentration of albumin. Each 1.0 g/dL decrease or increase in serum albumin from 4.4 g/dL results in a corresponding increase or decrease in the anion gap approximately 2.3–2.5 meq/L. Consequently, hypo- or hyper- albuminemia must be considered when calculating anion gap. In a metabolic acidosis with decreased serum bicarbonate, serum electroneutrality is maintained by a compensatory increase in either serum chloride or unmeasured anions present in the anion gap. If electroneutrality is maintained by increasing chloride concentrations, the anion gap remains normal and we refer to the process as a "non anion gap metabolic acidosis" or "hyperchloremic metabolic acidosis". Causes of a non-anion gap metabolic acidosis are outlined in Table 14.2. If, however, electroneutrality is maintained by increasing unmeasured serum anions, the anion gap increases. We refer to this process as a "high anion gap metabolic acidosis" or "hypochloremic metabolic acidosis". Causes of a high anion gap metabolic acidosis are outlined in Table 14.3. It should be noted that the terms "hypochloremic" and "hyperchloremic" are not in relation to normal laboratory val-

Table 14.2 Causes of non-anion gap metabolic acidosis: HARD-UP

Hyperalimentation
Acetazolamide administration
Renal tubular acidosis
Diarrhea
Ureteroenteric fistula
Pancreaticoduodenal fistula

Table 14.3 Causes of high anion gap metabolic acidosis: MUD PILES

Methanol intoxication
Uremia
Diabetic ketoacidosis
Propylene glycol toxicity
Isoniazid toxicity
Lactic acidosis
Ethylene glycol intoxication
Salicylate toxicity

ues, but rather in relation to relative ionic composition of the plasma. It is possible to see a non-anion gap metabolic acidosis with a normal serum chloride.

Acidemia leads to cellular and enzymatic dysfunction with multiple deleterious effects including a decrease in cardiac output, hypotension and decreased binding of epinephrine to adrenergic receptors. Several physiologic mechanisms have developed which serve to correct plasma pH. The increase in plasma H^+ is sensed by the carotid bodies, which in turn stimulate the medullary respiratory center to increase minute ventilation and decrease pCO_2. The decreased plasma pH is also sensed by the kidneys, which respond by increasing H^+ secretion in the distal nephron. While respiratory compensation takes place very quickly renal response often require approximately 12–24 hours to complete. Expected compensation can be estimated by Winter's formula:

$$\text{Compensated } pCO_2 = 1.5 \times \left[HCO_3^- \right] + 8$$

If the pCO_2 is less than that predicted by Winter's formula, a secondary respiratory alkalosis is present. Similarly, a secondary respiratory acidosis would be indicated by a pCO_2 higher than that predicted by Winter's formula.

Treatment of metabolic acidosis is aimed at correction of the underlying cause. As such, accurate diagnosis of cause is essential. Debate exists as to whether or not correcting the acidemia is necessary. Current guidelines suggest correction of pH less than 7.10 until the underlying process can be corrected. Classically this

has been done with sodium bicarbonate to replace the whole body deficit of bicarbonate. However, the volume of distribution for bicarbonate varies significantly with the degree of acidemia from between 50% and 100% total body water volume, which makes accurate dosing difficult. Recently the use of sodium bicarbonate as an alkalinizing agent has come under scrutiny. Several studies have demonstrated a lack of benefit, and in some populations increased mortality with the use of sodium bicarbonate to treat acidosis. Numerous adverse physiologic effects can occur from infusing sodium bicarbonate, although no single cause seems to be at fault. Sodium bicarbonate is usually infused as a hypertonic solution. A 50 mL ampule containing 50 meq of sodium bicarbonate (1000 mmol/L) will raise the serum sodium concentration of a 70 kg person by about 1 meq/L and expand the ECF volume by about 250 mL. In addition, the infused bicarbonate will combine with plasma H^+ and dissociate into CO2 and H_2O. In patients with impaired ventilatory function this will lead to a respiratory acidosis. Alternative alkalinizing agents exist, such as the amino alcohol THAM. The buffering action of THAM does not generate CO_2, and has been used successfully for the treatment of various metabolic acidoses. It is excreted by the kidneys and should be dosed with caution in patients with renal insufficiency. Reported toxicities of THAM include hyperkalemia, hepatic necrosis in neonates, and respiratory depression secondary to an increase in pH and subsequent decrease in CNS CO_2.

Metabolic Alkalosis

Any process that leads to an accumulation of extracellular bicarbonate, via either decreased excretion of bicarbonate or increased loss of non-volatile acid, is termed a metabolic alkalosis. Non-volatile acids are lost either via the upper GI tract (vomiting, naso- or oro-gastric suctioning) or via increased urinary excretion. The kidney is able to excrete large amounts of bicarbonate in response to an alkalosis, thus maintenance of an alkalosis is due to an underlying disease state. These disease states can be grouped into either volume expanded or volume contracted states Table 14.4.

Table 14.4 Causes of metabolic alkalosis

Volume contracted state
Loss of gastric secretions: excessive NGT suctioning or vomiting
Loss of intestinal secretions: villous adenoma, congenital secretory diarrheas
Loop or thiazide diuretics
Sweat losses in cystic fibrosis
Volume expanded states
Primary mineralcorticoid excess
Liddle's syndrome

Alkalemia is associated with a variety of negative physiologic effects. The affinity of hemoglobin for oxygen is acutely increased, resulting in a right shift of the oxygen-hemoglobin dissociation curve. This leads to impaired oxygen delivery to peripheral tissues. The increased pH causes a decrease in the ionized concentration of calcium. This relative hypocalcemia can cause some of the classic clinical manifestations such as paresthesias and tetany. Other electrolyte abnormalities are seen, such as hypokalemia and hypomagnesemia. The compensation for a metabolic alkalosis is a decrease in ventilation with subsequent rise in pCO_2. Appropriate compensation can be calculated by the following equation:

$$pCO_2 = 0.9 \times \left[HCO_{3^-} \right] + 9$$

Once the underlying mechanism responsible for the alkalosis has been identified, treatment is aimed at correction of the metabolic abnormalities. Treatment of choice for the hypovolemic causes is IV rehydration, preferably with normal saline. Attention must be paid to potassium and calcium hemostasis so as not to worsen existing electrolyte abnormalities. If upper GI losses cannot be controlled, starting an H2 blocker or PPI may be warranted to decrease acid loss. Patients with volume expanded states would not benefit from further volume administration, instead acetazolamide can be used to increase renal bicarbonate wasting. Attention must be paid to serum potassium concentrations if acetazolamide is used, as renal potassium wasting also increases. In states of

mineralcorticoid excess, spironolactone can be used to antagonize the effects of aldosterone. Spironolactone is considered a potassium sparing diuretic and so the potential for hypokalemia is less than with acetazolamide. Infusions of HCl have been used successfully to correct pH in cases of severe, refractory metabolic alkalosis. These infusions must be given slowly via central line with frequent lab measurements to avoid creating an iatrogenic metabolic acidosis.

Respiratory Abnormalities

Respiratory Acidosis

Any process that leads to an increase in pCO_2 due to an imbalance in alveolar minute ventilation and carbon dioxide production is termed respiratory acidosis. A respiratory acidosis may be caused by increased production of CO_2 with insufficient respiratory compensation, or decreased minute ventilation with normal production of CO_2. A third cause unique to the ventilated patient is rebreathing of exhaled CO_2 in the ventilator circuit. Respiratory acidosis is classified as either acute or chronic which can be determined by a large extend by the degree of compensation. As previously stated, respiratory abnormalities are compensated via metabolic mechanisms. In the case of a respiratory acidosis, the compensation is by increased renal HCO_3^- reabsorption. During the acute phase of a respiratory acidosis, the kidneys are able to raise serum HCO_3^- by approximately 1 meq/L for each 10 mmHg rise in pCO_2 above 40. Over time, the kidneys are better able to compensate and can raise plasma HCO_3^- by approximately 3.5 meq/L for every 10 mmHg rise in pCO_2. Serum HCO_3^- levels not consistent with expected levels of compensation indicate concurrent metabolic abnormalities.

Elevated CO_2 is associated with numerous systemic effects across multiple organ systems. Carbon dioxide is a direct myocardial depressant and acts directly on the vasculature to decrease overall tone. This is offset by increased sympathetic output, which

results in elevated heart rate and net increase in cardiac output. Hypercapnia results in a rightward shift of the oxygen-hemoglobin dissociation curve and facilitates oxygen unloading in peripheral tissues. In the central nervous system, hypercapnia results in cerebral vasodilation, which increases cerebral blood flow and ICP. This can be an important consideration in patients with preexisting elevated ICP or space occupying lesions. In the lungs, hypercapnia results in vasoconstriction and dilation of the small airways. In cases of severe hypercapnia ($pCO_2 > 90$ mmHg), carbon dioxide displaces oxygen in the alveoli resulting in hypoxia, which can be fatal unless FiO_2 is increased.

As with the metabolic abnormalities, treatment of a respiratory acidosis should be aimed at the underlying cause. Occasionally intubation and mechanical ventilation are necessary as temporizing measures until the underlying cause has been reversed. Care must be exercised in patients with long standing respiratory acidosis with metabolic compensation. Increased ventilation and CO_2 elimination in these patients may lead to a relative hypocapnea and resultant metabolic alkalosis.

Respiratory Alkalosis

Any process that leads to a reduction in pCO_2, from increased alveolar minute ventilation relative to production, will result in a respiratory alkalosis. Most often this is secondary to increased alveolar minute ventilation but rarely may be due to decreased production of carbon dioxide with unchanged minute ventilation, such as the hypothermic mechanically ventilated patient. Similarly to a respiratory acidosis, a respiratory alkalosis can be classified as either acute or chronic given the degree of metabolic compensation. In an acute respiratory alkalosis, every 10 mmHg drop in pCO_2 from 40 is accompanied by a 2 meq/L decrease in serum bicarbonate. A chronic respiratory alkalosis is expected to be compensated by a 5 meq/L decrease in serum bicarbonate for every 10 mmHg drop in pCO_2 from 40. This metabolic compensation is accomplished by decreased renal reabsorption of bicarbonate from the proximal renal tubule and an increase in ammonia

excretion. This renal compensation begins within 2 hours of a prolonged alkalosis, but is not maximally effective for 2–3 days.

The physiologic effects of decreased pCO_2 inversely correlate to those of an increase in pCO_2. Perhaps the most clinically significant effect of decreased pCO_2 is its effect on cerebral vascular tone. A decrease in pCO_2 results in cerebral vasoconstriction and a subsequent reduction in cerebral blood volume and ICP. In patients with TBI, CBF changes approximately by 3% for each millimeter of mercury change in $PaCO_2$ over the range of 20–60 mmHg. This can cause a significant reduction in ICP, as a 0.5 mL change in CBF is associated with a 1 mmHg change in ICP. This effect is transient, though, as cerebral vasculature resets to the elevated CO_2. Current consensus does not recommend iatrogenic lowering of $PaCO_2$ lower than 30 mmHg due to the increased risk of cerebral ischemia and lack of demonstrable clinical benefit. In addition to changes in CBF, other metabolic derangements occur as well. The decreased serum H^+ leads to translocation of H^+ from the intracellular to the extracellular space with a concurrent translocation of K^+ from extracellular to intracellular space. This relative intracellular alkalosis causes activation of the enzyme phosophofructokinase and increase in glycolysis with generation of H^+.

Treatment of the alkalosis is aimed at reversal of the underlying cause. In rare cases intubation and controlled mechanical ventilation may be necessary. However, in cases of chronic metabolic alkalosis correction must be done in a controlled manner allowing for renal compensation, lest a metabolic acidosis result from rapid correction.

Evaluating Multiple Disorders

It is not uncommon for multiple acid-base abnormalities to coexist in the same patient. Diagnosis of these disorders requires knowledge of not only the expected direction, but also the expected magnitude of compensatory responses. The interplay of these complex interactions can be explained numerically as follows: in the absence of other metabolic derangements, the fall in

the serum HCO_3 should equal the rise in the serum anion gap. We refer to the difference between changes in serum anion gap and serum HCO_3 as the "Delta Gap." There have been multiple ways to approach this calculation, but one simple way is as follows:

$$\text{Delta Gap} = (\text{Anion Gap}) - (\text{Serum}HCO_3),$$
$$\text{where Anion Gap} = AG_{\text{measured}} - AG_{\text{normal (12)}}$$
$$\text{and Serum}HCO_3 = 24 - HCO_{3\ \text{measured}}.$$

If the Delta Gap is significantly positive (> +6), a concurrent metabolic alkalosis is usually present because the rise in anion gap is more than the fall in HCO_3. Conversely, if the Delta Gap is significantly negative (< −6), then a second acidosis is present because the rise in anion gap is less than the fall in HCO_3. This is usually a hyperchloremic metabolic acidosis.

For example, let's say a blood gas shows an anion gap of 25 and a serum HCO_3 of 18. The Δ Anion Gap is 13 (25–12 = 13) and the Δ Serum HCO_3 is 6 (24–18 = 6), thus the delta gap is 7 (13–6 = 7). Therefore, for this patient we know in addition to the high anion gap metabolic acidosis, a concurrent metabolic alkalosis exists, as the serum HCO_3 would be expected to be lower if the alkalosis were not present.

Case Study

A 34-year-old man is posted for emergent exploratory laparotomy. He presented to the emergency department complaining of abdominal pain for the past 18 h following a 1-day history of diarrhea. His past medical history is significant for insulin-dependent (Type 1) diabetes, ethanol abuse, and poor medical adherence. On physical exam he has dry mucous membranes, a fruity odor to his breath, and has slurred speech. He is guarding his abdomen. Vital signs are: HR: 120, BP: 101/74, RR: 20, SpO_2: 99% on room air, Temp: 101.4 F.

What laboratory evaluation would you order preoperatively? Why?

Given the history of diabetes, poor medical adherence, and 2 days of fluid losses and likely little or no oral intake, it is almost certain that he has some metabolic derangements. You should order a metabolic panel, a complete blood count, and probably a serum or urine ketone test. If you suspect an acid/base disturbance, a blood gas is also needed.

Laboratory values are returned and are shown below. What metabolic disturbance is likely responsible for these values?

- *Sodium: 134 mmol/L*
- *Chloride: 110 mmol/L*
- *Potassium: 4 mmol/L*
- *Bicarbonate: 13 mmol/L*
- *BUN: 36 mg/dL*
- *Creatinine: 1.10 mg/dL*
- *Glucose: 284 mg/dL*
- *WBC: 21 × 10^3/mcL*
- *Hemoglobin: 16 g/dL*
- *PCV: 48%*
- *Platelet: 200 × 10^3/mcL*
- *MCV: 104 fL*
- *RDW: 16%*
- *Serum Beta-hydroxybutyrate: 4 mg/dL*
- *ABG: pH 7.21/$pCO_2$28 mmHg/$pO_2$99 mmHg/$HCO_2$13 mmol/L*

This patient is in diabetic ketoacidosis (DKA) as confirmed by his hyperglycemia, serum ketones, and acidemia present on ABG. DKA usually presents in patients with IDDM who have a concurrent illness and/or poor insulin regimen adherence.

What acid base abnormalities are present? Is there more than one? Are they appropriately compensated?

The low pH, low bicarbonate and low pCO_2 point to a metabolic acidosis with respiratory compensation. To evaluate the etiology of the metabolic acidosis, we must first calculate the ion gap.

$$\left(\text{Serum } Na^+ + \text{Serum } K^+\right) - \left(\text{Serum } HCO_{3^-} + \text{Serum } Cl^-\right)$$
$$= \left(134 + 4\right) - - \left(13 + 110\right) = 15$$

As the normal anion gap is 8–12, there is a high anion gap metabolic acidosis present. To determine whether or not we have appropriate compensation, we will use Winter's formula to calculate what his pCO_2 should be.

$$pCO_2 = 1.5 \times \left[HCO_{3^-}\right] + 8 = \left(1.5 \times 13\right) + 8 = 27.5$$

This is very close to the measured value of 28, so appropriate respiratory compensation has occurred. To determine whether or not multiple acid base abnormalities are present, we must calculate the delta-gap for this patient.

$$\text{Delta Gap} = \left(\text{ Anion Gap}\right) - \left(\text{ Serum}HCO_3\right)$$

$$\text{Anion Gap} = AG_{\text{measured}} - AG_{\text{normal (12)}}$$
$$\text{and} \quad \text{Serum } HCO_3 = 24 - HCO_{3\text{ measured}}$$

$$DG = \left(15 - 12\right) - \left(24 - 13\right) = -8$$

If a single acid base disturbance is present, the delta gap should be 0 +/− 6. The delta gap in this case is significantly negative, which is to say we would expect the change in the anion gap to be larger given the change in the serum bicarbonate. Consequently, in addition to a high-anion gap metabolic acidosis, we can also conclude that a non-anion gap metabolic acidosis is present.

What is the likely etiology of the second metabolic acidosis?

The patient demonstrates a combined high-anion gap and non-anion gap metabolic acidosis with appropriate respiratory compensation. His high anion gap acidosis is likely secondary to his DKA, and his non-anion gap acidosis is likely secondary to his diarrhea. In diarrhea, bicarbonate is lost and acidemia occurs; depending on the fluids administered subsequently, chloride may also increase ("hyperchloremic acidosis").

He is started on an insulin infusion and taken to the OR. 15 min into the case he has received 500 mL of normal saline, and the operation is under way. You look up at the ECG and notice ST-segment depression and flattening of the T wave. What is the most likely diagnosis and appropriate treatment?

The patient has most likely developed hypokalemia, which has manifest as ST segment depression and T wave flattening. U waves may also be seen in cases of severe hypokalemia. Patients with DKA may present with normal serum potassium, however they often have a total body potassium deficit. This is due to the transcellular shift of potassium caused by the acidosis and resultant osmotic diuresis from the elevated plasma glucose. This deficit is revealed with the re-introduction of insulin, which stimulates the membrane bound Na^+/K^+-ATPase and causes an intracellular shift of potassium. Treatment is hydration (ideally prior to insulin administration) and repletion of potassium; in severe cases it may be necessary to temporarily pause the insulin infusion.

Halfway through the case, a serum osmolality value is reported by the lab at 340 mosmol/kg. How do you interpret this result? Is this consistent with the calculated serum osmolality?

Calculated serum osmolality is given by the equation:

$$\text{Serum Osmolality} = \left(\text{Serum } Na^+ \times 2\right) + \left(\text{Serum glucose} / 18\right) + \left(\text{Serum BUN} / 2.8\right)$$

In this case: (134 ∗ 2) + (284/18) + (36/2.8) = 297.

Therefore, we can say that an osmolal gap exists in the amount of 43 mosm/kg. An osmolar gap can occur by one of two mechanisms: either an osmotically active solute other than electrolytes, glucose or urea is present, or pseudohyponatremia. In the case of an unmeasured osmotically active solute, the serum osmolality is actually increased and the measured value is the correct value. In the case of pseudohyponatremia, the measured osmolality is spuriously reduced by the presence of increased lipids or proteins (such as triglycerides or immunoglobulins), which reduce the fraction of serum that is water. This represents a measurement artifact and the calculated serum osmolality is the correct osmolality. Osmolar gaps are important to calculate, particularly in the case of high anion gap metabolic acidosis, as potential causes include toxic alcohols and glycols, which will cause a serum osmolar gap. The most common cause is acute ethanol ingestion, the contribution of which can be estimated by dividing the serum ethanol concentration by 3.7.

You recall that the patient has a history of ethanol abuse and had slurred speech on initial presentation. Using the osmolality you calculated and measured, how would you estimate his blood alcohol concentration?

Assuming the osmolar gap is caused by ethanol, we would multiply the gap by the contribution of ethanol to the osmolality, or 3.7: 43 * 3.7 = 159 mg/dL which is the same as a BAC of 0.16 (twice the U.S. legal limit for drivers).

A colonic perforation is found, and a subtotal colectomy is performed with end colostomy placement. The abdomen is closed and the patient is transported to the surgical ICU. On arrival to the ICU, your most recent BMP is as follows:

- *Sodium: 140 mmol/L*
- *Chloride: 108 mmol/L*

- *Potassium: 3.5 mmol/L*
- *Bicarbonate: 21 mmol/L*
- *BUN: 42 mg/dL*
- *Creatinine: 1.3 mg/dL*
- *Glucose: 120 mg/dL*

Noting the glucose of 120, the nurse asks if she can discontinue the insulin infusion. What should your response be?

No! When treating DKA insulin administration should be continued until the anion gap is normal, which represents a resolution of ketoacidosis. In this case the anion gap is still 14.5, so insulin therapy should be continued, with IV dextrose administration to prevent hypoglycemia. Usually you would want to start a dextrose infusion when your glucose level reached 200 mg/dL.

Suggested Reading

1. Fairley J, Glassford NJ, Zhang L, Bellomo R (2015) Magnesium status and magnesium therapy in critically ill patients: a systematic review. J Crit Care. 30(6):1349–1358
2. Gauthier PM, Szerlip HM (2002) Metabolic acidosis in the intensive care unit. Crit Care Clin 18(2):289–308
3. Gehlbach BK, Schmidt GA (2004) Bench-to-bedside review: treating acid-base abnormalities in the intensive care unit—the role of buffers. Crit Care 8:259–265
4. Kelly A, Levine M (2013) (2011) Hypocalcemia in the critically ill patient. J Intens Care Med 28(3):166–177
5. Kraft MD, Btaiche IF, Sacks GS, Kudsk KA (2005) Treatment of electrolyte disorders in adult patients in the intensive care unit. Am J Health Syst Pharm. 62(16):1663–1682. https://doi.org/10.2146/ajhp040300
6. Kraut JA, Madias NE (2007) Serum anion gap: its uses and limitations in clinical medicine. Clin J Am Soc Nephrol 2(1):162–174
7. Lindner G, Funk GC (2013) Hypernatremia in critically ill patients. J Crit Care 28(2):216.e11–216.e2.16E20
8. McKnight CL, Newberry C, Sarav M, Martindale R, Hurt R, Daley B (2019) Refeeding syndrome in the critically ill: a literature review and clinician's guide. *Curr Gastroenterol Rep*. 21(11):58
9. Sabatini S, Kurtzman NA (2009) Bicarbonate therapy severe metabolic acidosis. JASN 20(4):692–695

10. Sterns RH, Hix JK, Silver SM (2013) Management of hyponatremia in the ICU. Chest 144(2):672–679. https://doi.org/10.1378/chest.12-2600
11. Williamson JC (1995) Acid-base disorders: classification and management strategies. Am Fam Physician 52(2):584–590
12. Wooten EW (2004) Science review: quantitative acid-base physiology using the Stewart model. Crit Care 8(6):448–452
13. Wrenn K (1990) The delta (delta) gap: an approach to mixed acid-base disorders. Ann Emerg Med 19(11):1310–1313

Fluids and Transfusion Therapy

15

Sarah Jane Bost, Roger L. Royster, Adam Kingeter, and Matthew D. McEvoy

Educational Objectives

1. Understand physiologic fluid compartments
2. Be able to describe volume status and estimate fluid requirements
3. Describe options available for crystalloid and colloid fluid resuscitation
4. Describe options for blood and blood component therapy
5. Understand risks and benefits of various transfusion strategies

S. J. Bost (✉) · R. L. Royster
Department of Anesthesiology, Wake Forest School of Medicine, Winston-Salem, NC, USA
e-mail: sbost@wakehealth.edu; rroyster@wakehealth.edu

A. Kingeter · M. D. McEvoy
Department of Anesthesiology, Vanderbilt University Medical Center, Nashville, TN, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_15

Fluid Therapy

Body Fluid Compartments

Water represents 60% of the total body weight of the average adult, and is divided into two major compartments: intracellular and extracellular. The two compartments are separated by the semi-permeable cell membranes that enclose all cell types in the body. Of the two compartments, intracellular is by far the larger and constitutes 66% of total body water (TBW) with the remaining 33% residing in the extracellular compartment. The volume of the extracellular compartment is composed of the interstitial space (~75%) and intravascular space (~25%). The interstitial compartment is the space between the capillaries and the cells where interstitial fluid supports the matrix and cells therein. The intravascular space is defined as the volume contained within the lumen of the body's vasculature, including arteries, veins and capillaries. Eighty-five percent of the volume in the intravascular space is contained in the venous system, and the remaining 15% is contained in the arterial system. The total volume of the arterial and venous system is referred to as "circulating blood volume." The blood volume contains both a cellular and non-cellular component. The cellular component is composed of red blood cells, white blood cells, and platelets, and the non-cellular component is referred to as plasma. Transcellular fluid is the smallest compartment of the ECF and is defined as the portion of TBW contained within the epithelial-lined spaces (eg – synovial fluid, cerebrospinal fluid, urine, etc.) See Fig. 15.1 for the visual breakdown of the fluid compartments.

Water travels freely across cellular membranes and between the intravascular and interstitial spaces. The distribution of water is dependent on the interplay of two main forces: hydrostatic and osmotic. Hydrostatic forces are generated by the heart when it contracts, and forces blood through the vasculature. Hydrostatic forces can be thought of as pressure that can be measured inside

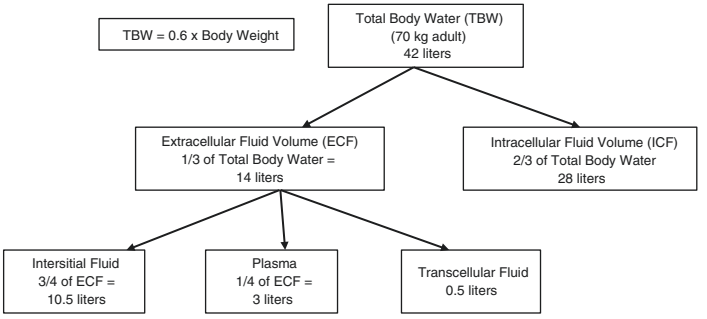


Fig. 15.1 Body Fluid Compartments of a 70-kg Adult

and outside the vasculature, such as blood pressure and compartment pressures. Osmotic forces are generated by the differential distribution of proteins in the various compartments; the higher the protein concentration in a given compartment, the greater the force drawing water into that compartment through diffusion. Protein concentrations are higher in the intracellular compartment and the intravascular space, promoting the movement of water into these areas. Hydrostatic forces are greater than osmotic forces in the arterial side of the intravascular space, which forces water out of the intravascular space and into the interstitial space. However, osmotic forces are greater than hydrostatic forces on the venous side of the intravascular space resulting in water being drawn back into the intravascular space.

In addition to differences in protein content, the electrolyte composition of the extracellular and intracellular compartments varies greatly. The extracellular fluid has a relatively high concentration of sodium and bicarbonate, while the intracellular fluid has a very high concentration of potassium and magnesium. These concentration gradients are maintained by active transport transmembrane pumps, and are essential for the proper functioning of many cellular processes. Electrolyte balance is further discussed in another chapter.

Perioperative Fluid Balance

Significant water losses occur daily via a variety of routes. As water leaves the body, it often takes with it electrolytes and proteins. The electrolyte and protein composition of these losses is highly variable and must be replaced in order to maintain homeostasis and continue normal physiologic processes. In addition to physiologic fluid losses, pathologic losses (e.g., hemorrhage, diarrhea, or vomiting) and losses due to certain disease states and medications (e.g., poorly controlled diabetes with osmotic diuresis from high plasma glucose concentrations) must be considered when assessing a patient's volume status. Therefore, a thorough history and physical exam are vital to determining a patient's volume status and resuscitation requirements. Key elements to be covered in the pre-operative history to assess volume status include but are not limited to: hours NPO, recent diarrhea or vomiting, diuretic use, presence of orthopnea or presence of leg swelling. Physical exam findings suggesting of a fluid deficit include flattened neck veins, tachycardia, dry mucous membranes, and low blood pressure. Physical exam findings suggestive of volume overload include full or distended neck veins, normal to high blood pressure, pitting edema in bilateral lower extremities and auscultation of rales or crackles during inspiration. Once the volume status has been determined, attention can then be turned to selection of resuscitation fluid and administration. The traditional approach to fluid management involves calculating a patient's preoperative fluid loses (NPO duration), ongoing losses during surgery (maintainance rate calculation), and anticipated surgical and "interstitial" fluid losses (based on patient's weight and anticipated tissue trauma).

Maintenance fluid requirements can be estimated according to patient body weight using the "4-2-1" rule as follows:

0–10 kg: 4 mL/kg/hr
11–20 kg: 2 mL/kg/hr
>20 kg: 1 mL/kg/hr

For example, maintenance fluid rate for a 70 kg man can be calculated as follows:

40 mL/hr for the first 10 kg of body weight, 20 mL/hr for the next 10 kg, and 1 mL/hr for the remaining 50 kg yields an additional 50 mL/hr. Adding these together we get a total of 110 mL/hr maintenance fluid rate. A short cut applying to patients weighing more than 20 kg is to add 40 to the patient's weight in kg to obtain maintenance fluid requirement in mL/hr (e.g., 70 kg + 40 = 110 mL/hr).

Then one must take into account resuscitation requirements for the ongoing surgical losses (e.g., estimated blood loss [EBL]) and the ongoing "interstitial" losses based on the patient's weight and surgical tissue trauma, as follows [1]:

Minimal tissue trauma (e.g., herniorrhaphy): 2–4 mL/kg/hr
Moderate tissue trauma (e.g., cholecystectomy): 4–6 mL/kg/hr
Severe tissue trauma (e.g., bowel resection): 6–8 mL/kg/hr

Typically, 3 mL of crystalloid is given for every 1 mL of blood loss, and 1 mL of colloid/PRBC is given per 1 mL of blood loss.

While these calculations serve as a good estimate and a place to start, a more modern approach to fluid management is based on goal-directed therapy, in which interventions are made to affect a meaningful clinical variable (e.g. hemodynamic improvement or optimized stroke volume.) This newer style of fluid therapy is based on the reality that fluids are potentially harmful medications that should only be given when they will be expected to produce some benefit [2].

Selection of Resuscitative Fluid

Non-blood product fluid replacement options can be grouped as either crystalloid or colloid. Crystalloid solutions contain water, electrolytes, and occasionally dextrose. Colloid solutions contain water, electrolytes, and large-molecular weight substances that, in theory, remain in the intravascular space for several hours and

increase osmotic forces drawing water into the vasculature. Colloids and crystalloids both are devoid of clotting factors and cellular blood components. Large volume resuscitation with either crystalloid or colloid will cause dilution of blood cellular components and coagulation factors leading eventually to coagulopathy and impaired oxygen delivery. As such, attention must be paid to type of fluid selected and amount of resuscitation needed. More importantly, the electrolyte and acid-base content of the fluid is recently being shown to have profound effects on end-organ dysfunction and possibly mortality in the perioperative period.

Crystalloids

Crystalloid solutions may be classified as hypertonic, hypotonic or isotonic relative to normal plasma osmolarity. Crystalloid solutions distribute freely between intravascular and interstitial compartments, and as such 25–33% of the intravenously administered crystalloid can be estimated to remain intravascular.

Isotonic solutions include normal saline, so-called "balanced salt solutions," and solutions containing 5% dextrose. Normal saline (NS, 0.9% NaCl) contains equal parts sodium and chloride, both of which are higher than physiologically found in plasma. Normal saline has no buffer or other electrolytes, and relative to plasma is slightly hypertonic (308 Osm) and very acidic (pH ~5.0). "Balanced salt solutions" include Plasma-Lyte, Lactated Ringer's (LR) and Normosol. These solutions contain electrolyte compositions similar to those found in plasma, and are buffered to varying degrees. Relative to plasma they tend to be more isotonic and of a more physiologic pH. Dextrose containing solutions typically contain either 5% or 10% dextrose, and may or may not contain other electrolytes. In the absence of other electrolytes, dextrose containing solutions are functionally equivalent to free water because the dextrose is metabolized leaving behind only free water. Free water itself cannot be administered intravenously; the hypotonicity would result in lysis of red cells. Dextrose is added to increase the osmolality; however, the solution is not

buffered and is acidotic relative to plasma pH. Hypertonic solutions contain high concentrations of sodium and chloride and typically range from 3–5% NaCl. Similar to NS, they do not contain other electrolytes or buffers. They are significantly hypertonic relative to plasma and are typically administered in lower volumes than isotonic or hypotonic solutions.

Selection of the appropriate crystalloid depends on the clinical situation and is based on crystalloid electrolyte composition, pH and osmolality. For example, in neurosurgical cases NS may be the preferred crystalloid, as NS is hypertonic relative to plasma and helps limit cerebral edema, whereas LR has 100 mL of free water per liter as compared to normal plasma osmolarity. For example, in craniotomies for resection of large brain tumors, NS is the preferred crystalloid, as NS is hypertonic relative to plasma and helps reduce cerebral edema, whereas LR has 100 mL of free water per liter as compared to normal plasma osmolarity which could further exacerbate cerebral edema. LR also contains calcium and potassium and can cause a metabolic alkalosis secondary to metabolism of lactate (which produces bicarbonate). Transfusion of blood products typically occurs concurrently with crystalloid to help decrease viscosity. LR is relatively contraindicated for this purpose, as the calcium present in LR binds to citrate present in blood products and can occlude IV lines.

Classically, NS has been the crystalloid of choice for virtually all clinical scenarios. However, a growing body of evidence is beginning to demonstrate that it may not be so "normal" after all, and can in fact lead to significant negative clinical outcomes. Hyperchloremic metabolic acidosis can occur with the administration of large volumes of NS and NS-balanced fluids, such as some albumin 5% solutions. When compared to NS, balanced salt solutions have been associated with a large variety of beneficial outcomes in the perioperative setting including: greater urinary output, decreased nausea and vomiting in elderly surgical patients, lower incidence of metabolic acidosis, and decreased use of blood products [3–5]. NS has been preferred for patients with renal failure due to the theoretical concern that balanced salt solutions would lead to hyperkalemia. However, a prospective randomized controlled trial assigning 0.9% NS or LR for intraoperative use

during kidney transplantation found that 31% of patients receiving NS developed potassium concentrations >6 mEq/L vs. 0% of patients receiving LR [6]. Although a study of this size does not warrant a change in clinical practice, it does challenge the long held belief that saline is superior to balanced salt solutions in patients with renal failure.

Colloid Solutions

Colloid solutions use either a complex sugar or protein suspended in an electrolyte solution and can be grouped accordingly. Multiple preparations of each type of colloid exist and vary according to electrolyte composition and concentration of osmotically active substance. Compared to crystalloids, colloids create a greater amount of intravascular volume expansion if equal volumes are infused. Compared to crystalloids, colloids on average are significantly more expensive.

Albumin is the principal protein based colloid, and is available as either 5% or 25% solution suspended in saline solution. The electrolyte composition of albumin is solely sodium and chloride, with 145 mEq/L of each. Colloid albumin is derived from large pools of human plasma that have been processed and sterilized. The intravascular half-life of albumin is highly variable based on capillary basement membrane integrity and ranges from 3 to 16 h [7]. Severe, life-threatening anaphylactic reactions to albumin have been reported, but these cases appear to be extremely rare [8]. Five percent albumin has a colloid oncotic pressure of approximately 20 mmHg, which is close to physiologic plasma oncotic pressure, while 25% albumin has an oncotic pressure of approximately 100 mmHg. Compared to other colloids, albumin is significantly more expensive.

Complex sugar-based colloids include the Dextrans and Hydroxy-ethyl starch (HES). Dextran solutions contained polymerized glucose which is synthesized by certain bacteria. Two preparations of dextran exist differentiated by mean molecular weight: 40 and 70 kDa. Dextran 70 is typically administered in a 6% solu-

tion with saline for use in volume expansion. Dextran 40 is used mainly to improve microcirculatory flow across microvascular anastomosis and seldom is used for volume expansion. Significant allergic responses occur to dextrans in about 1 of every 3300 administrations. Other side effects associated with dextrans include decreased platelet adhesiveness, decreased levels of factor VIII and increased bleeding time [9]. Dextran molecules bind to erythrocyte cell membranes and interfere with blood typing and cross matching. Dextrans are excreted primarily by the kidneys with a plasma half-life ranging from 6 to 12 h. HES solutions are classified according to concentration (6% vs. 10%), average molecular weight in kDa, and molar substitution. Molar substitution refers to the modification of the original polysaccharide by the addition of hydroxyethyl groups. Higher degrees of molar substitution are associated with greater resistance to degradation by plasma amylase, and therefore longer plasma half-lives. HES concentrations typically result in a volume expansion similar to that seen with 5% albumin, and lasts 8–12 h. Recently the safety of HES solutions has been brought into question. Most of the early work on HES solutions was found to be fraudulent, and a recent meta-analysis found that HES was associated with a significantly increased risk of mortality and renal failure [10]. In addition to the well-documented deleterious effects of HES on renal function, HES solutions have also been shown to interfere with vWF, factor VIII, and platelet function [11]. Newer formulations of HES are currently in clinical trials and their safety remains to be demonstrated.

Crystalloid Versus Colloid

Much debate has existed as to which resuscitative fluid is superior: crystalloid or colloid. Crystalloid proponents are quick to point out the significantly higher cost of colloids and their rarely associated allergic and hematologic adverse effects. The largest randomized control trial comparing normal saline to 5% albumin, the Saline versus Albumin Fluid Evaluation (SAFE) trial [12],

involved nearly 7000 ICU patients. No difference was noted between saline and albumin in terms of overall mortality and morbidity. But other outcomes, such as the Postoperative Vision Loss Study Group [13], have shown improved outcomes when a higher colloid as a percentage of nonblood replacement is administered. Thus, the debate continues.

Transfusion Therapy and Blood Components

Oxygen is carried in the blood in two different forms: dissolved and bound to hemoglobin (Hgb).The amount of dissolved oxygen that is being delivered can be calculated by knowing the partial pressure of oxygen multiplied by the solubility coefficient of oxygen. This number is added to the Hgb concentration multiplied by the oxygen saturation of Hgb and the amount of oxygen carried on one gram of Hgb as follows:

$$\begin{aligned}\text{Oxygen Delivery} &= \text{Hgb} \times \left(\%\text{Sat} \times 1.34\,\text{mL / gram Hgb}\right) \\ &\quad + \text{PaO}_2 \times \left(0.0031\right) \text{or} 15\,\text{g} \times 100\% \times 1.34 \\ &\quad + 100\,\text{mmHg} \times 0.0031 \\ &\quad = 20.4\,\text{mL O}_2\,/100\,\text{mL blood}\end{aligned}$$

Oxygen delivery to the tissues is primarily composed of oxygen bound to Hgb and is reduced as red blood cells are lost. A coagulopathy may develop in massive transfusions as coagulation factors and platelets are consumed or diluted by appropriate fluid resuscitation. Replacement of red blood cells and coagulation factors is accomplished by administration of blood and blood components. To obtain blood components, whole blood is collected from donors and separated into a cellular and liquid phase by fractionation. Packed red blood cells and platelets are then further isolated from the cellular component, while the liquid component yields plasma and cryoprecipitate. These four components are the most commonly used blood transfusion products.

Blood Groups and Compatibility

There are more than 300 different antigens present on the surface of red blood cells. These have been separated into more than 20 different antigen systems which are used to classify blood groups. The two most clinically important are the ABO system and the Rh system. ABO typing is determined by the presence or absence of A or B surface antigens. Type A blood has the A surface antigen, type B blood has the B surface antigen, type AB blood has both A and B surface antigens, and type O blood has neither A nor B surface antigen present. Individuals almost universally have IgM antibodies present in their serum against the missing antigen; thus individuals with type A blood have antibodies against B surface antigens and vice versa. The Rh system classifies individuals by the presence or absence of the D Rhesus antigen as Rh-positive or Rh-negative, respectively. In contrast to the ABO antigens, antibodies against the Rh antigen do not typically naturally occur, and develop after Rh-negative individuals are exposed to Rh-positive blood. The probability of developing anti-D IgG antibodies after a single exposure to the Rh antigen is 50–70%. Administration of Rh immunoglobulin (Rhogam) to Rh- negative individuals can protect against Rh sensitization following exposure, and is particularly important in Rh-negative mothers with Rh-positive fetuses. Transfusion of incompatible blood leads to reaction of recipient antibodies against donor antigens and leads to compliment activation and intracellular hemolysis. These reactions can be catastrophic, and as such blood products are screened for the type of antigen present prior to transfusion.

Red Blood Cells

Red blood cells are separated from donor whole blood, mixed with an anticoagulant (usually citrate) and can be stored up to 42 days at 1–6 °C. The hematocrit of stored blood is between 70% and 80%, and 1 unit of packed red cells is expected to raise the Hgb by 1 g/dL and the hematocrit (HCT) by 3% in non-bleeding,

average sized adults. Blood bank stored red cells have low levels of 2,3-DPG which results in a leftward shift of their oxygen dissociation curve. This effect is temporary, as 2,3-DPG levels return to normal within 24 h of transfusion. Blood banked red cells also leak potassium, and although each unit supplies a relatively small amount of potassium, massive transfusion may result in clinically significant hyperkalemia.

The appropriate Hgb at which to transfuse has been the subject of debate. Multiple studies have demonstrated that a restrictive strategy (target Hgb 7–9 g/dL) is superior to a liberal strategy (target Hgb 10–12) in terms of lower mortality and lower rates of complication. However, subset analyses of these trials show that in older patients and patients with cardiovascular disease a liberal strategy may be more appropriate. The ultimate goal of transfusion therapy is to maintain optimal oxygen delivery, and as such transfusions at higher Hgb concentrations may be indicated if signs of end organ ischemia manifest. Transfusion thresholds may be set preoperatively, and the allowable blood loss (ABL) can be estimated with the following equation:

$$\mathrm{ABL} = \mathrm{EBV} \times \left(\mathrm{Hct_i} - \mathrm{Hct_t} / \mathrm{Hct_i} \right)$$

where EBV represents estimated blood volume, $\mathrm{Hct_i}$ is initial hematocrit and $\mathrm{Hct_t}$ is threshold hematocrit for transfusion. EBV is estimated to be 70 mL/kg for adults.

Thus in a healthy, 70-kg adult with Hgb of 15 g/dL and HCT of 45, and assuming a safe Hgb is 7 gm/dL or HCT of 21:

$$\mathrm{ABL} = 4900\,\mathrm{mL} \times \left(45 - 21 / 45 \right) = 2613\,\mathrm{mL}$$

Continued large volume blood loss results in the need for massive transfusion. Massive transfusion is defined as transfusion of blood components in excess of 1 blood volume within a 24-hr period, which is usually the equivalent of 10 units of red cells. Massive blood loss also requires the replacement of plasma and platelets. Experience in civilian and military trauma has shown better outcomes if the ratio between products is equal. This 1:1 (red cell:plasma) ratio with one phresis unit of platelets (equivalent to

half a blood volume) given for each 6 units of red cells mimics whole blood and is associated with improved outcomes. Now many hospitals are giving several units of whole blood when available initially to trauma patients prior to administering red cells and blood components.

Plasma

Fresh frozen plasma (FFP) is isolated from whole blood and frozen within 8 h of donation to prevent inactivation of labile coagulation factors. Because it may be difficult to freeze plasma within 8 h due to the distance from collection centers to blood bank facilities, it is acceptable to freeze plasma within 24 h of collection (FP24). Both FFP and FP24 may be stored frozen for up to 1 year. Thawing of Frozen Plasma (FP) is usually accomplished by soaking in a 37 °C water bath for 30–45 min. Once thawed, FP can be refrigerated for a maximum of 24 h, but can still be used as thawed plasma for up to 5 days. FP contains physiologic concentrations of coagulation factors, complement, albumin and globulins. ABO-compatibility is ideal, but not mandatory as it is for red cell transfusion.

Liquid plasma (never frozen) has a theoretical shelf life as long as red cells when stored at 1–6 °C. Liquid plasma appears as effective at restoring coagulation factors as 5-day-old thawed plasma. However, factor levels drop fairly quickly after 14 days. Liquid plasma is indicated only for use in massive blood transfusions and can be given quickly because of no need for thawing.

Platelets

Platelets are isolated from donor whole blood and suspended in approximately 50 mL of plasma. Individual platelet units can be stored for up to 5 days at room temperature. Platelets can be pooled from multiple donors prior to administration, but apheresis is now more typically performed with one donor. The usual number of units pooled or pheresed is 6, and can be expected to raise

the platelet count by 30,000–60,000/μL in an average sized, non-bleeding adult. ABO and Rh compatibility, although desirable, is not necessary for transfusion. However, transfusion of Rh-positive platelets may sensitize an Rh-negative individual due to small concentrations of red cells present in platelet units. The lifespan of transfused platelets is between 1 and 7 days in the absence of active bleeding or immune-mediated destruction. Guidelines for transfusion of platelets are not hard and fast, and continue to change. Patients with platelet counts <50,000/μL are at increased risk for significant surgical hemorrhage. Most guidelines propose prophylactic platelet transfusions for counts <10,000/μL in all patients. Platelet transfusions are of little benefit, and may be harmful, in cases of thrombocytopenia due to immunologic processes such as TTP and ITP. If given quickly or through an in line warmer, platelet activation and histamine release can occur leading to hypotension. Because platelets are stored at room temperature they have an increased risk for infection.

Cryoprecipitate

Cryoprecipitate (Cryo) is produced by centrifuging frozen plasma that has been thawed to 6 °C and re-suspending the precipitated proteins in 15 mL of supernatant plasma. Similarly to platelets, several units are pooled prior to dosing, and are a concentrated source of factors VIII, XIII, von Willebrand factor, fibronectin, and fibrinogen. The advantage of Cryo over FP is the ability to deliver specific proteins with less total volume. Cryo was historically used for the treatment of inherited coagulopathies such as hemophilia A, Factor XIII deficiency and von Willebrand's disease. Isolated factor concentrates are now used for these diseases and Cryo is now most often administered to replenish fibrinogen. No specific guidelines exist regarding the administration of Cryo, but the usual dose for treatment of hypofibrinogenemia is 5–10 units to start, then 5 units every 8 h as necessary to keep fibrinogen above 100 mg/dL. In surgical patients there are increasing data to suggest that the fibrinogen levels should be kept above

200 mg/dL because fibrinogen is the primary factor lost in surgical bleeding and coagulation problems can develop when the level is below 50%. Fibrinogen (Factor 1) has a two-fold use in binding platelets together as well as producing fibrin in the clotting cascade. As with platelets, ABO and Rh compatibility is not required for administration. Fibrinogen concentrates are now available which is a safer product and is reducing the use of Cryo.

Complications of Product Transfusion

Complications arising from product transfusion can be classified as either immune-mediated or infectious. Immune-mediated reactions can be further classified as hemolytic and non-hemolytic. Hemolytic reactions are most commonly due to ABO blood incompatibility with an approximate frequency of 1:38,000 transfusions. These reactions are often severe and can result in disseminate intravascular coagulation, shock, and death. Fatal hemolytic transfusion reactions occur in about 1 in 100,000 transfusions. Non-hemolytic transfusion reactions include febrile reactions, anaphylactic reactions, and transfusion-related acute lung injury (TRALI). TRALI occurs in about 1 in 5000 transfusions and is thought to be caused by damage to alveolar capillaries from transfused anti-leukocyte or anti-HLA antibodies. TRALI manifests as acute hypoxia and non-cardiogenic pulmonary edema within 6 h of blood product transfusion. Treatment is supportive, and TRALI typically resolves spontaneously within 4 days.

Transfusion-associated infections may be viral, parasitic, or bacterial. The rise of HIV in the 1980s and 1990s led to more stringent donor criteria and increasingly sensitive screening tests. Rates of transmission for HIV and Hepatitis C are approximately 1:2,000,000 and rates of transmission for hepatitis B are about 1:200,000. Bacterial contamination of blood products is far more common, and is the second leading cause of transfusion-associated mortality. Gram-negative and Gram-positive bacteria can contaminate blood products and cause sepsis in recipients. The preva-

lence of bacterial contamination varies by blood product, ranging from 1:2000 for platelets to 1:7000 for red blood cells. Transmission of parasites (e.g., malaria, toxoplasmosis, and Chagas' disease) has been reported, but is extremely rare.

Conclusions

Resuscitative fluids should be thought of as medications. Blood and blood component transfusion can be thought of as a liquid transplant. Both fluid therapy and transfusion therapy have specific indications and doses. Appropriate resuscitation involves understanding the composition of both the resuscitative fluids and the perioperative fluid losses. Most balanced resuscitations consist of multiple types of crystalloid, colloid, and blood products. Much research continues to be done on the ideal composition of resuscitative fluids, and the field will likely continue to evolve quickly in the years to come.

Case Study

Planning for Major Blood Loss

A 25-year-old, otherwise healthy woman is to undergo radical resection of a pelvic sarcoma with prosthetic reconstruction to attempt to salvage the hip joint and thigh. The surgeon estimates blood loss will be 2–5 L, depending on the findings at operation and extent of major vascular involvement. The estimated surgical time is 6 h. She has a peripheral 14 G IV, a three-lumen central venous catheter in the right internal jugular vein, and a 20 G right radial arterial line. She has 4 units of packed red cells available. She weighs 60 kg. Her preoperative Hgb and HCT are 12 and 36, respectively. She has fasted overnight and is scheduled for the first case in the morning.

How will you estimate her basic fluid requirements for the case?

You can estimate her hourly maintenance fluid needs with the "4-2-1" rule, calculating 4 mL/kg/hr. for the first 10 kg of body weight, 2 mL/kg/hr. for the next 10 kg, and 1 mL/kg/hr. for each additional 10 kg. This results in 40 + 20 + 4(10) = 100 mL/h. Assuming an 8 h. overnight fast, her deficit preop is 800 mL. Her ongoing maintenance fluid requirement for 6 h of surgery will be 600 mL. Her EBL is likely extreme, and will be replaced initially at three-times EBL, or some 6–15 L of fluid. Clearly, some of this will be replaced with blood or colloid solutions, not merely crystalloid. Her "third space" or interstitial fluid losses will be moderate to severe, depending on whether the peritoneum is exposed by the dissection or not. We can estimate these losses at 6 mL/kg/hr. or more, totaling 360 mL/hr. or approximately 2.5 L for the case.

How low are you comfortable letting her Hgb fall to?

The overwhelming preponderance of the evidence suggests that the optimal Hgb target for most healthy patients is 7 g/dL. For patients with coronary artery disease or other significant disease, a Hgb of 8 g/dL may be targeted.

What is her acceptable blood loss?

ABL is often calculated with a formula based on the assumption that blood loss occurs at a constant rate throughout the case, and that the patients blood volume remains constant by replacement with blood-free solutions. In this young woman, her estimated blood volume is 65 mL/kg × 60 kg ≈ 4 L. Her ABL, given a starting HCT of 36 and an acceptable nadir of 21 (equivalent to a Hgb of 7 g/dL), is ABL = 4 L*(36 − 21)/36 = 1.7 L. In practice, anesthesiologists will check Hgb/HCT periodically as well as make judgments regarding the rate of ongoing blood loss and the adequacy of volume repletion and thus begin transfusion either earlier or later than when this amount has been lost.

How will you assess and correct other blood product requirements?

In sudden blood loss situations such as massive trauma, some recommend empirical administration of packed red cells, plasma, and platelets. In the case of operative losses, it is generally prudent to replace factors by monitoring PT and PTT and platelets by monitoring the platelet count. Keeping the PT <1.5-times control and the platelet count >50,000 is generally recommended, although in the setting of ongoing blood loss, more aggressive replacement is often performed. Fibrin is the ultimate substrate for blood clot, so fibrinogen should also be monitored and kept >200 mg/dL in severe bleeding [14].

What options do you have for reducing transfusion requirements?

There are at least three possibilities. First, controlled hypotension is a strategy to reduce blood loss by reducing the hydrostatic pressure causing blood to leave traumatized blood vessels. Reducing the blood pressure to a mean of approximately 50–60 mmHg is considered safe in "**healthy"** (must avoid in patients whose "normal" physiology has been altered by disease states, such as chronic hypertension or carotid/coronary plagues) patients and reduces blood loss in a variety of types of surgery. This can be achieved with short-acting beta blockers (e.g., esmolol), high concentration of inhaled agents, or direct acting vasodilators (e.g., nitroprusside). Second, normovolemic hemodilution is a technique which "pre-dilutes" the blood of the patient to a lower HCT prior to surgery, so that surgical blood loss contains fewer red cells. Blood is removed from the patient and stored in the same containers used in the blood bank; it is replaced with crystalloid or colloid solutions in a normovolemic fashion (typically 3:1 or 1:1, respectively, or as guided by a CVP catheter). Later in the case, the patient's own blood is returned by transfusion [15]. Finally, intraoperative cell salvage has been successfully employed in a

variety of clinical situations. Blood is aspirated from the surgical field into a reservoir where it is periodically washed and filtered to yield a high hematocrit blood product from the patient's own blood. It is controversial in cases of malignancy, because theoretically tumor cells can be aspirated and reinfused intravenously. Recently, however, leukocyte depletion filters (which do not allow cells much larger than RBCs to remain in the product to be infused) have been shown to efficiently remove all tumor cells from the aspirated blood. Moreover, it is not at all clear that infusion of tumor cells is actually a risk for metastasis, which requires numerous other cellular steps.

References

1. Kalamas AG (2007) Fluid management. In: Stoelting RK, Miller RD (eds) Basics of anesthesia, 5th edn. Churchill Livingstone, Philadelphia, p 349
2. Gurgel ST, do Nascimento P Jr (2011) Maintaining tissue perfusion in high-risk surgical patients: a systematic review of randomized clinical trials. Anesth Analg 112:1384–1391
3. Waters JH, Gottlieb A, Schoenwald P, Popovich MJ, Sprung J, Nelson DR (2001) Normal saline versus lactated Ringer's solution for intraoperative fluid management in patients undergoing abdominal aortic aneurysm repair: an outcome study. Anesth Analg 93:817–822
4. Wilkes NJ, Woolf R, Mutch M, Mallett SV, Peachey T, Stephens R, Mythen MG (2001) The effects of balanced versus saline-based hetastarch and crystalloid solutions on acid-base and electrolyte status and gastric mucosal perfusion in elderly surgical patients. Anesth Analg 93:811–816
5. Scheingraber S, Rehm M, Sehmisch C, Finsterer U (1999) Rapid saline infusion produces hyperchloremic acidosis in patients undergoing gynecologic surgery. Anesthesiology 90:1265–1270
6. O'Malley CM, Frumento RJ, Hardy MA, Benvenisty AI, Brentjens TE, Mercer JS, Bennett-Guerrero E (2005) A randomized, double-blind comparison of lactated Ringer's solution and 0.9% NaCl during renal transplantation. Anesth Analg 100:1518–1524
7. Tullis JL (1977) Albumin. 1. Background and use. JAMA 237:355–360

8. Laxenaire MC, Charpentier C, Feldman L (1994) Anaphylactoid reactions to colloid plasma substitutes: incidence, risk factors, mechanisms. A French multicenter prospective study. Ann Fr Anesth Reanim 13:301–310
9. Van der Linden P, Ickx BE (2006) The effects of colloid solutions on hemostasis. Can J Anaesth 53(6 Suppl):S30–S39
10. Zarychanski R, Abou-Setta AM, Turgeon AF, Houston BL, McIntyre L, Marshall JC, Fergusson DA (2013) Association of hydroxyethyl starch administration with mortality and acute kidney injury in critically ill patients requiring volume resuscitation: a systematic review and meta-analysis. JAMA 309:678–688
11. Treib J, Haass A, Pindur G (1997) Coagulation disorders caused by hydroxyethyl starch. Thromb Haemost 78:974–983
12. Finfer S, Bellomo R, Boyce N, French J, Myburgh J, Norton R, SAFE Study Investigators (2004) A comparison of albumin and saline for fluid resuscitation in the intensive care unit. N Engl J Med 350:2247–2256
13. Postoperative Visual Loss Study Group (2012) Risk factors associated with ischemic optic neuropathy after spinal fusion surgery. Anesthesiology 116:15–24
14. Shaz BH, Dente CJ, Nicholas J, MacLeod JB, Young AN, Easley K, Ling Q, Harris RS, Hillyer CD (2010) Increased number of coagulation products in relationship to red blood cell products transfused improves mortality in trauma patients. Transfusion 50:493–500
15. Shaz BH, Winkler AM, James AB, Hillyer CD, MacLeod JB (2011) Pathophysiology of early trauma-induced coagulopathy: emerging evidence for hemodilution and coagulation factor depletion. J Trauma 70:1401–07

16 Peripheral, Arterial, and Central Lines and Gastric Tube Placement

Andrea J. Strathman

Peripheral Intravenous Lines

Peripheral intravenous catheter (PIV) placement is a necessary task for almost every anesthetic. Intravenous access provides the anesthesiologist the ability to administer fluids, medications, and, if necessary, blood products during the perioperative period.

The site of cannulation should be based on the patient's position during surgery, the site of surgery, and the gauge (size) of the cannula being placed. PIV placement should be avoided in areas where there are signs of infection, burns, trauma, previous or present arteriovenous fistulas, radiation exposure, or recent IV infiltration. Along with choosing a site for PIV placement, the size of cannula should also be considered. There is an inverse relationship between the gauge of the catheter and the IV size; the lower number gauge a catheter is, the larger the diameter of the catheter. (e.g. a 14 g catheter is larger than a 24 g). Poiseuille's law describes the flow of liquid through an IV catheter and should be considered when the catheter gauge is chosen (Fig. 16.1).

A. J. Strathman (✉)
Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA
e-mail: astrathm@wakehealth.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_16

$$Q = \frac{\Delta P \, \pi \, r^4}{8 \, \eta \, l}$$

Fig. 16.1 Poiseuille's law, in which ΔP symbolizes the pressure differential between the two ends of the tube, η is the viscosity of the fluid, ⌊ is the length of the tube and r is the radius of the tube

$$Q = \frac{\Delta P \pi r^4}{8 \eta l}$$

For all practical purposes, when selecting the size of an IV it is the radius and length of the catheter that matters. The viscosity of blood products is higher than that of crystalloid fluids, however this does not alter the fact that a larger bore (smaller gauge) peripheral IV will have a greater flow rate, based on its radius and length. It is difficult to give exact flow rates through any given catheter, but in general larger catheters and higher inflow pressures result in exponentially higher flow rates.

The upper extremities are usually the preferred site of placement as this location allows for easier access to the IV during the surgical procedure and a greater ability to reassess the site during a procedure. Common sites of cannulation in the upper extremities include the veins of the hand and forearm, which include the cephalic and basilic vein systems. The median antecubital vein can usually accommodate a larger bore PIV, however flow may be limited if the arms are positioned with even a slight bend. Furthermore, a PIV in this position can be frustrating to the patient and care team after surgery as it will consistently cause an infusion pump to alarm if the arm is bent, thus causing the catheter to be kinked within the vessel. The dorsal veins of the foot can also be accessed. However, this is associated with a higher risk of thrombophlebitis, along with patient discomfort. If a lower extremity PIV is needed, the saphenous vein can often be easily palpated just anterior to the medial malleolus and it can typically accommodate a larger gauge catheter if the upper extremities are not accessible.

The external jugular vein is another peripheral intravenous site frequently used by the anesthesiologist because of its reliable anatomical position. It is typically located close to the surface of the skin superficial to the sternocleidomastoid muscle. Placement of this line requires a shallow angle when attempting cannulation. Caution should be taken when placing an external jugular cannula due to the risk of inadvertent puncture of the deeper structures of the neck, including the carotid artery, internal jugular vein, and pleural space. External jugular intravenous catheters also frequently require turning of the head to the contralateral side to run effectively.

Technique

As with any procedure, an explanation of what the patient can expect (mild, temporary discomfort during placement) and the risks, including infection and bleeding, should be discussed with the patient. Gloves should be worn during the placement of any PIV and the area should be thoroughly cleaned with alcohol or chlorhexidine. A tourniquet should be tied tightly proximal to the site of cannulation to promote engorgement of the vein.

The gauge of the intravenous cannula needed for each patient is dependent upon their surgical procedure, likelihood of blood loss or need for vasoactive drugs, their specific comorbidities and the size of the vein being accessed. Once the gauge has been determined, inspect the metal needle and plastic cannula noting the distance between the tip of the needle and the tip of cannula. The amount of exposed needle increases with increasing size of the catheter, thus requiring deeper entry into the vein before the catheter can be advanced off of the needle.

The decision to use local anesthetic at the site for pain depends on multiple factors, including patient anxiety, anticipated ease of placement, size of the catheter and physician preference. Local anesthetic creates a sympathectomy that can prevent venoconstriction, however it may also obscure the view of the vein. Lidocaine 1% is typically used and a volume of 0.5–1 mL with a

27 or 28 gauge needle at the insertion site is adequate to reduce or eliminate pain.

Prior to insertion of the intravenous catheter, it is important to stabilize the intended target vein. Do so by using your non-dominant hand to pull the skin taut distal to the site of insertion. Use your dominant hand to insert the cannula and needle together at a 5–30° angle to the skin. The idea is simply to put a tube (catheter) inside another tube (vein). Thus, lining up the axis and angle of the two is the most important step. Once the vein as been entered a "flash" of blood will appear in the reservoir of the catheter. Lower the angle of the catheter so that it is parallel to the axis of the vein and continue to advance the needle and cannula simultaneously an additional 2–3 mm. This ensures that the tip of the cannula has also entered the vein. Next, thread the cannula off of the needle into the vein. Once the cannula has been threaded to its hub, remove the tourniquet and apply pressure proximal to the cannula to occlude the vein in order to prevent back bleeding when the needle is removed. Remove the needle, placing your sharp in a safe location, and attach the intravenous tubing. The intravenous fluid should flow freely into the catheter if the fluids are above the level of the heart. Finally, apply a sterile dressing to secure the intravenous catheter in place.

Troubleshooting

Difficulty locating a vein can be one of the most challenging aspects of PIV insertion. Placing a warm compress/blanket on the extremity, having the patient open and close their first, letting the arm hang below the level of the heart, and gently tapping the vein can all help increase its size by encouraging venous filling. If no extremity veins are visible or palpable, or if multiple attempts have been unsuccessful, ultrasound can be used to locate the deeper veins in the arm. The basilic vein and deep brachial vein are reliable choices in this setting. A landmark-based approach to these deep veins has been shown to lead to frequent complications, such as arterial puncture and nerve injury. As such, these

veins should be located and cannulated with ultrasound guidance. A longer cannula (>2 in.) may be needed to access these veins.

Valves inside a vein can sometimes prevent complete advancement of the cannula. Removing the needle and advancing the cannula further into the vein while flushing it with saline solution creates positive pressure which may help open the valve and allow passage of the cannula past the obstruction.

If a cannula is advanced outside of the vein, there is usually swelling at the site of cannulation when fluid is administered as it infiltrates the extravascular tissue. The cannula should be removed immediately and a new cannula inserted at a different site. Repeated attempts at flushing the catheter or readjusting the position should be avoided. It is advisable that a replacement catheter be placed proximal to the infiltrated site on the extremity to avoid further extravasation of fluids and medications through the infiltrated site.

Arterial Catheters

The indications for arterial blood pressure monitoring include the need for beat-to-beat blood pressure monitoring due to patient comorbidities or procedure, frequent blood gas analysis, unreliability of non-invasive blood pressure cuff (e.g. the obese patient), or contraindication to use of a cuff (e.g. a patient with extensive burn wounds over the extremities).

Site of Cannulation

The most common site of arterial cannulation is the radial artery. However, the femoral, brachial, axillary, and dorsalis pedis are alternative sites based on the patient's anatomy or surgical site. Contraindications to placement include infection at the site, arterial thrombus, trauma or burn proximal to the vessel, and concern for collateral flow. Arterial cannulas are typically 20 gauge catheters, but smaller sizes may be required for frail or pediatric

patients. Their length depends on the site being accessed with longer catheters required for femoral arteries as compared to radial arteries, particularly in the obese patient.

The Allen's Test has been traditionally used to assess the collateral flow to the hand via the ulnar artery. To perform the test, the hand is held in a fist above the level of the heart for 30 seconds. The radial and ulnar arteries are occluded and the hand is opened and then the ulnar artery is released. The palm is observed to see if the pallor resolves within 10 seconds. Although some experts still recommend using the Allen's Test, a recent study comparing the Allen's Test to Doppler flow found that it was not reliable in predicting collateral flow.

Technique

Prior to performing the procedure, the patient should be appropriately consented and the procedure explained. Only the technique for cannulation of the radial artery will be discussed in this chapter. Although the incidence of arterial line infection is minimal, it is recommended that a hat, mask, and sterile gloves be worn during the procedure. A small gauze roll is placed under the wrist to slightly extend it and the hand is taped to a table or arm board for immobilization (Fig. 16.2). The radial artery should be located by palpation of the pulse at the wrist between the radius and the flexor carpi radialis tendon. The area should be prepped with chlorhexidine and draped with sterile towels. A small amount of local anesthetic (0.5–1 mL of 1% lidocaine without epinephrine) can be injected at the entry site to prevent pain during needle insertion if the cannula is placed in an awake patient. This also creates a sympathectomy that reduces vasospasm when accessing the vessel. The needle is held in the dominant hand like a pencil and should enter the skin at a 30–40° angle. Once a flash is seen in the catheter chamber, the needle is advanced 1 mm further and the angle is decreased to 10–15° as the guidewire is advanced into the artery. The cannula can then be passed over the guidewire in a Seldinger technique and the guidewire and needle can be removed. Prior to removing the guidewire, pressure should be applied prox-

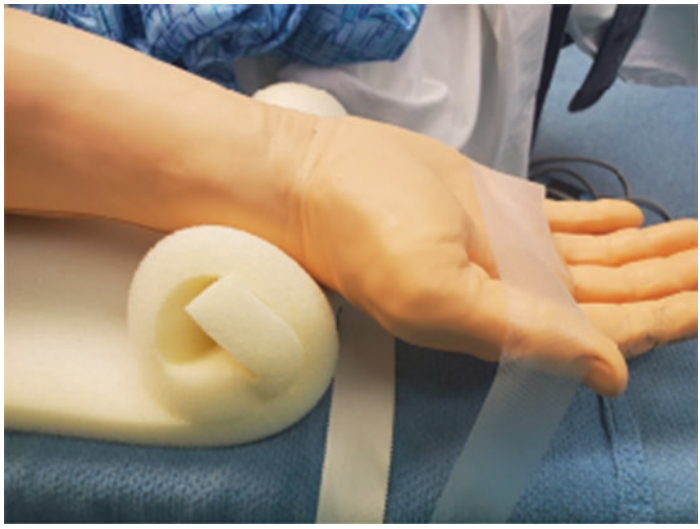


Fig. 16.2 Preparation of the arm for placement of a radial arterial line

imal to the site of cannulation to prevent bleeding through the catheter. The cannula should then be attached to high pressure, low compliance arterial pressure tubing. The catheter should be sutured or securely taped into place and dressed with a sterile, transparent dressing.

Troubleshooting

Frequently there is only a small "flash" of blood into the arterial cannula chamber and the chamber does not fill completely or the chamber fills but the guidewire does not pass easily. In these situations, the artery can be transfixed, meaning the needle and cannula are purposely passed through the artery. The needle is then removed and the cannula is slowly pulled out of the skin until spontaneous arterial flow is identified. The guidewire can then be inserted into the cannula and the cannula advanced into the artery.

If there is no palpable pulse or multiple attempts at arterial cannulation have been made without success, an ultrasound should be

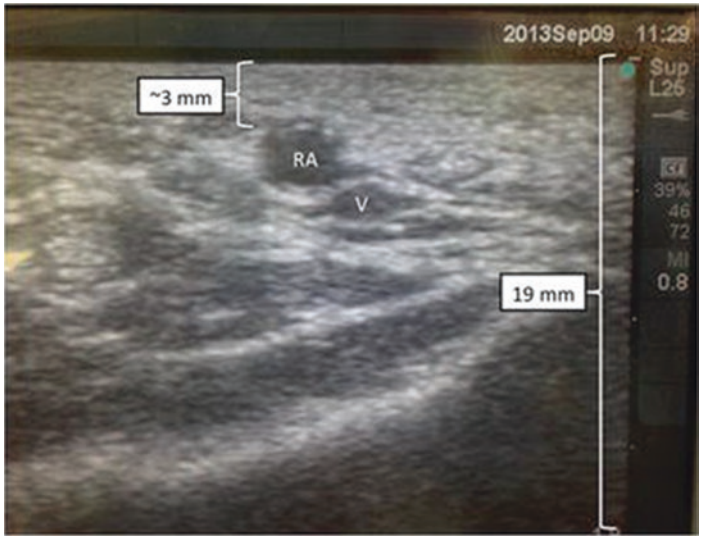


Fig. 16.3 This figure shows a short axis view of the radial artery (RA) along with an accompanying radial vein (V), depicting the superficial nature of the artery in relation to the skin [*RA* radial artery, *V* radial vein]

used to provide a visual target. The use of ultrasound can also increase the likelihood of accessing the artery on the first attempt, which is particularly helpful in hypovolemic patients or patients with difficult anatomy, such as the obese, the very thin/frail, or those with advanced peripheral vascular disease (see Fig. 16.3).

Central Venous Catheter Insertion

Central venous catheters (CVC) provide reliable central intravenous access. There are many indications for placement of a CVC, including the lack of adequate peripheral venous access, surgical cases with anticipated large volume of blood loss, the need to administer infusions of vasoactive medications, or placement of a pulmonary artery catheter. Prior to performing the procedure, informed consent should be obtained. Handwashing should occur

immediately before line placement. A sterile gown, hat, mask, gloves should be worn during the procedure. The area should be prepped with chlorhexidine and a full body drape applied to decrease the risk of central line-associated blood stream infection (CLABSI). This series of steps has been shown to significantly reduce CLABSI. For the placement of an internal jugular or subclavian vein CVC, the patient should be positioned in the Trendelenberg position to promote engorgement of the vein.

Cannula Size and Length

CVCs come in varying sizes, lengths and numbers of ports. The diameter of the catheter is expressed as a French gauge. Adult central lines typically range from 7 to 9 French which equate to a catheter 2.3–3 mm in diameter, respectively. Each catheter can have 1–3 ports, and as the number of ports increases the diameter of each port decreases. If the CVC is placed for volume resuscitation, it is better to have a larger diameter catheter with fewer ports. As discussed earlier, according to Poiseuelle's Law the length of the catheter also affects the rate of flow, with shorter catheters allowing for faster flow. The resistance to flow through any catheter is directly proportional to the length of the catheter and the viscosity of the blood and inversely proportional to the radius of the catheter to the fourth power. Therefore, a short catheter with a large diameter provides the least resistance to flow and thus, the ability to most rapidly provide large volume fluid and blood resuscitation.

Ultrasound Guidance

According to the most recent guidelines by the American Society of Anesthesiologists for CVC placement, real-time ultrasound is recommended for all attempts at central line placement. Randomized controlled trials show that the use of real-time ultrasound increases the first attempt success rate, decreases the time to venous access, results in higher overall successful cannulation

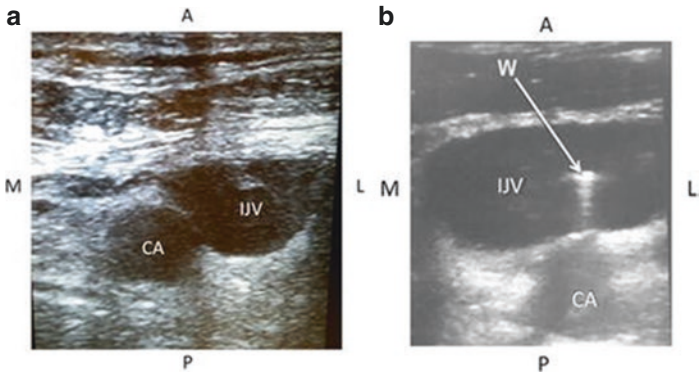


Fig. 16.4 (**a**) and (**b**) illustrate two different short axis views of the internal jugular vein and the carotid artery. Figure (**a**) shows the classical description of the anatomic relationships with the artery laying medical to the vein, whereas (**b**) shows a variant where the artery is posterior to the vein, making arterial puncture more likely if the needle passes too deep [*IJV* internal jugular vein, *CA* carotid artery, *W* wire]

and decreases the risk of arterial puncture. Observational studies and expert opinion recommend confirmation of the wire or catheter in the vein before dilation. This confirmation may be obtained in a number of ways, including surface ultrasound, TEE, fluoroscopy or manometry. Figures 16.4a, b and 16.5 show examples of this in short axis and long axis. The long axis is the most reliable method for ensuring that the entire course of the wire remains intravascular (Fig. 16.6).

Internal Jugular Vein

The internal jugular vein is the most commonly cannulated vein by anesthesiologists due to its ease of access. To find the vessel using anatomic landmarks, locate the cricoid cartilage and move laterally until the carotid artery is palpable. The vein runs just lateral and anterior to the artery.

The head is turned slightly to the contralateral side. The entire side of the neck down to the level of the clavicle should be prepped

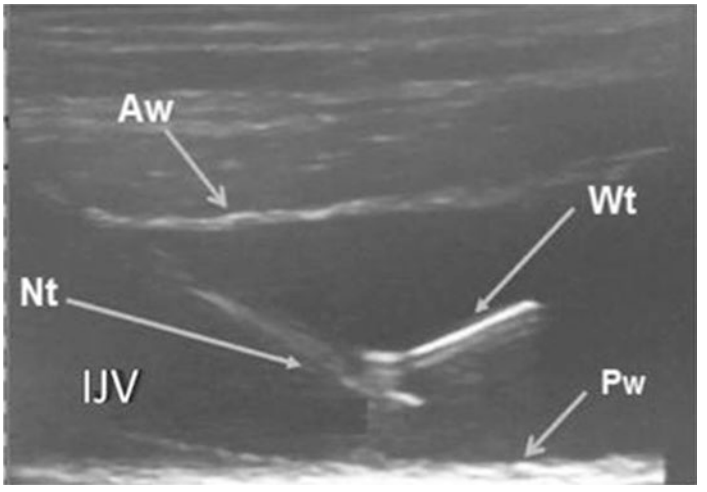


Fig. 16.5 This figure illustrates a long axis view of the internal jugular vein (IJV) with the anterior wall (Aw) and posterior wall below (Pw). The needle tip (Nt) can be visualized within the lumen and the needle tip (*Nt*) can be seen exiting the bevel of the needle [*IJV* internal jugular vein, *Aw* anterior wall, *Pw* posterior wall, *Nt* needle tip, *Wt* wire tip]

and draped. The ultrasound probe with a sterile cover should be used to visualize the internal jugular vein and the carotid artery. The vein should be compressible while the artery is pulsatile. If the patient is awake, 3–5 mL of lidocaine 1% without epinephrine should be infiltrated above the vein. An empty syringe is attached to the needle used to access the vein. Gentle suction is applied to the syringe while the needle enters the skin and subcutaneous tissue at a 30–45° angle. Once the vein is accessed, blood will be able to be aspirated into the syringe. The syringe should be removed and a guidewire passed through the needle into the vein. Advancing the guidewire too far and into the right atrium can lead to ectopy seen on the ECG and the wire should be pulled back. If any resistance is met during insertion of the wire the syringe should be re-attached and confirmation of blood flow confirmed with gentle needle aspiration. If this does not occur, the needle position should be checked with ultrasound. The wire positioning

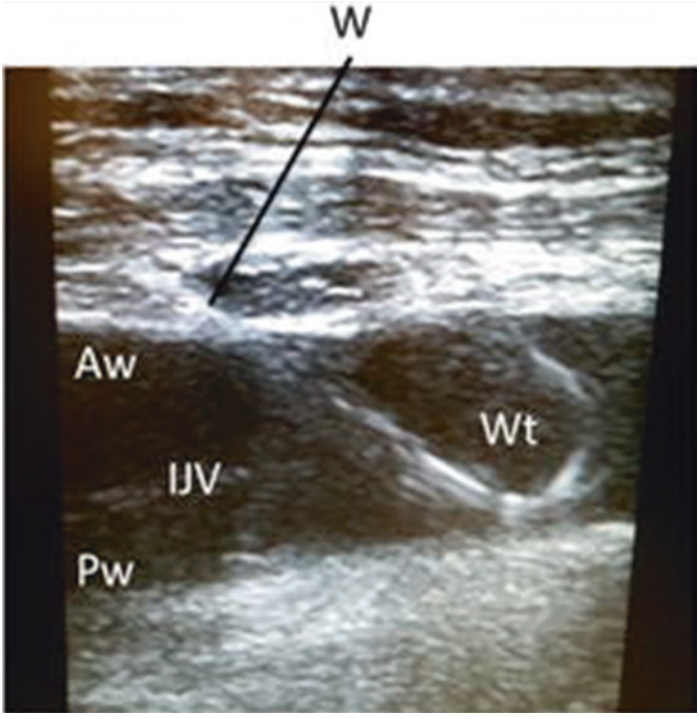


Fig. 16.6 This figure also shows a long axis view of the internal jugular vein (IJV) lumen with the anterior wall (Aw) above and the posterior wall (Pw). The wire tip (Wt) is visualized as it is advanced through the needle tip. This ensures that the entire wire is visualized within the internal jugular vein lumen [*IJV* internal jugular vein, *Aw* anterior wall, *Pw* posterior wall, *Nt* needle tip, *Wt* wire tip, *W* wire]

can be checked in the short and long axis views. The wire should be seen traversing through the vein down to the level of the clavicle. These views ensure that the wire has not passed through the vein and into the artery.

Once the wire is positioned in the vein, the needle should be removed. A small skin nick should be made in the skin at the wire insertion site to allow passage of the dilator. The dilator should be passed over the wire and inserted just through the fascial layer but

not farther to avoid shearing the vein. The dilator is removed and the catheter is passed over the wire into the vein. The wire is removed after the catheter is fully advanced into the vein. The ports on the line are then aspirated, flushed and capped. The line is sutured in place and a sterile, antibiotic impregnated bio-occlusive dressing is applied. A chest x-ray should be ordered after insertion of all central lines to ensure proper positioning.

Subclavian Vein

The subclavian vein is a common site of CVC placement. Not only does it have the lowest risk of infection of the CVC sites, it is typically regarded as more comfortable by the patient post-operatively. The landmarks for accessing the subclavian vein include the bend in the lateral two thirds of the clavicle and the sternal notch (Fig. 16.7). The entire side of the chest above and below the clavicle should be prepped and draped including the sternal notch. The bend in the clavicle is palpated and the needle is inserted 1 cm caudad and 1 cm lateral to this site. Typically, a gap can be palpated between the anterior border of the deltoid and the lateral border of the pectoralis major as an additional anatomical landmark that helps in finding the insertion site. The needle is advanced just underneath the bend in the clavicle aiming at the sternal notch. The needle should be advanced with minimal vertical angulation, due to the proximity of the underlying lung tissue. The vein should be encountered directly below the clavicle. Once the aspiration of blood is confirmed, the syringe should be removed and the additional steps performed as detailed above in the internal jugular vein section.

Femoral Vein

The femoral vein is a less common site of central line placement due to concern for infection, however it may be a preferred site of cannulation if there is concern for damage to the superior vena cava or if the neck and subclavian sites would be inaccessible,

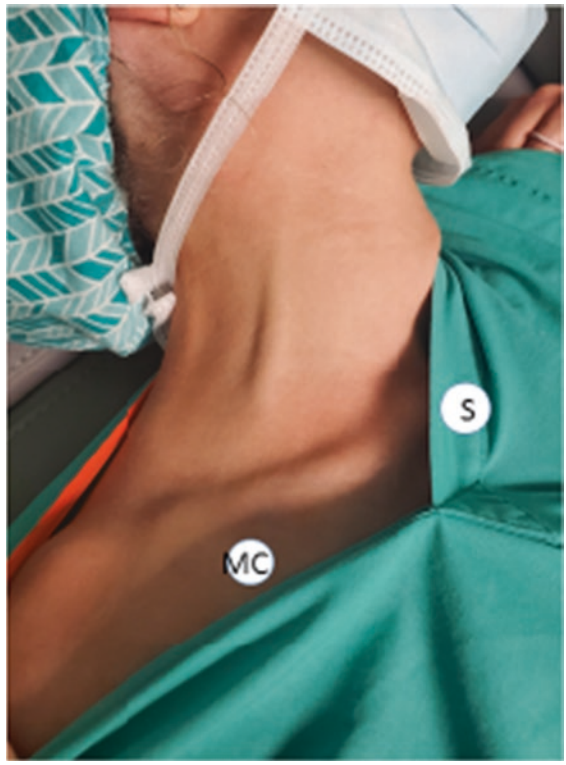


Fig. 16.7 This figure demonstrates the surface landmarks for the placement of a subclavian CVC. The sternal noech ($) and mid-clavicular (MC) curve are important landmarks for placement of a subclavian central line

such as during major head and neck surgery. The vein is located inferior to the inguinal ligament between the superior anterior iliac spine and the pubic tubercle within the inguinal crease just medial to the femoral artery. The anatomy of this space from lateral to medial is: femoral nerve, femoral artery, femoral vein, lymphatics. The contents of the surrounding structures should be understood in order to avoid injury. The entire inguinal region should be widely prepped and draped. Ultrasound should be used to visualize the femoral vein and artery. The needle should be

directed cephalad at a 30–45° angle to the skin when entering the femoral vein, and the needle should be directed in a slight medial direction, based on the anatomic trajectory of the femoral veins. Once aspiration of blood is confirmed, the syringe should be removed and the additional steps performed as detailed in the internal jugular vein section above.

Complications

Potential complications for central venous lines include infection and bleeding. Accessing the femoral vein has the highest risk of arterial puncture (6%), thrombosis (8–34%) and infection (15%). However there is no risk of pneumothorax so this approach may be preferred in patients with severe lung disease in which a pneumothorax could lead to respiratory or hemodynamic instability. Placing a central line in the subclavian vein carries the highest risk of pneumothorax (1.5–3%) but the lowest risk of infection and arterial puncture (0.5%). Central lines placed in the internal jugular vein have a relatively low risk of pneumothorax (0.2%) but a slightly higher risk of arterial puncture (3%). All central lines carry a risk of damage to surrounding nerves, which can result in a paresthesia and temporary or permanent nerve damage.

Orogastric and Nasogastric Tubes

Orogastric (OGT) and nasogastric (NGT) tubes are frequently placed to decompress the stomach to decrease the risk of aspiration, improve surgical exposure or decompress gastric and intestinal contents when there is concern for ileus or obstruction. If the patient is awake, a nasogastric tube is typically preferred. This procedure may be uncomfortable for the awake patient, so its necessity and procedural steps should be explained to the patient prior to placement.

To estimate the length of insertion for a nasogastric tube, the distance from the nose to the ear and then to 5 cm below the

xiphoid process should be marked. The nare should be prepared with oxymetazoline to provide vasoconstriction and decrease the likelihood of epistaxis. The tube should be lubricated and directed along the floor of the nostril towards the back of nasopharynx. Do not advance in a cephalad direction, as this can cause epistaxis from injury to the inferior turbinate. Upon entering the nasopharynx, NGT must take a 90° turn to enter the posterior oropharynx and then continue into the esophagus. If the patient is awake, they should be encouraged to swallow during the procedure to facilitate successful placement in the esophagus. If the patient is asleep, the non-dominant hand can be used to perform a jaw lift to displace the tongue and guide the tube into the esophagus. If resistance is met during placement the tube should not be forced, as this will help to avoid submucosal placement or epistaxis. NGTs should not be placed in patients at high risk for bleeding due to coagulopathy or blood thinner usage, patients with basilar skull fractures, previous gastric bypass surgery or high-grade esophageal varices. In addition to not being in the oral cavity, a major benefit of NGT placement for the awake patient is that it lies behind the tonsillar pillars and is thus associated with less gag reflex.

The orogastric (OG) approach is preferred if the patient is asleep and will only need the tube while intubated and unconscious. The OGT should be lubricated and directed toward the base of the tongue and through the oropharynx into the esophagus. A jaw lift can help displace the soft tissue if difficulty is encountered when attempting to advance the orogastric tube. The tube should be guided into the esophagus using the index finger of the dominant hand. Contraindications to orogastric tubes include previous gastric bypass surgery and high-grade esophageal varices. As with the NGT, the OGT should not be forced past resistance as this could lead to submucosal placement and significant tissue injury.

Placement of an NGT or OGT should be confirmed. This can be done by attaching the tube to suction and checking for the return of gastric contents. A post-placement x-ray can confirm the location of the tube. Additionally, injecting air through the tube and listening with a stethoscope over the stomach can also be per-

formed, although this method can be associated with false positives. Finally, NGTs and OGTs are often placed on low continuous wall suction or on intermittent suction. A high level of continuous suction is not recommended in order to avoid mucosal damage and bleeding.

Case Study

A 35 year-old woman comes to the OR for emergency laparoscopic resection of a ruptured ectopic pregnancy. She was admitted to the emergency department with abdominal pain and was found to have a positive beta-HCG, a mass on abdominal ultrasound in her right Fallopian tube, and an empty uterus. Her last menstrual period was approximately 8 weeks ago. She states that she is otherwise healthy. She ate dinner approximately 4 h ago but had little appetite at the time so states that it was "just a little." She has a 20 G antecubital IV in place, which is slowly infusing lactated Ringer's.

Is this IV sufficient for this case? How will you decide whether or not you need better IV access?

You can open up the IV fluids and assess how well this 20 G catheter flows. In a large vein, even an IV of this relatively small size will often run briskly. Check the tubing set and make certain it is a high-flow set; you may choose to change it to the standard set you use in the OR, which generally is optimized for rapid flow and injection of drugs. You can inspect the IV site itself and see if there are signs of swelling or redness indicative of infiltration (i.e., migration out of the vein). You can ask the patient if the IV is comfortable or painful. Properly situated IVs are generally painless. You should also discuss the prospect of blood loss and other fluid shifts with the surgeon, including the possibility of requiring an open procedure and the expected duration of the operation.

Exhaustive search for other veins yields no obvious prospects for additional access. The patient states that she has always been "a tough stick." Will you proceed?

You can certainly try to induce anesthesia with this IV and then attempt to locate a second site after induction. General anesthesia often leads to vasodilation and easier location of veins, due to direct effects of anesthetics as well as relief of anxiety, which may cause sympathetic activation and vasoconstriction. This presumes that you believe that the present IV is indeed intravascular. You should not proceed with induction if you are unsure about the placement of the peripheral IV. The PIV can be flushed with saline, tested for aspiration of blood and when in doubt tested with a number of different medications. Esmolol is one commonly used medication, as you will see a definitive, but transient, drop in heart rate after dosing without a significant risk of tissue damage, should the IV be infiltrated.

You plan a rapid sequence induction with propofol and succinylcholine. 60 s after injecting propofol, the patient has not lost consciousness. You have not yet injected succinylcholine. How will you proceed?

At this point, you should suspect that the IV might not be intravascular. You can determine if this is a pharmacodynamic or kinetic problem (i.e., the patient has just not yet fallen asleep but the drug is indeed intravascular) by assessing whether your injection has had any effect at all on the patient's level of consciousness. Although the rapid sequence technique generally implies quick sequential injection of a hypnotic and a paralytic, you should not inject succinylcholine at this point. This is because even if not IV, succinylcholine will eventually be absorbed and will produce weakness or paralysis in an unsedated patient. Extravascular propofol and lactated Ringer's are likely benign and unlikely to cause tissue damage. However, you should monitor the limb for signs of edema, or compartment syndrome by observation and palpation of the distal pulse. If possible, elevate the arm somewhat over the level of the chest.

Can you induce anesthesia by inhalation instead?

This technique is commonly performed in children, but is rarely employed in adults in modern practice. In this case, inhalation induction and mask ventilation are contraindicated because of the risk of aspiration, due to the fact that the patient has consumed food in the last few hours and the intraabdominal nature of the surgical emergency.

You decide that you will need another IV to proceed. What options do you have to establish access?

There are many "tricks" anesthesiologists use to secure venous access in patients with difficult anatomy. The first is to look beyond the forearms: the upper arm, distal hand, and feet are sometimes options. Only a small IV is needed for induction, and then as you had previously planned, better veins may become visible after induction. The external jugular vein can be percutaneously cannulated in many patients Gentle pressure applied to the distal neck just above the clavicle can help you visualize this valveless vein. The femoral vessels are sometimes used. A second option is to enhance visibility of veins. Warming the extremity or use of topical nitroglycerin ointment to promote vasodilation are sometimes successful (thought the latter causes headache as a side effect). Inflating a blood pressure cuff on the arm to above the arterial pressure for a few minutes, then lowering it to approximately 30 mmHg, which is above venous but below arterial pressure, may reveal veins by causing mild ischemia-induced vasodilation. Commercial "vein finder" machines use special optics to allow visualization of veins through intact skin that are otherwise not visible. Ultrasound guided placement of a peripheral IV is an excellent option in this scenario. Finally, central venous access via the internal jugular or subclavian veins may be the safest option. Again, ultrasound has been shown to reduce complications, particularly for the internal jugular approach, and is considered the standard of care in nonemergency situations.

Regardless of the site, this patient needs adequate peripheral or central venous access in a timely fashion, given their need for emergent abdominal surgery and the potential for significant blood loss.

Suggested Readings

1. American Society of Anesthesiologists Task Force on Central Venous Access, Rupp SM, Apfelbaum JL, Blitt C, Caplan RA, Connis RT, Domino KB, Fleisher LA, Grant S, Mark JB, Morray JP, Nickinovich DG, Tung A (2012) Practice guidelines for central venous access: a report by the American Society of Anesthesiologists Task Force on Central Venous Access. Anesthesiology 116:539–573
2. Barcelona SL, Vilich F, Coté CJ (2003) A comparison of flow rates and warming capabilities of the level 1 and rapid infusion system with various-size intravenous catheters. Anesth Analg 97:358–363
3. Berg K, Riesenberg LA, Berg G, Schaeffer A, Davis J, Justice EM, Tinkoff G, Jasper E (2014) The development of a validated checklist of radial arterial line placement: preliminary results. Am J Med Qual 29:242–246
4. Graham AS, Ozment C, Tegtemeyer K, Lai S, Braner D (2007) Central line placement. N Engl J Med 356:e21
5. Harty E (2011) Inserting peripheral intravenous cannulae- tips and tricks. Update Anaesth 27:22–26
6. Jarvis MA, Jarvis CL, Jones PR, Spyt TJ (2000) Reliability of Allen's test in selection for patients for radial artery harvest. Ann Thorac Surg 70(4):1362–1365
7. Jedd Roe E III (2020) Central venous access via infraclavicular (subclavian/subclavicular) approach to subclavian vein technique. eMedicine. https://emedicine.medscape.com/article/80336-technique
8. Ortega R, Sekhar P, Song M, Hansen CH, Peterson L (2008) Peripheral intravenous cannulation. N Engl J Med 359:e26
9. Shiloh AL, Savel RH, Paulin LM, Eisen LA (2011) Ultrasound-guided catheterization of the radial artery: a systemic review and meta-analysis of randomized controlled trials. Chest 139:524–529
10. Tegtmeyer K, Brady G, Lai S, Hodo R, Braner D (2006) Placement of an arterial line. N Engl J Med 354:e13
11. Walters J, McEvoy M (2015) Chap. 16. In: Anesthesia student survival guide. Springer

Intraoperative Problems

17

Andrea J. Strathman

General Concepts

Anesthesiologists have the opportunity and challenge of caring for a wide array of patients ranging from completely healthy to moribund. Despite the complexity and uniqueness of each patient, there are many common problems that occur in the operating room of which you should be aware. It is important that you have a thorough understanding of both physiology and pharmacology in order to care for patients undergoing anesthesia, and in order to be able to recognize and confidently manage intraoperative events.

Unique to the field of anesthesiology is the real-time nature of much of the work. Clinical scenarios often change in a matter of minutes and it is imperative that members of the anesthesia team act quickly to recognize problems that may occur. In doing so, they are often able to diagnose and treat problems before they cause significant harm to the patient. Intraoperative problems typically occur in a setting in which the problem is witnessed from its onset, the patient is extensively monitored, and the past medical and surgical history of the patient is known. As such, while many of the

A. J. Strathman (✉)
Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA
e-mail: astrathm@wakehealth.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_17

underlying principles and goals of ACLS for assessment of patients in unstable, near-arrest, and arrest situations apply, numerous management steps are different. ACLS algorithms are primarily designed for unwitnessed arrests in which the etiology of the arrest is unknown. Intraoperative arrests may also have unknown etiology, but the immediate recognition of these events may result in variations in management given the rapid ability to gather diagnostic information on an anesthetized patient.

The goals of this chapter include providing you with a framework by which to think about the approach to the unstable patient, how you might construct a differential diagnosis for that instability, and the proper steps for initial management of common intraoperative problems. When there is a concern for an acute change in patient condition under anesthesia, having a structured approach for assessment of the patient is beneficial. In this chapter we will focus on a systems-based approach to addressing intraoperative problems. The most common intraoperative issues can typically be put into one of the following categories: cardiovascular, respiratory, toxins (allergies) and temperature/metabolic. This is in no way a comprehensive grouping, but provides a reasonable framework for initial assessment of common intraoperative problems and should help the anesthesiologist to quickly assess a situation and come to a reasonable differential diagnosis and treatment plan. An additional aspect that must always be considered in troubleshooting intraoperative problems are surgery-related issues. For instance, rapid surgical blood loss will indeed result in hypovolemia and likely hypotension. This is not an inherent anesthetic problem, but it requires timely recognition and intervention by the anesthesia team to treat and stabilize the patient.

In an emergency scenario, you should first start by assessing the general hemodynamic state of the patient. First, verify that the concerning information is accurate and not a monitoring or technical problem (blood pressure cuff or pulse oximeter disconnected, technical error with the circuit or anesthesia machine, etc). This should start with the steps of defining whether the patient has a pulse. If not, proceed immediately with advanced cardiac life support (ACLS) management while noting the differences in the operative setting [6, 10]. If the patient has a pulse,

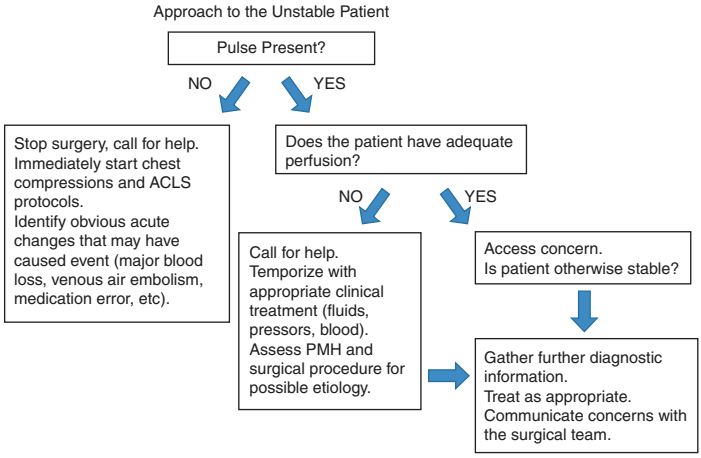


Fig. 17.1 Approach to the unstable patient

then one should define whether there is an acute hemodynamic instability to be addressed. If the patient appears to have adequate cardiac output, then an assessment can proceed to other potential areas of concern noted above, with pulmonary being most important in order to ensure that adequate oxygenation and ventilation are present. A progression of thought through the other possible major categories should be undertaken in sequence. At each step, one should ask the questions outlined in Fig. 17.1, which will aid in constructing a differential diagnoses, picking a leading diagnosis, and then proceeding with initial management plan [14].

Of note, the initial diagnosis may simply be a patient state (e.g. severe hypoxemia) rather than a particular known cause. Thus, in the acute care setting the first step is to ensure that cardiopulmonary function is at a level that meets basic metabolic requirements in order to avert patient harm and then proceed to defining an exact etiology. There are entire books written about intraoperative problems and thus, the following discussion cannot be considered comprehensive. It should, however, provide a solid foundation for understanding some of the most common intraoperative issues that frequently occur. Additionally, the phrase “common things

are common" should always be kept in mind by the anesthesiologist. Malignant hyperthermia, intraoperative pulmonary embolism, local anesthetic toxicity, spontaneous pneumothorax, acute coronary syndrome are all rare events intraoperatively. The morbidity and potential mortality of these events is high, so they must always remain on the differential. However, it is much more common that intraoperative hypotension is related to hypovolemia, medication effects or lack of surgical stimulation. Creating a broad differential, while focusing on the most likely etiology of an intraoperative problem, will help the anesthesiologist to provide the most comprehensive care to the patient. In the following sections, we will explore some of the most common intraoperative problems in a systems-based fashion.

Cardiovascular

The cardiovascular system is often the source of many intraoperative problems as there are numerous forces at play that can affect normal homeostasis in preload, afterload, chronotropy, and inotropy. Disturbances of the cardiovascular system can be thought of originating from the following etiologies: preload, afterload, contractility, valves, vessels (coronary arteries), and voltage (conduction system). Systematically reviewing these six categories provides structure within the cardiovascular system to critically evaluate the patient's condition, formulate a differential diagnosis, and quickly identify and treat the problem. For a more in-depth discussion of cardiovascular physiology, please see Chap. 18.

The most common cardiac events seen in the intraoperative setting are hypotension and hypertension. Hypotension can result from a myriad of causes that fit into each of the more broad categories listed above. Preload is defined as the volume of blood in the right and left ventricles at the end of diastole. This volume is important for determining the strength of contraction, which is due to myocardial stretch at the beginning of systole, according to the Frank-Starling law. The extremes of preload (severe hypovolemia and hypervolemia) both result in reduced cardiac output, but by

different mechanisms. Hypovolemia may be due to preoperative NPO status, surgical blood loss, insensible losses or a combination of all three. Afterload is the systemic vascular resistance that the heart must pump against. Many anesthetic agents cause vasodilation and thus decrease the systemic vascular resistance, resulting in hypotension. Contractility is the inherent ability of the heart to pump blood throughout the body. This can be impacted by anesthetic medications. Preexisting congestive heart failure, myocardial infarction or cardiac tamponade may also be causes of hypotension related to decreased contractility. It is unusual to have an acute valvular issue cause acute hypotension in the perioperative period, however valvular pathology may have significant impacts on the management of anesthetics, which is beyond the scope of this chapter. Coronary arteries (vessels) and their potential for thrombus, vasospasm and infarction are important to consider with acute hypotension without another obvious source. EKG findings may be helpful in determining whether myocardial ischemia is a possible etiology, particularly the V5 tracing. Underlying coronary artery disease or cardiac stents should always be carefully evaluated prior to any anesthetic. The electrical conduction system (voltage) may result in hypotension if there is inadequate cardiac filling (tachycardia), or low cardiac output due to bradycardia. Additionally, acute onset of dysrhythmias may cause hypotension. Other less common causes of hypotension include, but are not limited to: shock (septic, anaphylactic), pneumothorax, vagal responses and reactions to medications [3, 4].

All medications used for anxiolysis, induction, sedation, and maintenance of anesthesia can cause a centrally mediated depression in sympathetic tone. This causes vascular dilation and a decrease in blood pressure from both arterial and venous dilation. This is a predictable consequence of almost all anesthetic inductions and many sedation techniques. Another notable cause of hypotension is perioperative continuation of angiotensin converting enzyme (ACE) inhibitors and angiotensin receptor blockers (ARB). Both classes of medications cause pronounced hypotension in the OR, which is often refractory to standard treatment.

Hypovolemia is also a common cause of hypotension during anesthesia. The American Society of Anesthesiologists guidelines

on preoperative fasting state that patients should be NPO for up to 8 hours prior to surgery [11]. This often results in mild dehydration and the resultant hypovolemia may cause hypotension, which may be even more pronounced after induction with medications that cause vasodilation. Additionally, the geriatric population often takes diuretic medications in order to control hypertension and heart failure. If these medications are not held prior to surgery they can lead to a hypovolemic state. Finally, hypovolemia may be due to acute blood loss from the surgical procedure. While rapid exsanguination is normally obvious, it is important to routinely assess the suction canisters as well as soaked laparotomy sponges in order to account for ongoing blood loss throughout an operation.

It is important to remember that one should aim to keep patient's intraoperative blood pressure within 15–20% of their baseline, as this is important for end organ perfusion. Studies have shown that intraoperative hypotension, with a greater than 40% decrease in mean arterial pressure, can be associated with increased perioperative and postoperative morbidity and mortality. As a fixed cutoff point, one retrospective trial involving over 30,000 patients demonstrated a strong association between the intraoperative duration below a mean arterial of pressure of 55 mmHg and postoperative acute kidney injury, myocardial injury, and all-cause cardiovascular complications [12].

Treatment of acute hypotension involves a rapid assessment of all of the above issues to determine the most likely cause. Most commonly, a small dose of a vasoconstrictor such as phenylephrine (50–100 mcg dosing increments) or ephedrine (5–10 mg dosing increments) will adequately treat the hypotension. If severe hypotension persists, it may be necessary to use stronger alpha and beta agonists including epinephrine, norepinephrine, vasopressin, and dopamine. Should the escalation of presssors become necessary, the anesthesiologist should reevaluate the etiology of the hypotension and assess for other issues causing the persistent hypotension. If there is hypovolemia, a fluid bolus or transfusion of blood products may be necessary. If there is a relative overdose of anesthetic medications, these can be titrated down, taking care to ensure that the patient has an amnestic level of anesthetic on

board at all times. Persistent hypotension of unknown etiology can be further assessed by transthoracic or transesophageal echocardiography, which can occur in real-time and provide helpful diagnostic information [13].

Dysrhythmias may require pharmacologic or electrical treatment, depending on the hemodynamic stability of the patient and the type of dysrhythmia. The most important initial step in assessing dysrhythmia is evaluating for the presence of a pulse. If pulseless, immediate CPR while determining further treatment steps is critically important and allows for maintenance of perfusion to the brain and other organs while treatment of the dysrhythmia occurs. In the community and non-operative health care settings, ACLS algorithms are standardized and followed by all health care professionals [11]. However, the operating room presents a unique setting for the performance of ACLS, which is often modified to a tailored approach for each patient because the anesthesia provider usually witnesses the event, knows the patient's medical comorbidities, and understands the surgical pathophysiology that may have led to the event [6]. Figure 17.2 provides a comprehensive algorithm for the management of dysrhythmia in an unstable patient [8].

Hypertension is also commonly seen in patients who are undergoing surgery. There are fewer purely physiologic causes of intraoperative hypertension, but underlying essential hypertension is one such etiology. Additionally, inadequate anesthesia for the surgical stimulus, surgical pain, tourniquet pain, hypervolemia, hypercarbia and medication response (relative overdose of vasopressors) are all commonly seen sources of hypertension in the operating room. Less commonly seen etiologies for hypertension include acutely increased afterload (aortic cross-clamp), pheochromocytoma, malignant hyperthermia and autonomic hyperreflexia. Common intraoperative medications for treatment of hypertension include beta-blockers (esmolol and labetolol), calcium channel blockers (nicardipine), and vasodilators (nitroglycerin, nitroprusside, and hydralazine).

Bradycardia in an adult is defined as a heart rate less than 60. Some patients may have native heart rates that are below this, which is typically not a problem as long at they can maintain an

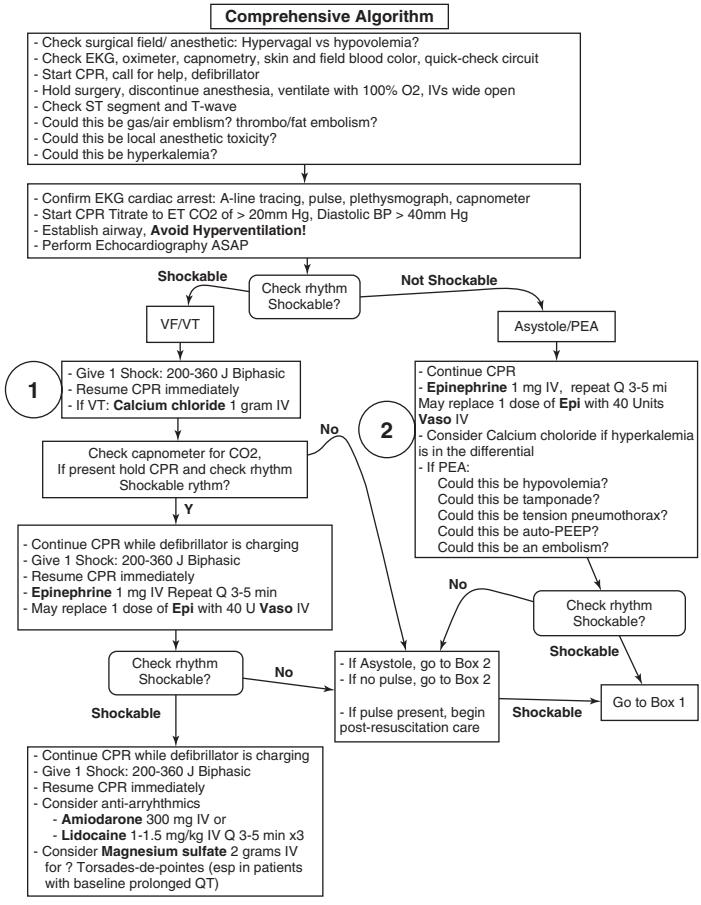


Fig. 17.2 Comprehensive anesthesia-centric ACLS algorithm

appropriate blood pressure. If symptomatic bradycardia develops, refer to Table 17.1 for potential causes. Common causes of bradycardia intraoperatively include a patient who took their beta-blocker preoperatively, administration of vagotonic medications (e.g. fentanyl), reversal of neuromuscular blockade with a cholinesterase inhibitor and insufficient vagolytic agent, and a vagal

Table 17.1 Common causes of pulseless arrest

H's	T's
Hypovolemia	Toxins
Hypoxia	Tamponade
H+ ion (acidosis)	Tension pneumothorax
Hyperkalemia	Thrombosis (coronary or pulmonary)
Hypokalemia	
Hypothermia	Trauma

reaction. Vagal reactions may occur as a result of insufflation of the abdomen during laparoscopy, surgical traction on the eye during ophthalmologic surgery, stimulation of the vagus nerve or a high spinal after a patient receives a subarachnoid block for surgical anesthesia.

If a patient is hemodynamically unstable but still has a pulse, you should give a direct acting chronotrope, such as epinephrine or norepinephrine. Typically 10–25 mcg IV is sufficient to increase the heart rate, but increasing doses and an infusion may be needed depending on the etiology. Anti-cholinergic agents can also be of benefit, but administration of direct-acting chronotropes should not be delayed if the patient is unstable. If chemical chronotropes are not working or if the patient has a 3rd degree AV block, call for help and begin external pacing through defibrillator pads immediately.

Tachycardia can occur due to a wide array of causes. As with other dysrhythmias, consider the common Hs and Ts (i.e. reversible causes) in the perioperative period (Table 17.1). Common surgical causes include hypovolemia (due to acute blood loss, preoperative dehydration, etc), pain/surgical stimulus, and medication administration including anticholinergics and chronotropes. If the patient is acutely unstable due to a tachycardic rhythm, they should undergo synchronized cardioversion (see Fig. 17.2). If the patient is stable (i.e. adequate perfusion pressure and no signs/symptoms of instability), the patient should be further assessed, as this will direct treatment. If the rhythm is wide complex, this should be treated with amiodarone and the patient should be monitored closely for conversion to normal sinus rhythm or hemody-

namic deterioration. All tachycardic rhythms do not require intervention and the etiology as well as the stability of the patient will help guide decision making in these scenarios.

In a normal heart, there is a wide range of hemodynamic parameters at which the heart can still function adequately. However, with an increasingly elderly, obese, and diabetic population, there is a large part of the population with occult coronary artery disease who are susceptible to new ST segment changes consistent with a myocardial ischemia or infarction while in the operating room. Should a patient begin to display signs of myocardial ischemia (ST segment changes, hemodynamic instability, unexplained hypotension or dysrhythmia), the anesthesiologist should alert the surgeon and discuss how to proceed based upon the stage of the operation. Short-term management strategies include optimization of myocardial supply and demand, with a goal of maintaining a normal blood pressure, especially the diastolic pressure, as this is required for coronary perfusion. A heart rate under 65 bpm is ideal as long as perfusion appears normal. Beta-blockers are a first line therapy for this. Nitroglycerin may be useful for coronary vasodilation if the systolic blood pressure tolerates. Anemia, hypothermia, and shivering should be corrected and the administration of antiplatelet therapy and systemic heparinization should be considered, but these latter measures should be discussed with the surgeon and cardiologist prior to initiation [5].

There are a few specific complications that may cause cardiac arrest as a direct result of anesthesia. Many surgeries including orthopedic, urologic, gynecologic, and obstetric procedures are done under either spinal or epidural anesthesia. Approximately 2 out of 10,000 patients who receive neuraxial anesthesia will suffer a cardiac arrest. In this situation, local anesthetic blocks the cardiac accelerator fibers that emerge from spinal levels T1–4 causing bradycardia, sometimes to an extreme level. The block may affect even higher cervical spinal cord levels, which results in the patient having respiratory and neurologic collapse. A high spinal, as it is known, can be treated with airway management to maintain oxygentation/ventilation and hemodynamic support in the form of aggressive dosing of vasopressors [9]. Another cause of

pulseless arrest in regards to anesthesia is unintentional intravascular injection of local anesthetic. This may occur during neuraxial procedures as well as peripheral nerve blocks. It may occur with any local anesthetic and symptoms include tinnitus, metallic taste, hypotension and seizures with potential progression to cardiac arrest. If the patient has suffered an arrest due to local anesthetic systemic toxicity, then a lipid emulsion (10–20%) should be started immediately with adherence to published guidelines, which require reduction of epinephrine doses and avoidance of vasopressin [10].

Gas embolus is another unique event that occurs in the operative setting that is capable of causing hemodynamic instability. A CO_2 embolus may occur with pneumoperitoneum during laparoscopic or vascular surgery. Venous air embolus may occur when there are open venous structres and the surgical field is above the right atrium, most commonly during a craniotomy or a caesarean delivery. Treatment should include stopping the entrainment of air by flooding the surgical field with a crystalloid solution, placing the patient in a position where the surgical field is below the heart and assuring that bony edges are covered. If this occurs during a laparoscopic case, insufflation should be discontinued immediately. Contemporaneously to halting the entrainment of air is giving the patient supportive care, including inotropic and chronotropic support as needed, as well as full ACLS protocols if necessary.

Respiratory

The pulmonary system consists of the rib cage and muscles of respiration, the tracheobronchial tree, alveoli, and the pulmonary capillaries, which together are responsible for gas exchange (both oxygen and carbon dioxide). All components must function in harmony for adequate oxygenation and ventilation to occur. During normal breathing, inspiration requires energy and utilizes diaphragmatic and intercostal muscle activation, and expiration is due to passive recoil. Induction of general anesthesia increases pulmonary dead space and decreases functional residual capacity.

These changes are usually tolerated relatively well in patients with healthy lungs but even in healthy patients, there are many common respiratory complications that can occur.

Normal PaO_2 on room air (21% O_2) is between 85 and 100, and is slightly decreased with increasing age. On supplemental oxygen, such as during general anesthesia, the PaO_2 should be greater than 200. If sudden hypoxemia occurs during an anesthetic, one must first determine the severity of the hypoxemia. Severe hypoxemia may be defined as an SpO_2 of less than 90%, which corresponds to a PaO_2 of under 60 mmHg. An arterial blood gas sample is more sensitive at revealing changes in oxygenation than a peripheral pulse oximeter and and arterial blood gas should be obtained to verify the degree of the hypoxia, as there can be technical difficulties with pulse oximeters giving inaccurate readings in certain clinical scenarios. Physiologic characteristics of hemoglobin described by the hemoglobin-oxygen dissociation curve explain the disparity in results between blood gas sampling and pulse oximeter readings (see Fig. 17.3). Note that at the right side of the curve, the additional PaO_2 from 70 to 100 mmHg and beyond (which represents a significant increase in concentration

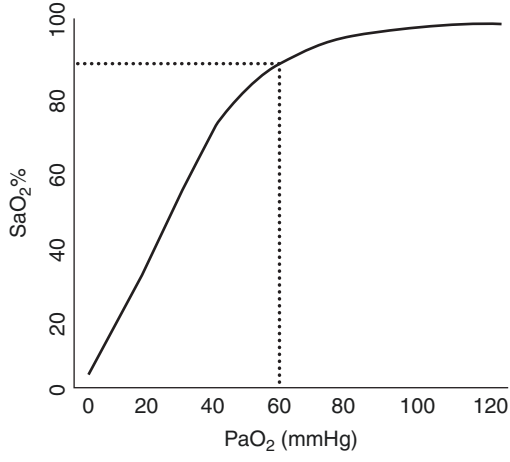


Fig. 17.3 Oxygen saturation curve

in the administered O_2) only increases the oxygen saturation of hemoglobin slightly. In clinical practice, this means that a patient may have a significant alveolar to arterial oxygen gradient that is not detected by pulse oximetry alone. Therefore, time is of the essence when responding to hypoxemia as detected by desaturation on a pulse oximeter, as the problem or process causing the hypoxia may have been going on for quite some time before its severity reached the threshold of the pulse oximeter.

Common causes of acute hypoxia in the operative room include shunt (e.g. mucus plug, endobronchial intubation, ARDS), diffusion defects (e.g. pulmonary edema), alveolar hypoventilation (e.g. asthma, bronchospasm or neuromuscular disease), significant dead space (e.g. high airway pressures), and decreased oxygen carrying capacity of hemoglobin (e.g. hypothermia or carbon monoxide poisoning). Initial treatment for all of these includes administration of FiO_2 1.0, verification of correct placement of the endotracheal tube, manual ventilation to assess lung compliance and chest excursion, assessment of ventilator disconnection or kinking in the tube and circuit, assessment of $EtCO_2$ level and the capnograph waveform, auscultation of the chest, suctioning the endotracheal tube, and considering bronchoscopy to assess for an endobronchial pathology (e.g. mucus plug, tube position, etc.).

One additional cause of a low oximetry reading that is unique to the operating rooms is the administration of intravenous dye used to identify structures during surgery (i.e. indocyanine or methylene blue). The administration of these medications may cause an acute drop in oxygen saturation readings on the pulse oximeter, however this is not actual hypoxemia, but the pulse oximeter misreading the dye as deoxygenated hemoglobin. This usually resolves within 30–60s and is typically not a cause for significant concern.

Hypocarbia is a reflection of decreased carbon dioxide (CO_2) levels as measured by either end-tidal monitoring or a blood gas. It can be due to either increased CO_2 elimination or decreased CO_2 production. The most common cause is hyperventilation (intentional or accidental), however an acute drop in CO_2 may also be a surrogate marker for a sudden drop in cardiac output. Other etiologies include decreased metabolic rate (e.g. hypother-

mia and hypothyroidism), hypovolemia, pulmonary embolism, cardiac arrest, endotracheal tube dislodgement, circuit disconnect, or a disconnected CO_2 sampling line.

The first step in investigating causes of hypocarbia is to check the breathing circuit in order to rule out any loose connections or other mechanical problems. The next step should be to examine the patient's blood pressure, heart rate, and SpO_2 to evaluate for signs of hemodynamic compromise. Finally, if the patient is being mechanically ventilated, one should scrutinize the ventilator settings to ensure they are appropriate, with average settings being a tidal volume of ~6 mL/kg and a rate of 12–16 bpm.

Hypercarbia, as measured by end-tidal CO_2 or blood gas analysis, is a common occurrence during general anesthesia. The normal $EtCO_2$ value is 38–42 mmHg. Hypercarbia may result from either increased CO_2 production or decreased CO_2 elimination. Causes of increased CO_2 production include fever, or a hypermetabolic state such as burns, malignant hyperthermia, shivering, and thyrotoxicosis. Causes of decreased CO_2 elimination from the body include hypoventilation, airway obstruction, atelectasis, residual effects of paralytics or opioids, endobronchial intubation, and an exhausted CO_2 absorber. When thinking about the potential causes of hypercarbia, it is often useful to consider when the hypercarbia is occurring [1, 2]. Elevations in CO_2 at the beginning of a case are more likely to be from improper ETT placement, oversedation, or inadequate ventilator settings, whereas elevated CO_2 at emergence is more likely to be from residual medication effects.

The first step in investigating causes of hypercarbia is to check the pulse oximeter to ensure adequate oxygenation and evidence of circulation. One should also examine the ventilator settings and CO_2 absorber for signs of exhaustion. If the patient is spontaneously breathing, it is often helpful to gently assist the patient or lighten sedation to increase the overall minute ventilation.

The airway pressures measured during general anesthesia with positive pressure ventilation should ideally be less than $40cmH_2O$. Elevated peak airway pressures can cause barotrauma to the lungs and should be avoided. Common causes of elevated peak airway pressures include bronchospasm, endobronchial

intubation, a kinked tube or circuit, the patient biting on the tube, light anesthesia, surgical manipulation, extrinsic compression of the chest or elevated intraabdominal pressures (abdominal compartment syndrome). To address this problem, you should first assess the plane of anesthesia and rule out light anesthesia. Auscultation of the lung fields can help to identify the etiology of elevated airway pressures. Wheezing is a sign of bronchospasm, which can be treated with deepening anesthesia (with propofol or volatile anesthetic), bronchodilators (such as albuterol) or epinephrine. Additionally, diminished breath sounds on one side could signal endobronchial intubation or pneumothorax, which would require repositioning of the endotracheal tube or needle thoracostomy, respectively. Finally, closely examining the circuit and following it from the anesthesia machine to the patient can identify the other causes of elevated peak pressures, including a kinked tube or circuit.

Gastric acid aspiration can occur during intubation, intraoperatively, or during emergence from anesthesia. Aspiration of gastric contents can have devastating effects on the patient including aspiration pneumonitis, pneumonia, acute respiratory distress syndrome and death. Early signs of aspiration may include coughing, hypoxia, wheezing, and cyanosis. Late signs can show lung infiltrates on the chest x-ray and fever.

Prevention includes making sure patients are NPO per the ASA guidelines [10], but if this isn't clinically feasible, performing a rapid sequence intubation without bag-mask ventilation is the safest option. Other preventative measures include administration of a non-particulate antacid within 30 min of induction (sodium citrate), an H2 blocker, and metoclopramide to increase gastrointestinal motility and increase lower esophageal sphincter tone. In some cases where a bowel obstruction is suspected, pre-induction placement of a nasogastric tube may help to decompress the GI tract and decrease the likelihood of aspiration. In situations where a patient is not NPO but a pre-induction nasogastric tube is not placed, an orogastric tube should be placed after induction of anesthesia. This will prevent the risk of aspiration during the surgery, as well as around the time of extubation. If you suspect a patient has aspirated, you should suction the airway and place

them in head-down position to prevent aspirate from entering the lungs. Administer 100% oxygen. Steroids are contraindicated for gastric acid aspiration and there is no indication for antibiotics for aspiration. Bronchoscopy should only be performed if there are large particles that need to be removed from the lungs, otherwise bronchoscopy with lavage should be avoided.

Temperature Disturbances

In patients who are not anesthetized, the hypothalamus is responsible for regulating core body temperatures within a tight range. If body temperature becomes elevated, the hypothalamic reflexes induce sweating and vasodilation whereas, at low temperatures, vasoconstriction and shivering occur. Under general anesthesia, these mechanisms are ablated because of the inhibition of anesthetic agents on central thermoregulation. Thus, both hypothermia and hyperthermia are common problems encountered in the operating room.

A temperature less than 36 °C defines hypothermia, which is a common occurrence intraoperatively. Cold ambient room temperatures, extremes of age (i.e. poor thermoregulation), large abdominal surgeries, and long procedures are all responsible for hypothermia. Without attempts to actively warm the patient, core temperature will usually decrease 1–2 °C during the first hour of anesthesia and then continue to gradually decline for another hour before stabilizing. Severe hypothermia can cause ventricular fibrillation and cardiac arrest. While hypothermia does reduce cerebral metabolic rate and is commonly induced during cardiac procedures with cardiopulmonary bypass, it also causes multiple negative physiologic effects. These include impaired renal function, coagulopathy, impaired wound healing, increased risk of wound infection, decreased activity of drugs, prolongation of neuromuscular blockade and shivering post-operatively, which can increase metabolism and oxygen consumption fourfold. Strategies to warm patients include warming the operating room, using convective forced-air warming, infusing warmed fluids, and using low gas flows.

While hypothermia is commonly encountered in the operating room, hyperthermia is a more rare occurrence, though it can have deleterious consequences if unrecognized and untreated. A temperature greater than 38 °C defines hyperthermia. Causes include overwarming, malignant hyperthermia, sepsis, neuroleptic malignant syndrome, and febrile transfusion reactions. Overwarming can occur due to iatrogenic warming of the patient. Should the patient become overwarmed, the anesthesiologist should cool the patient to return to normothermia. This can be accomplished by include turning off fluid warmers and setting the convective forced-air warmed to blow ambient air, which effectively cools the patient, as well as lowering the OR temperature.

Malignant hyperthermia is a very rare but extremely serious and even fatal complication of general anesthesia. It results from exposure to either a volatile agent or succinylcholine, which causes massive calcium release from the sarcoplasmic reticulum due to a dysfunctional ryanodine receptor. MH is genetically inherited in an autosomal dominant fashion with variable expressivity and penetrance, and can occur with either the first exposure to a triggering agent, or during subsequent exposures. Findings include muscular rigidity, in addition to a hypermetabolic clinical presentation which may manifest with tachycardia, hypertension, increased CO_2 production with elevation in $EtCO_2$ (even during controlled ventilation), and increased temperature. Treatment includes prompt cessation of all triggering agents with conversion to a total intravenous anesthetic and administration of dantrolene IV. Neuroleptic malignant syndrome manifests with similar clinical findings to malignant hyperthermia but is caused by dopamine deficiency, which can develop after administration of antipsychotic drugs [15].

Allergic Reactions

The immune system is a delicate balance of cells whose purpose is to protect the body from foreign pathogens. There are four types of hypersensitivity reactions, with Type I being an antigen-

antibody (IgE) cross-linkage that results in a large release of inflammatory mediators from mast cells. Anaphylaxis is a type I hypersensitivity reaction. Other type I reactions include atopic reactions, urticarial reactions, and angioedema.

Anaphylaxis is a shock state that results when the body is exposed to an antigen to which it has already been sensitized. Once triggered, mast cells release histamine, leukotrienes, and kallikreins, which cause increased vascular permeability, bronchial smooth muscle contraction, and vasodilation. The result is severe hypotension, circulatory collapse, and possibly death. Clinical presentation may be variable, but profound hypotension in concert with bronchospasm and a visible rash is the most common presentation. In the perioperative setting, the most common cause of anaphylaxis is neuromuscular blockers, both depolarizing (succinylcholine) and non-depolarizing. Other common causes include latex and antibiotics Anaphylactoid reactions are similar, and often indistinguishable from anaphylactic reactions, but they are not IgE mediated. A medication may cause either cause direct histamine release from mast cells or it can cause activation of the complement cascade.

Regardless of whether the reaction is thought to be anaphylactic or anaphylactoid, the treatment is the same. First, discontinue the suspected agent and make sure the patient is receiving 100% oxygen. Next, assess the cardiopulmonary state of the patient. Immediately administer a bolus of IV fluids. If cardiac instability is present, administer epinephrine 10–25 mcg IV with increasing doses every 30–60s until the patient is stabilized, noting that an infusion is frequently needed due to the bimodal nature of most severe reactions. If wheezes are present, administer a bronchodilator, such as albuterol. If the patient has not already received epinephrine, a low dose is an effective treatment for refractory bronchospasm. If the patient is not intubated, assess their airway and determine if they need invasive ventilatory support. After initial stabilization is underway, it is also recommended to administer hydrocortisone, an H1-blocker (e.g. diphenhydramine), and an H2-blocker (e.g. ranitidine or famotidine). Finally, continue to provide circulatory support with IV fluids, vasopressors, especially epinephrine, and proceed with ACLS if necessary. Tryptase levels should be sent to the laboratory for confirmation of an ana-

phylactic reaction. After recovery, the patient should be referred to an allergist with a comprehensive list of all possible triggers for their anaphylaxis so that they may be appropriated tested and counseled on their results.

The risk of serious reactions from blood transfusion is very rare as our system has become much safer, but both major and minor reactions to blood can still occur. When patients need blood products in the operating room, they should receive blood that is typed and cross-matched (with the exception of trauma patients who may receive type O, if their type is unknown). The most severe reaction is ABO incompatibility, which results in an acute hemolytic reaction. Administration of incorrectly typed blood is usually due to a misidentification of the patient, their blood type, or the unit transfused. The risk of a fatal hemolytic transfusion reaction is about 1 in every 100,000 transfusions administered. Common signs of an acute hemolytic reaction in an awake patient include chills, fever, nausea, and chest pain. If the patient is anesthetized, signs may include temperature elevation, circulatory instability (hypotension, tachycardia), hemoglobin in the urine, and coagulopathy (DIC may develop). Management includes immediately stopping the unit being transfused, sending both the unit of blood, as well as a sample from the patient to the lab for further testing. Additional management includes diuresing the patient and providing circulatory support.

Transfusion related acute lung injury (TRALI) presents within 6 h of transfusion and is the most common cause of mortality related to administration of blood products. The patient will become acutely hypoxemic and develop non-cardiogenic pulmonary edema. It most often occurs after administration of FFP, platelets, or after massive transfusion where large volumes of blood products were given. These patients usually require prolonged mechanical ventilation and supportive care. No definitive treatment is available for TRALI, but with supportive care the patient's oxygenation often improves and return to normal in 2–3 days.

Finally, febrile transfusion reactions are non-hemolytic and usually minor. They are allergic reactions and often due to either white cell or platelet sensitization. Patients are often pre-medicated with diphenhydramine and acetaminophen in the non-operative setting in order to avoid concerns. If a patient exhibits signs of

significant allergy, the transfusion should be stopped immediately and further conversation should occur with the blood bank.

Post Operative Complications

Neurologic complications have not yet been discussed in this chapter, but are potential complications that may occur while a patient is under anesthesia. Many of these complications are not noticed intraoperatively due to the inability to assess the neurologic status of a patient under general anesthesia. Stroke, blindness, corneal abrasions, and positioning-related neuropathies are all possible complications.

The most common of these complications is a corneal abrasion, which tends to occur during intubation (before the eyes are taped closed) or during emergence (when patients tend to rub their eyes). These injuries are usually mild, are not recognized until the patient is in the recovery room, and usually heal within several days. Treatment includes the use of eye lubricant or antibiotic eye drops.

Neuropathies are also commonly encountered post-operatively. Positioning during general anesthesia is extremely important and vigilance with positioning can help avoid many neuropathies. The most common neuropathy encountered is ulnar, which usually happens when the arm is pronated with compression of the ulnar nerve within the cubital tunnel. Common peroneal neuropathy is the most common lower extremity neuropathy, and occurs from compression of the nerve against the fibular head during lithotomy position. Careful positioning of the patient during prep, as well as frequent reassessment, may help to decrease the risk of positioning-related neuropathies. Other measures include moving or changing positions of the extremities during lengthy procedures. It is important not to hyperextend the elbow and to be cognizant of some patients' flexion deformities, which may make it impossible to fully extend some joints.

Postoperative visual loss (POVL) is a rare but devastating complication. POVL is associated with specific patient risk factors such as lengthy surgery, prone position, anemia, edema of the

orbit, and hypotension. Postoperative blindness has also been particularly associated with prone spine surgery cases and cardiopulmonary bypass. The two most common etiologies are ischemic optic neuropathy (related to hypotension, anemia and degree of blood loss) or central retinal artery occlusion (commonly caused by direct pressure on the orbit). Should postoperative blindness occur, an ophthalmologic consultation should be obtained and a careful eye exam documented.

Stroke is also a devastating complication in the operative setting. Should a patient not proceed through emergence from anesthesia as expected, this diagnosis should be considered. When considered, other common causes of delayed emergence should be ruled out, including residual neuromuscular blockade, hypoglycemia, hypoxemia, and hypercarbia. If stroke is still being considered, a neurologic consult should be requested immediately, a non-contrasted CT scan should be ordered STAT, and the surgical team should be notified of the concern. Patients who have had previous strokes may have a differential emergence from anesthesia, in which they manifest some degree of their previous stroke-like symptoms as they begin to emerge from anesthesia. This should be transient and the patient should quickly return to their pre-procedure baseline. If they do not, further workup is indicated.

Intraoperative awareness is another rare complication in the operative setting. Studies cite rates of intraoperative awareness between 1–2 per 1000 surgical cases [7]. However, certain types of surgical cases have higher rates and thus, the true risk of unintentional recall is not well delineated. Caesarean deliveries under general anesthesia, cardiac cases and emergency/trauma cases are at high risk for intraoperative awareness. Intraoperative recall may occur when a patient is paralyzed with neuromuscular blockers but does not have an adequate level of amnestic agents. Thus, they may be able to hear and feel things, but not respond or alert the anesthesiologist that they are aware. Scenarios in which this may occur include a profoundly unstable patient (trauma) that cannot tolerate any anesthetic and maintain an adequate blood pressure, a broken or empty vaporizer, infiltrated IV during a total IV anesthetic (TIVA), provider distraction (particularly after

repositioning a patient) or an inadequate dosing scheme. It is important to realize that sudden tachycardia and hypertension may be the first clinical signs of intraoperative awareness. Should there be a suspicion of the risk of recall, the anesthetic should be immediately deepened and the anesthesiologist should follow up with the patient after they have recovered from their anesthetic. It is important to note that many patients will recall being in the operating room either prior to induction or immediately after emergence, or will remember being extubated. Many patients also recall cases in which they were not under general anesthesia, but rather had a peripheral nerve block, neuraxial or sedation for their procedure. These scenarios may be moderately distressing to patients, but do not meet the criteria for intraoperative awareness. Should true recall occur, the patient should be given the opportunity to discuss the events with the anesthesiologist and risk management should be contacted.

Case Study

Now that you have a thorough understanding of common problems encountered during anesthesia, it's time to test your knowledge.

A 52-year-old male is undergoing proctocolectomy for rectal cancer. He was admitted this morning for the operation after undergoing a bowel prep at home the day before. Vital signs were as follows: BP 130/84, HR 80, RR 14, O2 98% on room air. He does not take any medications. Anesthesia was induced with propofol and vecuronium and intubation was uneventful. You have placed a peripheral IV, a right internal jugular central line, and a right radial arterial line. You are infusing cefazolin prior to incision.

Five minutes after induction, the blood pressure has decreased to 82/50. What is the differential diagnosis? What will your initial steps be to manage his blood pressure?

The patient is likely hypovolemic after his bowel prep the day before surgery and his overnight fast. Induction agents frequently lead to vasodilation and in some cases myocardial depression, both of which can cause hypotension even in normovolemic patients. The combination of induction agent (propofol) and volume depletion is the most likely etiology. Other common causes of hypotension early in a case include relative anesthetic overdose, when the anesthetic dose exceeds that required for the amount of surgical stimulation. Incision has not taken place yet, and it has been several minutes after laryngoscopy, so stimulation is likely very light. In this case, you will most likely treat with intravenous fluids to counteract hypovolemia and a vasoconstrictor such as phenylephrine, 100–200 mcg.

The differential diagnosis also includes rarer but serious causes, including anaphylaxis from the antibiotic (cefazolin) or the neuromuscular blocking drug (vecuronium), or pneumothorax from central line placement. One should also rule out data collection artifact by comparing the tracing on the arterial line to the reading on the blood pressure cuff.

Your intervention is successful and the case begins. The patient develops tachycardia in the first few minutes. What is your differential diagnosis and initial response?

The first response is to determine whether it is sinus tachycardia or a dysrhythmia. Abnormal rhythms are more likely to be accompanied by normal or low blood pressure; sinus tachycardia is more likely to parallel hypertension. Initial incision is one of the more stimulating aspects of the procedure, and light anesthesia is a common cause of tachycardia, often preceding by a few seconds or minutes the development of hypertension. If this is the case, then deepening of anesthesia by increasing the inspired concentration of volatile anesthetic or administration of a opioid would be prudent.

The patient's hemodynamic status has stabilized and the case is proceeding. 15 min later the patient's oxygen saturation begins to decrease and is now 90%. The patient is breathing 50% oxygen and 50% air by volume controlled ventilation. What is your differential diagnosis? What will be your response?

Hypoxia demands a prompt response. The first step is to increase the FiO_2. You can then check for adequacy of ventilation by observing the CO_2 tracing on the capnograph, and the reading on the exhaled gas volume monitor. Most anesthesiologists will immediately listen to breath sounds to ensure that they are equal, bilateral, and free from wheezes or rhonchi. Common causes at this stage include migration of the endotracheal tube into the right mainstem bronchus (particularly if the patient's position has changed), and mucus plugging of the endotracheal tube or a bronchus. If unequal breath sounds are heard, checking insertion depth of the tube, possibly verifying proper position with a bronchoscope, or empirically pulling the tube back slightly are all reasonable interventions. Suctioning of the tube with a flexible suction catheter is a prudent maneuver, particularly if breath sounds are unequal or diminished, and/or if airway pressures are increased.

Your initial response to hypoxia has raised the saturation to 92% on 100% oxygen. Auscultation of the lungs reveals bilateral wheezes on exhalation. What steps will you take?

Wheezing can be due to reactive airway disease, or more rarely to anaphylaxis, aspiration of gastric contents, or cardiac failure. The initial steps in management are to ensure adequate oxygen delivery (by increasing FiO_2, checking the circuit, tube, and ventilator settings) and length of exhalation time (by decreasing the respiratory rate or the I:E ratio). Deepening the anesthetic with inhalation anesthetics, which are potent bronchodilators, may help. Inhaled beta-adrenergic agonists administered into the endotracheal tube will

help treat bronchospasm. Far more than the usual 1–2 puffs given to awake patients is needed, typically 5–10 puffs, as much drug is lost in the tubing and upper part of the trachea. A side effect of inhaled beta-agonists will cause tachycardia, this should be considered as some patients may not tolerate this tachycardia.

The wheezing has resolved but the patient develops tachycardia and ST segment depressions. How will you respond?

There are many possible causes of myocardial ischemia, and the tachycardia from beta-adrenergic drugs is one possibility. However, the etiology is less relevant intraoperatively, it is more important to manage the ischemia and evaluate the source after the patient is stabilized. The initial steps include ensuring or augmenting coronary perfusion pressure; if the patient is hypotensive or even significantly below their preoperative baseline, raising the blood pressure with phenylephrine is indicated. Tachycardia from albuterol or other inhaled beta agonists is usually short lived, but a short acting beta-1-selective beta blocker (esmolol) will slow the heart rate without causing bronchospasm. Nitroglycerin may be administered intravenously if hemodynamic maneuvers fail to resolve the ST segment depressions. The patient should be evaluated postoperatively for ischemia and possibly for myocardial infarction.

References

1. Adrogue H, Madias N (1998) Management of life-threatening acid-base disorders. First of two parts. N Engl J Med 338:26–34
2. Adrogue H, Madias N (1998) Management of life-threatening acid-base disorders. Second of two parts. N Engl J Med 338:107–111
3. Barash PG, Cullen BF, Stoelting RK (eds) (2013) Clinical anesthesia, 7th edn. Lippincott Williams and Wilkins, Philadelphia
4. Butterworth JF et al (2013) Morgan and Mikhail's clinical anesthesiology, 5th edn. McGraw-Hill Education

5. Kheterpal S, O'Reilly M, Englesbe MJ et al (2009) Preoperative and intraoperative predictors of cardiac adverse events after general, vascular, and urologic surgery. Anesthesiology 110:58–66
6. Laffey JG, Kavanagh BP (2002) Hypocapnia. N Engl J Med 347:43–53
7. Mashour G, Orser BA, Avidan MS (2011) Intraoperative awareness: from neurobiology to clinical practice. Anesthesiology 114(5):1218–1233
8. Moitra VK, Gabriella A, Macciolo G, O'Connor M (2012) Anesthesia advanced circulatory life support. Can J Anesth 59:586–603
9. Neal JM et al (2010) The ASRA evidence-based medicine assessment of ultrasound-guided regional anesthesia and pain medicine: executive summary. Reg Anesth Pain Med 35(2):S1–S9
10. Part 8: Adult advanced cardiovascular life support: 2010 (2010) American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. Circulation 122(suppl 3):S729–S767
11. (2017) Practice guidelines for preoperative fasting and the use of pharmacologic agents to reduce the risk of pulmonary aspiration: application to healthy patients undergoing elective procedures: an updated report by the American Society of Anesthesiologists Task Force on preoperative fasting and the use of pharmacologic agents to reduce the risk of pulmonary aspiration*. Anesthesiology 126(3):376–393
12. Sessler DI, Sigl JC et al (2013) Hospital stay and mortality are increased in patients having a "triple low" of low blood pressure, low bispectral index, and low minimum alveolar concentration of volatile anesthesia. Anesthesiology 166(6):1195–1203
13. Walsh M, Devereaux PJ, Garg AX, Kurz A, Turan A, Rodseth RN, Cywinski J, Thabane L, Sessler DI (2013) Relationship between intraoperative mean arterial pressure and clinical outcomes after noncardiac surgery: toward an empirical definition of hypotension. Anesthesiology 119:507–515, 520
14. Westman A, McEvoy M (2015) Chapter 17. In: Anesthesia student survival guide. Springer
15. Yao FF, Fontes ML, Malhotra V (eds) (2012) Yao and Artusio's anesthesiology: problem oriented patient management, 7th edn. Lippincott Williams and Wilkins, Philadelphia

Part V

Systems Physiology and Anesthetic Subspecialties

Cardiac and Thoracic Anesthesiology

18

Laura S. González and Hemanckur Makker

Key Learning Objectives

- Learn relevant cardiovascular physiology and common pathologic conditions
- Understand the anesthetic considerations for cardiac surgery
- Learn thoracic physiology and anesthetic considerations for thoracic surgery

Cardiac Anesthesia

Normal Cardiovascular Anatomy

The heart is made up of four distinct chambers, two atria and two ventricles. A fibrous tissue skeleton forms the annuli of the four valves and the roots of the aorta and pulmonary artery, and supports the structure of the valves. The three layers of the heart tis-

L. S. González (✉) · H. Makker
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: lagonzalez@mcw.edu; hmakker@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_18

sue include the endocardium, myocardium, and epicardium. The **endocardium** is a single cell layer on the inner surface of the heart valves, atria, and ventricles, and is in direct contact with the blood. The **myocardium** is the muscle layer of the heart and makes up the bulk of cardiac mass. The muscle fibers are angled to allow the left ventricle to both shorten and twist during contraction. The **epicardium** is a connective tissue layer that covers the external surface of the heart and makes up the **visceral pericardium** that, together with the **parietal pericardium**, comprises the **pericardial sac**. The pericardial sac is normally filled with a small amount of pericardial fluid, which minimizes friction during contraction of the muscle.

- **Vascular Supply**

  There are two main coronary arteries, the **right coronary artery** and the **left main coronary artery**, which arise from the aortic root. The left main coronary artery bifurcates into the **left circumflex (LCX)** and **left anterior descending (LAD) arteries**. The LCX provides blood flow to the lateral wall of the left ventricle, while the LAD supplies the anterior surface of the left ventricle and the anterior portion of the interventricular septum. The right coronary artery gives rise to the **posterior descending artery (PDA)** in 80% of patients ("right dominant circulation"); in the remaining 20%, the PDA arises from the LCX artery ("left dominant circulation"). The PDA supplies the right ventricle and the posterior portion of the interventricular septum. Because left ventricular pressure exceeds aortic pressure during systole, it receives the majority of its perfusion during diastole (when aortic pressure exceeds left ventricular pressure). The right ventricle generates lower pressures during systole and is therefore perfused during both systole and diastole.

  Venous drainage of the heart occurs in parallel to the arterial supply. The coronary veins drain into the coronary sinus, which returns deoxygenated blood to the right atrium.
- **Valves**

  The valves of the heart ensure unidirectional blood flow throughout the cardiac cycle, and open and close based on the

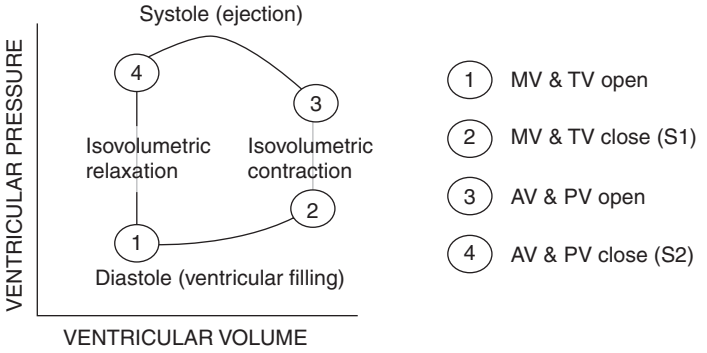


Fig. 18.1 The cardiac cycle. Abbreviations: AV aortic valve, MV mitral valve, PV pulmonic valve, S1 first heart sound, S2 second heart sound

pressure changes during the cardiac cycle (Fig. 18.1). The atrio-ventricular valves open during diastole to allow ventricular filling and prevent backflow from the ventricle into the atrium during systole, while the semilunar valves open during systolic ejection and prevent backflow from the great vessels into the ventricles during diastole.

The **tricuspid valve** (TV) is the trileaflet atrioventricular valve that separates the right atrium from the right ventricle. The **pulmonic valve** (PV) has three cusps and allows ejection of blood from the right ventricle into the pulmonary artery during systole. The **mitral valve** (MV) has two leaflets (anterior and posterior) and separates the left atrium from the left ventricle. During systole, the mitral valve closes and backflow of blood into the left atrium is prevented by the papillary muscles, which are extensions of the left ventricular myocardium that attach to the mitral valve leaflets via chordae tendinae and pull them taut to prevent prolapse. The **aortic valve** (AV) has three cusps and opens during systole to allow ejection of blood from the left ventricle into the aortic during systole.

- **Conduction System**

  Within the heart, the conduction system contains cells capable of initiating electrical activity and rapidly conducting action potentials throughout the cardiac chambers. The **sino-**

atrial (SA) node is a bundle of cells in the right atrium that are commonly referred to as the pacemaker of the heart. An impulse started in the SA node is then conducted to the **atrio-ventricular node**, into the **Bundle of His** which splits into the right and left bundle branches and terminates in Purkinje fibers, which propagate the action potential through the ventricles.

Normal Cardiovascular Physiology

- **Cardiac Cycle**

  The cardiac cycle encompasses all the electrical and mechanical events that must occur in order for the ventricles to fill with blood during diastole and eject blood during systole (Fig. 18.1).

  During **diastole**, a period of **isovolumic relaxation** occurs as the ventricles relax but all four cardiac valves remain closed. When ventricular pressure drops below atrial pressure, the tricuspid and mitral valves open, allowing **ventricular filling** to occur. Early ventricular filling occurs during the active relaxation phase of diastole, when blood from the superior vena cava and inferior vena cava drain into the right atrium through the open tricuspid valve into the right ventricle; blood from the four pulmonary veins drains into the left atrium and then into the left ventricle through the open mitral valve. Late ventricular filling occurs with atrial contraction. As the electrical impulse is conducted throughout the ventricles this leads to systole, which begins with **isovolumic contraction**: as ventricular pressure rises, the atrio-ventricular valves (TV, MV) close (producing the S1 heart sound). During this time, ventricular pressure is not yet high enough to open the semi-lunar valves and ventricular volume remains constant. Once ventricular pressure exceeds the pressure in the great vessel downstream, **systolic ejection** occurs; increased ventricular pressure allows ejection of blood into the pulmonary artery and aorta as the semilunar valves (PV and AV) open. After ejection, the pressure the ventricle begins to fall, the pressure in the great vessels once again exceeds the pressure in the ven-

tricles, and the semilunar valves close (leading to the S2 heart sound).

The amount of blood ejected during systole is referred to as the **stroke volume**, and it equals the **end diastolic volume** minus the **end systolic volume.** The **ejection fraction** is the stroke volume divided by the end diastolic volume and provides an assessment of overall ventricular function (See Table 18.1).

- **Myocardial Oxygen Supply and Demand**

  Myocardial oxygen supply is determined by the coronary perfusion pressure (CPP, equal to the aortic diastolic pressure minus left ventricular end diastolic pressure), heart rate (lower rate and more diastolic time increase supply), hemoglobin concentration, oxygen saturation, and coronary blood vessel diameter. Because the left ventricle is perfused during only diastole,

Table 18.1 Cardiac Physiology Definitions & Equations

Cardiac output (CO)	Volume of blood pumped per minute.
	CO = HR × SV CO = (MAP-CVP)/SVR
Fick equation	CO = VO_2 /([CaO_2] – [CvO_2])
Stroke volume (SV)	Amount of blood pumped with each contraction LV SV = LVEDV –LVESV
Ejection fraction (EF)	LV EF = LV SV / LVEDV
Preload	Volume of blood in the ventricle before systole LV end-diastolic pressure (LVEDP) is often used to estimate LVEDV
Afterload	Resistance to ejection of blood from the ventricle
Coronary perfusion pressure (CPP)	CPP = aortic diastolic blood pressure – LVEDP
Left ventricular wall tension	Wall tension = (interventricular pressure × chamber radius)/(thickness × 2)

Abbreviations
CaO_2 arterial oxygen content, *CvO_2* venous oxygen content, *CO* cardiac output, *CVP* central venous pressure, *HR* heart rate, *LV* left ventricle, *LVEDP* Left ventricular end-diastolic pressure, *LVEDV* Left ventricular end diastolic volume, *LVESP* Left ventricular end-systolic pressure, *MAP* mean arterial pressure, *SV* stroke volume, *SVR* systemic vascular resistance, *VO_2* oxygen consumption

any factor affecting diastolic time also impacts myocardial oxygen delivery. Myocardial oxygen demand is determined by heart rate, myocardial contractility, left ventricular wall tension, and left ventricular end diastolic pressure. Coronary blood flow is determined by coronary perfusion pressure, myocardial compression of vessels, myocardial metabolism, and neurohormonal controls (parasympathetic and sympathetic innervation).

Cardiac Pathophysiology

- **Ischemic Heart Disease**

  Ischemic heart disease is a leading cause of death in the United States. Atherosclerosis of the coronary arteries, which results in inflammation, lipid accumulation, and smooth muscle growth in the arterial wall, produces impaired endothelial function, partially or completely occludes coronary vessels over time, and/or leads to formation of plaques which are vulnerable to rupture and acute occlusion. These atherosclerotic lesions result in impaired coronary blood flow and oxygen delivery to the myocardium and can produce symptoms of ischemia (see below).

  Treatment for ischemic heart disease ranges from medical management with anti-platelet agents, statins, and beta blockers; to percutaneous coronary interventions such as stenting; to surgery (coronary artery bypass grafting). Revascularization therapy with stenting or surgery may be undertaken semi-electively in a patient with no symptoms or stable angina, or can be performed urgently or emergently in patients with ongoing ischemia, myocardial infarction, or cardiogenic shock. The precise indications for when to use each technique are complex. Indications for surgery typically include significant stenosis of the left main coronary artery, significant stenosis of multiple vessels, concomitant valvular disease, or complex anatomy for stenting. The diseased segment of the coronary artery is bypassed with a vein (saphenous vein graft) or artery (internal mammary artery or radial artery) that is

anastomosed proximally to the aorta (not required for internal mammary grafts) and distally to a segment of coronary artery.

- **Valvular Heart Disease**
  - **Aortic insufficiency**

    Aortic insufficiency (AI) results in flow from the aorta retrograde into the left ventricle during diastole. AI is caused either by dilation of the aortic root (i.e. aortic aneurysm, aortic dissection, aortic trauma, Marfan syndrome or other connective tissue disorder) or damaged/abnormal valve leaflets (endocarditis, rheumatic disease, or congenital bicuspid aortic valve). If AI develops acutely (as in aortic dissections or endocarditis), the sudden increase in left ventricular end diastolic volume leads to pulmonary edema, left heart failure, and hypotension/cardiogenic shock. With chronic AI, the left ventricle has time to adapt to the increased volume and over time, this produces left ventricular dilation that untreated can lead to left ventricular dysfunction, symptoms of left ventricular failure such as dyspnea or chest pain, and pulmonary edema. While acute AI is often a surgical emergency (especially when precipitated by trauma, aortic dissection, or endocarditis), chronic AI is addressed surgically only when symptomatic or in the presence of left ventricular dysfunction.

    The goals of anesthetic management in patients with AI are to maintain systolic function and contractility, maintain sinus rhythm, and prevent increases in afterload or bradycardia. A higher heart rate decreases diastolic time and reducing afterload decreases the regurgitant fraction of each stroke volume, both of which promote forward flow of blood.
  - **Aortic Stenosis**

    Aortic stenosis (AS) is narrowing of the aortic valve opening that increases the pressure gradient across the valve, obstructs blood flow to the aorta, leads to a fixed stroke volume, and increases left ventricular afterload. Most cases of AS are caused by senile calcific degeneration or congenital bicuspid valve disease; rheumatic AS occurs less commonly. An aortic valve area of 1–1.5 cm^2 or a mean gradient of 20–40 mmHg is considered moderate AS, 0.7–0.9 cm^2 valve area and/or mean gradient of >40 mmHg is severe AS, and

critical AS is a valve area <0.7 cm^2. Treatment of aortic stenosis involves either opening the calcified leaflets (percutaneous balloon valvuloplasty) or replacing the valve surgically or via a percutaneous technique (transcatheter aortic valve replacement [TAVR]). While initially TAVR was reserved for patients who were too frail or had a prohibitively high surgical risk, this procedure is increasingly used for patients with moderate surgical risk.

The goals of anesthetic management in patients with aortic stenosis include adequate preload, maintenance of sinus rhythm, and avoidance of tachycardia (to allow for adequate ventricular filling volume and time). It is also critically important to avoid decreases in systemic vascular resistance (SVR), which lead to decreased coronary perfusion pressure and can quickly precipitate ischemia, decreased stroke volume, and cardiogenic shock in a hypertrophied left ventricle (Table 18.2).

– **Mitral Regurgitation**

Mitral regurgitation (MR) is backflow of blood from the LV into the left atrium during systole due to failure of the MV apparatus (leaflets, chordae tendinae, or papillary muscles). Because the MV apparatus is a complex structure, there are

Table 18.2 Anesthetic Management of Valvular Heart Disease

Valvular Lesion	Heart rate & rhythm	SVR	PVR
Aortic insufficiency (AI)	Avoid bradycardia	Low-normal	
Aortic stenosis (AS)	Avoid tachycardia	Maintain	
Mitral regurgitation (MR)	Avoid bradycardia	Low-normal	
Mitral stenosis (MS)	Maintain sinus rhythm, avoid tachycardia	Maintain high-normal	Prevent increases

Abbreviations
AI aortic insufficiency, *AS* aortic stenosis, *MR* mitral regurgitation, *MS* mitral stenosis, *PVR* pulmonary vascular resistance, *SVR* systemic vascular resistance

multiple potential etiologies of MR, including myxomatous degeneration of the leaflets, chordae elongation or rupture, perforation of the valve leaflets, ischemic heart disease (affecting either the papillary muscles or leading to left ventricular failure and dilation which produces restricted, stretched valve leaflets), or rheumatic heart disease. Less common causes include endocarditis and hypertrophic obstructive cardiomyopathy (which promotes systolic anterior motion of the mitral valve and leads to both MR and LV outflow tract obstruction). Acute MR is not well tolerated, as the backflow of blood is transmitted directly to the pulmonary vasculature and can lead to pulmonary edema. Chronic MR leads to left atrial dilation to accommodate the increased volume, pulmonary hypertension, and decreased cardiac output over time as the regurgitant fraction increases, leading to increased backflow of blood and decreased forward flow. Medical management of MR includes vasodilators to reduce afterload and inotropic agents; definitive treatment of regurgitant lesions can be performed with open surgery (valve replacement or valve repair with a ring and/or replacement of chordae tendinae) or with a percutaneous catheter-based intervention where clips are placed to bring the anterior and posterior leaflets together and reduce the size of the orifice through which regurgitation can occur.

The goals of anesthetic management in patients with MR include maintenance of forward stroke volume by achieving a relatively higher heart rate (reduce time during which MR can occur), avoidance of cardiac depression, and avoiding a significant increase in SVR (which worsens regurgitation by increasing resistance to forward ejection of blood out of the left ventricle) (Table 18.2).

– **Mitral Stenosis**

Mitral stenosis (MS) occurs when narrowing of the MV opening increases the gradient across the valve and prevents adequate flow of blood from the left atrium to LV during diastole. This leads to increased left atrial pressure and raises pulmonary vascular resistance, decreased left ventricular filling,

and decreased stroke volume/cardiac output. A MV area of <2 cm^2 with a mean gradient <5 mmHg is considered mild mitral stenosis; an area <1 cm^2 or a gradient >10 mmHg is considered severe mitral stenosis. Surgical treatment includes medical therapy, balloon valvuloplasty to open the valve, surgical mitral commissurotomy to open the valve, or mitral valve replacement.

The goals of anesthetic management in patients with MS include targeting a low/normal heart rate to maximize diastolic filling time, maintenance of sinus rhythm (loss of atrial kick significantly reduces left ventricular preload), normal preload/stroke volume, preventing decreases in SVR, and preventing increases in pulmonary vascular resistance due to hypoxia, hypercarbia, acidosis, or pain (Table 18.2).

- **Heart Failure**

  Heart failure occurs when the heart can no longer pump adequate blood flow to the body to meet its metabolic requirements. Heart failure can be acute or chronic and can occur due to dysfunction of one or both ventricles. In its most severe form, it leads to cardiogenic shock, a condition where inadequate cardiac output leads to end-organ dysfunction. Medical therapy for heart failure includes diuretics, blockade of the renin-angiotensin-aldosterone system, beta blockers, inotropes, and/or vasodilators. Surgical therapy for heart therapy varies widely and includes placement of assist devices to augment cardiac output or heart transplant. Short-term support devices include intra-aortic balloon pumps (which inflate during diastole to improve CPP and deflate during systole to decrease afterload), percutaneous ventricular support devices such as the TandemHeart or Impella (which use an external pump to augment native cardiac output via a percutaneously inserted device), or veno-arterial extracorporeal membrane oxygenation (VA ECMO), in which blood is removed from the body, oxygenated, and pumped back to the body by an external pump. These devices may be placed in the operating room or cardiac catheterization suite. Long-term support devices

include implantable left ventricular assist devices (LVAD) and heart transplantation, both of which can offer definitive therapy for end-stage heart failure in appropriately selected patients.

- **Arrhythmias**

  Patients can present with arrhythmias related to ischemia or mechanical triggers (i.e. scarring, fibrosis, atrial enlargement), and these arrhythmias can be classified as supraventricular tachyarrhythmias (atrial fibrillation, atrial flutter, atrial tachycardia, atrioventricular reciprocating tachycardia [AVRT], or atrioventricular nodal reentrant tachycardia [AVNRT]), ventricular arrhythmias (ventricular tachycardia, ventricular fibrillation), sinus node dysfunction (i.e. sick sinus syndrome), or AV block (i.e. second-degree Mobitz type I block, complete heart block). Depending on the etiology and severity of symptoms, treatment may include medication management, cardiac electrical implantable devices (CIED) such as a pacemaker or implantable cardioverter/defibrillator (ICD), or catheter-based ablation.

  Management of CIED in the perioperative period is a multidisciplinary endeavor. Depending on their settings, pacemakers can be inhibited by electrocautery, and should be placed in an asynchronous mode (cannot be inhibited) by either placement of a magnet or device reprogramming by a member of the CIED team [1]. An ICD should have all tachytherapies disabled to prevent unnecessary shock delivery in response to electrocautery inference, which can be interpreted by the ICD as fibrillation. Magnet placement over an ICD disables tachytherapies; any pacemaker function is typically left intact, so pacemaker-dependent patients with combination pacemaker/ICD devices should undergo device reprogramming if electrocautery interference is anticipated. Whenever tachytherapies are disabled, the patient should have defibrillator patches applied, and a defibrillator should be immediately available in the procedure room or operating room.

Anesthetic Management for Cardiac Surgery

- **Preoperative Evaluation**

  Patients presenting electively for cardiac surgery will typically have undergone an extensive workup to investigate the severity of their disease process, rule out co-existing valve or coronary disease, and uncover any comorbidities that will render them poor operative candidates. The results of these studies (electrocardiogram, chest X-ray, echocardiogram, cardiac catheterization, and/or CT scan of the chest) should be reviewed thoroughly. Pre-operatively, labs should be obtained, with special attention paid to pre-surgical renal function, coagulation studies, and hemoglobin. Pre-existing anemia should be investigated and treated appropriately (i.e. iron infusions for iron-deficiency anemia) assuming this treatment will not delay necessary surgery. A thorough history and physical should be performed on the day of surgery, including clarifying any ongoing cardiac symptoms (duration, frequency, precipitating factors of angina, dyspnea, or syncope; orthopnea; lower extremity edema). Patients should be questioned to determine whether they have any contraindications to transesophageal echocardiography (such as history of chest radiation therapy, esophageal or gastric surgery, esophageal strictures, dysphagia/odynophagia, or esophageal varices), as this is a common and often-crucial monitor used during cardiac surgery. Any pre-existing neurologic symptoms or deficits (such as prior TIA or stroke, presence of carotid bruits, or radicular symptoms with cervical motion) should be carefully documented, as patients will be undergoing cardiopulmonary bypass which carries a risk of post-operative cognitive decline or stroke, and neck rotation will be necessary for the placement of an internal jugular central line.

  Patients presenting urgently or emergently for cardiac surgery (i.e. urgent CABG for left main disease with ongoing anginal symptoms, emergent ECMO insertion for cardiogenic shock, emergent ascending aortic replacement for type A dissection) may have an abbreviated workup, or may present with

little information available about their prior medical history. These patients, in addition to their life-threatening cardiac pathology, may also be at risk for aspiration (inappropriate NPO time) and may warrant a rapid sequence intubation. In these situations, the anesthesiologist's priority is stabilization of any hemodynamic perturbances, minimizing cardiac risk with induction, and obtaining information (labs, transesophageal echocardiogram) while simultaneously preparing the patient for surgery.

- **Monitoring**

  In addition to standard ASA monitors, an arterial line is placed pre-induction to allow careful titration of medication and rapid identification of hemodynamic instability peri-induction. Depending on the patient's stability and institutional practice, a central line and/or pulmonary artery catheter may be placed pre- or post-induction for venous access, pulmonary arterial pressure measurements, and determination of cardiac output and mixed venous saturation. A transesophageal echocardiogram (TEE) is often performed to allow assessment of cardiac anatomy, cardiac function, volume status, and any surgical complications pre- and post-surgical intervention. Temperature and urine output are closely monitored, particularly during the bypass period. Near infrared spectrometry (NIRS) may be used to monitor saturation in the right and left cerebral hemispheres and ensure adequate oxygen delivery to the brain during CPB.

- **Induction and Maintenance**

  Following arterial cannulation, intravenous induction is performed with IV agents. A high-opioid induction is commonly performed with fentanyl or other short-acting opioid such as sufentanil, to minimize sympathetic response to stimulation. Other induction agents can include propofol, etomidate, or ketamine, depending on cardiac pathophysiology and volume status. Propofol decreases SVR (and therefore mean arterial pressure) more so than etomidate but can be used safely when given judiciously. Etomidate is the most hemodynamically stable induction agent of the three and is therefore often

the first line agent for rapid induction in patients with hypovolemia, cardiogenic shock, or tamponade, but it can cause transient adrenal suppression. In patients with pericardial tamponade or hypovolemia, the tachycardia induced by ketamine may be desirable, but patients with ischemic heart disease, stenotic valve lesions, or heart failure tolerate tachycardia poorly and may not have adequate catecholamine stores to tolerate the relative cardiac depression brought on by ketamine. The choice of neuromuscular blocker takes into account the need for rapid induction (rocuronium or succinylcholine) or consideration of pre-existing renal dysfunction (cisatracurium).

Maintenance of anesthesia is typically achieved with a balanced anesthetic, relying on a volatile anesthetic (isoflurane of sevoflurane) combined with short-acting opioids and other hypnotic agents. Dexmedetomidine or propofol may be infused throughout the procedure to minimize volatile requirements, reduce vasodilation, and improve hemodynamic instability; these infusions can be continued for sedation in the immediate postoperative period if the patient remains intubated.

- **Pre-Bypass Considerations**

  During the pre-bypass period, the surgeon makes incision and sternotomy, accesses the heart and great vessels, and prepares arterial and venous access for cannulation for bypass. In a CABG, the graft vessels (typically left internal mammary artery and/or saphenous vein and/or radial artery) are also dissected out prior to going on bypass. Ensuring stable hemodynamics during this period is critical. Hypotension can occur from many causes (ischemia, sympathectomy from opioids or anesthetics, arrhythmias, surgical compression of the heart or great venous leading to decreased venous return) and the treatment varies based upon the cause.

  During sternotomy, the lungs are briefly deflated to prevent injury from the sternal saw. In patients who are undergoing a repeat or "redo" sternotomy, there is a heightened risk of injury to the heart, great vessels, or prior coronary artery bypass grafts upon re-entry into the chest, and the anesthesiologist should be prepared for rapid volume resuscitation (blood

available for transfusion, large bore IV access established) and rapid institution of cardiopulmonary bypass.

Prior to initiation of bypass, cannulas must be placed in a large vein and artery (see below) by the surgeon in order to drain blood from the body to the bypass circuit and return oxygenated blood to the systemic circulation. Prior to arterial cannulation, the systolic blood pressure is reduced to 90–100 mmHg systolic to minimize the risk of aortic dissection or trauma. An anti-fibrinolytic agent (aminocaproic acid or tranexamic acid) is typically administered to reduce bleeding. Heparin is administered to anticoagulate the blood by inhibiting anti-thrombin III; typical dose is 350–450 units per kilogram, and the efficacy of anticoagulation is monitored by the activated clotting time (ACT) with a goal ACT of >450 seconds (the exact ACT target varies by institution).

- **Management of Intraoperative Myocardial Ischemia**

  Intraoperative myocardial ischemia can occur as a result of increased oxygen demand, decreased oxygen supply, or both. When myocardial ischemia is diagnosed by TEE imaging (regional wall motion abnormalities) or ECG (new ST segment elevation or depression, new left bundle branch block), the treatment should be tailored to the etiology (see Table 18.3).

Table 18.3 Treatment of Intraoperative Myocardial Ischemia

Etiology	Treatments
Decreased Oxygen Supply	
Tachyarrhythmia	β blockers, cardioversion
Bradyarrhythmia	β agonist, muscarinic antagonist, pacing
Hypoxia	Increase FiO_2, increase PEEP
Anemia	Transfuse red blood cells
Vasospasm	Nitroglycerin
Hypovolemia	Administration of volume (crystalloid, colloid, blood, coagulation factors if indicated)
Thrombosis	Anticoagulation (i.e. heparin)
Increased Oxygen Demand	
Tachyarrhythmia	β blockers, cardioversion
Hypertension	Vasodilators, increase anesthetic depth, opioids

- **Cardiopulmonary Bypass (CPB)**

  Cardiopulmonary bypass serves to replace the pump function of the heart and the oxygenation/ventilation function of the lungs. A simplified diagram of the circuit is shown in Fig. 18.2. CPB is managed by a perfusionist who communicates closely with the surgeon and anesthesiologist about the patient's physiology before, during, and after CPB. CPB involves blood being drained from the right side of the circulation (via venous cannula(s) in right atrium, superior vena cava and inferior vena cava, or femoral vein) into a venous reservoir, then is passed through an oxygenator which removes CO_2 and adds O_2 to the blood, a temperature regulator, and either centrifugal or roller pumps to return blood back to the left side of the circulation (via an arterial cannula in the aorta, femoral artery or axillary artery). Prior to initiation of bypass, the circuit is primed with crystalloid, albumin, mannitol, steroids, and antibiotics. Drainage cannula such as a left ventricular vent allows decompression of the cardiac chambers by draining blood back to the circuit. The bypass circuit also has the

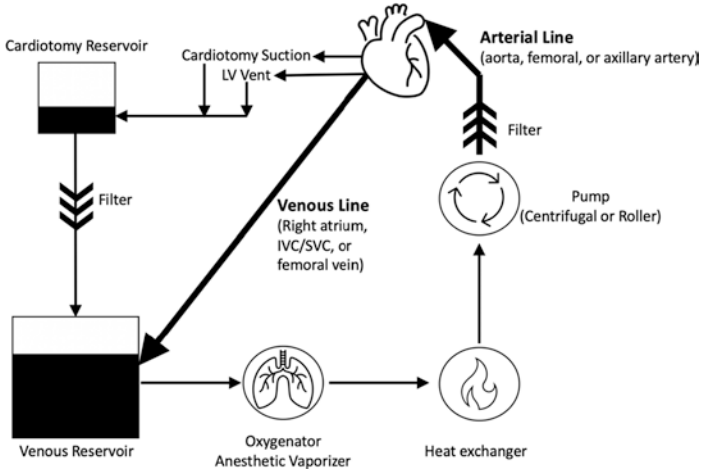


Fig. 18.2 Cardiopulmonary Bypass Circuit. Abbreviations: IVC inferior vena cava, LV left ventricle, SVC superior vena cava

ability to deliver cardioplegia (a high potassium solution that is used to arrest the heart to provide a still surgical field and is infused antegrade into the aortic root or retrograde into the coronary sinus), deliver volatile anesthetics into the blood to provide anesthesia, and provide rapid temperature control (warming or cooling).

During CPB, there is minimal blood flow through the lungs, so the ventilator is either turned off completely, or placed on a low tidal volume/low respiratory rate setting to reduce atelectasis. The delivery of volatile anesthetic continues via the CPB circuit and is controlled via the perfusionist; the anesthesiologist may also provide an intravenous infusion of hypnotic agent (propofol or dexmedetomidine), give benzodiazepines to ensure amnesia, and/or administer neuromuscular blockers to prevent patient movement. Immediately prior to delivery of cardioplegia, the aorta is cross-clamped, and the heart is deprived of blood flow. To provide the myocardium from ischemia, it is packed in ice to and cardioplegia solution is delivered to arrest the heart in diastole and decrease metabolic demand and oxygen consumption. Shortly after delivery of cardioplegia, asystole occurs; the heart may briefly enter a junctional or fibrillation rhythm prior to asystole. Because the heart is arrested and/or emptied, and the blood flow from the CPB circuit is non-pulsatile, the arterial line will record a mean pressure only; monitors depending on pulsatile blood flow (i.e. non-invasive blood pressure cuff, pulse oximetry) will not function accurately while on bypass. The perfusionist controls cardiac output via bypass flow, while the anesthesiologist can assist in the management of blood pressure only in the form of controlling SVR, lowering it with opioids, benzodiazepines, or vasodilators, or raising it with vasoconstrictors. The blood is frequently sampled to measure electrolytes, hemoglobin, and glucose; hyperglycemia (blood glucose >180 mg/dL) should be promptly treated to avoid adverse cardiac, neurologic, or infectious outcomes. Often, the patient is cooled to 30–32 degrees Celsius to decrease metabolic demand in other major organs (brain, kidneys) and minimize the risk of postoperative organ failure.

Initiation and maintenance of CPB carry risks to the patient, and the anesthesiologist must be vigilant for these complications. Vascular injuries including aortic dissection, incorrect arterial cannula placement (innominate artery, carotid artery, pulmonary artery), passage of venous cannula into the hepatic vein leading to inadequate venous drainage and hepatic injury, or obstruction of jugular venous return from cannula leading to cerebral edema can all occur. The circuitry should be meticulously de-aired, as air embolism can be catastrophic (causing air lock and cessation of flow in the CPB circuit or massive stroke). Heparinization must be maintained throughout the bypass period and is monitored with ACT; administration of the heparin reversal agent protamine while on CPB would lead to thrombosis of the circuit and catastrophic consequences (massive thromboembolus or cessation of CPB flow while the heart is arrested). In the post-bypass period, other complications of bypass flow can occur including stroke (air embolus or microthrombi from bypass circuit), global cerebral ischemia from prolonged hypotension, coagulopathy from platelet destruction by the pumps and clotting factor consumption by the circuit, fluid and electrolyte imbalances (hyperkalemia, hypocalcemia, fluid overload), myocardial dysfunction, and renal dysfunction.

- **Weaning from Cardiopulmonary Bypass**

  Following completion of the surgical intervention, the patient's blood is rewarmed to at least 36 degrees Celsius. Any electrolyte abnormalities are corrected, and the patient's hemoglobin concentration/hematocrit is optimized through blood transfusion or ultrafiltration of blood flowing through the bypass circuit. The aortic cross clamp is removed, and blood flow to the myocardium resumes; as cardioplegia is washed out of the myocardium, electrical activity of the heart resumes. Continuous assessment of cardiac function through direct observation of the heart muscle in the field and on TEE is performed by the surgeon and the anesthesiologist. Inotropic support (milrinone, dobutamine, dopamine, and/or epinephrine) may be necessary to support cardiac function, and temporary

atrial and/or ventricular pacing wires may be placed by the surgeon to allow pacing if the native heart rate or rhythm or inadequate to maintain cardiac output. A Valsalva maneuver is performed to recruit the atelectactic lungs and evacuate air from the heart and vessels, and ventilation is resumed. CPB flow is slowly decreased while heart function and hemodynamics are monitored by the anesthesiologist, perfusionist, and surgeon; excellent communication is critical to the weaning process. Hypotension during and after weaning may be related to hypovolemia, vasodilation, myocardial dysfunction, new valve abnormalities or inadequate valve repair/replacement, or pulmonary hypertension.

Following weaning from bypass, a focused TEE exam is quickly performed to assess the surgical intervention, look for new or worsened wall motion abnormalities, interrogate any valves that were repaired or replaced, and rule out aortic dissection. Once all parties are satisfied with the patient's hemodynamics and the surgical outcome, heparin reversal is administered with protamine. Protamine is a basic compound that binds to heparin, which is acidic, and neutralizes it, reversing its anticoagulant effects; following reversal, an ACT is checked and if it has not returned to normal (120–130 seconds), more protamine is given. A full dose of protamine is typically 1 mg per every 100 units of heparin administered at the onset of CPB; this dose is administered slowly over a period of approximately 5–10 minutes to prevent a protamine reaction. There are three major types of protamine reactions, all of which are capable of producing profound and life-threatening hypotension: vasodilation, anaphylactic/anaphylactoid, and severe pulmonary vasoconstriction. After reversal of heparin, meticulous surgical hemostasis and correction of any coagulopathy (hypofibrinogenemia, thrombocytopenia, or depletion of clotting factors) are both critical to ensuring resolution of bleeding and a successful surgical closure of the chest. Mediastinal and pleural chest tubes are placed, and wires and/or plates are placed in the sternum to close the chest. Hypotension following chest closure can be related to mechan-

ical compression of the right ventricle or bleeding causing pericardial tamponade, both of which can lead to decreased preload and cardiac output; TEE examination and inspection of the chest tubes can help rapidly diagnose the problem.

- **Post-Operative Care**

  Most patients remain intubated following cardiac surgery and are transferred to the cardiac surgical intensive care unit (ICU) on ventilatory support with ongoing sedation. Complications in the immediate postoperative period include ongoing bleeding requiring surgical re-exploration (from coagulopathy or inadequate surgical hemostasis), pericardial tamponade, depressed cardiac function (myocardial stunning, occluded bypass graft, inadequate myocardial protection during CPB). Patients with an uncomplicated surgical course are typically extubated within hours of their arrival to the ICU.

- **Enhanced Recovery After Cardiac Surgery**

  Interest in improving patient outcomes, promoting an earlier return to normal activities, reducing hospital costs, and shortening postoperative ICU and hospital stays has led to the development of enhanced recovery after cardiac surgery protocols [2]. These protocols are multidisciplinary perioperative initiatives; the anesthesiologist may play a role in preoperative optimization, intraoperative management, and postoperative ICU care. Preoperative optimization focuses on risk stratification, maximizing nutrition, treating anemia, and "prehabilitation" (a formalized preoperative program to maximize a patient's functional capacity). Intraoperative care focuses on use of multimodal analgesia strategies to both reduce the use of opioid medications and decrease delirium incidence, as well as reduction of coagulopathy and bleeding through use of antifibrinolytic medications and treatment of hypothermia post-bypass. Postoperative care includes a goal of weaning mechanical ventilation within 6 hours of arrival to the ICU to minimize postoperative pneumonia and prolonged ICU/hospital stay and providing goal-directed fluid and transfusion management to minimize exposure to blood products, vasopressors/inotropes, or excessive volume administration.

Minimally Invasive Cardiac Procedures

Avoidance of a traditional sternotomy and/or cardiopulmonary bypass may decrease risks and lead to improved patient outcome and satisfaction. As technology advances, more surgeries can be performed using these minimally invasive techniques, including:

- Off-pump coronary artery bypass surgery: performed via sternotomy, but avoids CPB, aortic cross clamp, and cardioplegic arrest. Requires operation on a beating heart and temporary occlusion of a coronary artery without the benefit of myocardial protection.
- Minimally-invasive or robotic CABG: Involves small incisions between the ribs, rather than sternotomy; dissection of the internal mammary artery and the graft placement itself can both be performed robotically. Performed without CPB on a beating heart.
- Minimally invasive valve replacement or repair: both the mitral and aortic valves can be replaced, and the mitral valve can be repaired, via small incisions or thoracotomy; performed with or without robotic assistance; access for CPB is typically via femoral vessels.

Thoracic Anesthesia

Anatomy

The trachea is a cartilaginous structure made of 18–22 D-shaped rings bound by the larynx superiorly and the main bronchi inferiorly. It ends at the sharp bifurcation of the carina, usually found at the level of T4, into the right and left main pulmonary bronchi. The right mainstem bronchus is shorter and takes off at a narrower angle than the left. On the right, the right upper lobe take off is usually 1.5–2 cm past the carina followed by the right middle and right lower lobes. The left main bronchus splits into left upper and lower lobes 4.5–5 cm past the level of the carina. The narrower

angle of the of right mainstem bronchus make it more likely for endobronchial intubation ("mainstem intubation") and for aspiration of orogastric contents.

Common Presenting Thoracic Pathology

Lung Cancer

Lung cancer is the leading cause of cancer death in the USA. Patients presenting with lung cancer should be evaluated for the "4 Ms". **M**ass effects from tumors may include obstructions of the bronchi or may obstruct the nearby vasculature and nerves. Several **M**etabolic syndromes have been associated with lung cancer such as Lambert-Eaton syndrome, Cushing syndrome, and electrolyte abnormalities. **M**etastases are most commonly to the brain, bone, liver, and adrenal glands. **M**edications used to treat lung cancer can be associated with pulmonary, cardiac and renal toxicity.

Mediastinal Mass

Mediastinal masses present a unique anesthetic challenge. Anterior and superior masses may cause obstruction to the airway and major vascular structures that lie underneath them. A patient's symptoms should be assessed both while sitting and lying flat, along with examination of their CT scan for structures that are high risk for compression. During general anesthesia lung volumes are decreased and smooth muscle relaxation leads structures underneath the mass to be susceptible to compression. Efforts should be made to keep the patient spontaneously ventilating to minimize muscle relaxation and airway collapse. Patients at high risk of cardiovascular or airway collapse should be considered for ECMO to provide cardiac or respiratory support prior to induction of anesthesia and/or surgical intervention.

Preoperative Evaluation

A complete history and physical examination are necessary for preoperative evaluation in patients presenting for thoracic surgery. This should include focus on dyspnea, cough, history of

tobacco use, exercise tolerance, history of pulmonary hypertension and risk factors for lung injury. Physical exam findings should focus on breath sounds, respiratory rate and pattern, indications of cyanosis, fingernail clubbing. Atelectasis, pneumonia, and respiratory failure are the most common cause of postoperative complications after thoracic surgery. Major adverse cardiac events are the second most common, and patients should be assessed for cardiac disease prior to undergoing thoracic surgery.

Respiratory function is determined in three ways (respiratory mechanics, gas exchange, cardiopulmonary reserve) and is aided by pulmonary function testing (PFTs). FEV1 (Forced expiratory volume in 1 second) is the most helpful measure from PFTs in determining respiratory mechanics. Calculation of the predicted postoperative FEV1 (ppoFEV1) is the most effective way to determine risk of postoperative complications. It is calculated as ppoFEV1% = Preoperative FEV1% × (100-% of functional tissue removed/100). A ppoFEV1 over 40% is low risk for postoperative complications, and while patients with a ppoFEV1 less than 30% are at an increased risk. Gas exchange is assessed by the DLCO (diffusing lung capacity of carbon monoxide), $PaCO_2$ (arterial partial pressure of oxygen), and PaO_2 (arterial partial pressure of carbon dioxide). A room air PaO_2 of less than 60 or $PaCO_2$ of greater than 45 have been associated with increased complications. A DLCO >40% correlates with low risk of postoperative pulmonary complications. Calculation of maximal oxygen consumption (VO_2max) less than 15 mL/kg/min indicates increased risk of complications from impaired cardiopulmonary reserve. It can be estimated as the ability to climb to flights of stairs, a six-minute walk test, and oxygen saturation drop during exercise of over 4%.

Anesthetic Management

Anesthetic management and intraoperative monitoring should be chosen based on the patient and surgical factors. Due to the operative field being close to major vascular structures, an arterial line is usually placed for most procedures except single lung wedge resections. Most procedures take place in the lateral decubitus position and care must be taken to ensure that eyes, ears, and pres-

sure points are properly padded to avoid positioning injuries. Fluid management is critical in these patients as excessive fluid can cause postoperative lung injury. The goal should be to maintain euvolemia with the preferential use of pressors or inotropes to manage hypotension. At the onset of one lung ventilation (OLV), 100% FiO_2 is utilized until it is proven that the patient will tolerate less inspired oxygen. Tidal volumes of 4–6 cc/kg during OLV are used to maintain peak and plateau pressures less than 35 and 25 cm H_2O, respectively. The management of hypoxia should be addressed with recruitment maneuvers to the ventilated lung and positive end expiratory pressure to the dependent lung. Permissive hypercapnia may be utilized in instances of difficult ventilation if pH is kept in an acceptable range. Thoracic epidurals are often used to provide postoperative pain management for thoracotomies.

One-Lung Ventilation

OLV is the isolation of one lung for ventilation allowing the non-ventilated lung to deflate and not participate in gas exchange. Indications for OLV include (1) surgical access (thoracic, mediastinal, cardiac, vascular and spinal surgery). (2) Control of ventilation (e.g. patients with bronchoplural fistula. (3) Lung isolation in cases of pulmonary hemorrhage, soiling, or whole lung lavage. (4) To allow for multiple modes of ventilation in patients with single lung injury.

Several physiologic changes during OLV must be kept in mind. First, the nondependent lung receives no ventilation and hypoxic pulmonary vasoconstriction occurs to shunt flow to the dependent lung and improve oxygenation by delivering blood flow to the ventilated long. Increased MAC levels of volatile anesthetic can inhibit this process. Perfusion to the nondependent lung is also decreased in the lateral decubitus position due to gravity. Compliance of the dependent lung is decreased from cephalad shift of the diaphragm, muscle relaxation, and surgical manipulation. The addition of PEEP can be added to improve this compliance.

OLV can be achieved by either a double lumen tube, bronchial blocker or endobronchial intubation. Each method carries its own advantages and disadvantages, and patient and surgical factors should be considered before deciding which method to use.

Double lumen tubes (DLT) exist to isolate both the left and right lung, however left-sided tubes are used more commonly due to the difficulty in positioning right sided tubes secondary to the abrupt take off of the right upper lobe which is easily occluded by the bronchial lumen. This has however been challenged in the recent literature [3]. A DLT consists of a tracheal and bronchial lumen each with its respective cuffs. Each lumen can be connected to the ventilator and be opened to air to allow for deflation of the desired lung. A DLT is placed similarly to a single lumen ETT through the oropharynx and into the trachea; direct laryngoscopy, video laryngoscopy, or bronchoscopy can be used for placement. The DLT tip is positioned anteriorly, then once the tip passes the vocal cords the DLT is rotated 90 degrees and advanced. The bronchial portion is then positioned into either the right or left mainstem bronchus (if it is a right of left sided DLT, respectively). The tracheal cuff is then inflated to allow for ventilation. The bronchial cuff is usually colored blue to allow for increased visibility, is inflated with 2–3 cc of air to achieve isolation and should be positioned with a small portion of the cuff visible just distal to the carina using fiberoptic bronchoscopy. Positioning of the DLT must be confirmed once the patient has been positioned laterally due to the risk of the DLT becoming malpositioned at this time. A bronchial blocker is a small balloon on the end of a long catheter that is placed through an existing ETT. The balloon is advanced to the desired bronchus and inflated once position is confirmed via fiberoptic bronchoscope. Mainstem intubation is achieved by advancing an ETT into the desired bronchus. Placement should be confirmed via fiberoptic bronchoscope.

Case Study

A 60-year-old man presents for laparoscopic cholecystectomy for acute cholecystitis. He has been admitted to the hospital for the last 12 hours, is NPO (nil per os), and has been receiving broad spectrum antibiotics. He is currently afebrile and hemodynamically stable, with a blood pressure of 140/80 and heart rate of 60. He has a history of moderate aortic stenosis and hypertension, for which he takes lisinopril and metoprolol.

How will you assess the severity of his aortic valve disease?

Assessment will begin with a thorough history and physical. Evaluate for symptomology such as pre-syncope, syncope, angina, dyspnea on exertion, or signs and symptoms of systolic dysfunction (dyspnea on exertion, edema, decreased exertion tolerance), which may indicate progression of his disease to severe. On exam, auscultation of a harsh systolic ejection murmur and palpation of a slowly rising, late-peaking pulse (*pulsus parvus et tardus*) are associated with aortic stenosis. Review of any available recent echocardiogram is crucial; if none are available or are older than 1 year in a patient with progressive symptoms, consider obtaining a new echocardiogram in this patient if the surgery can be safely be delayed several hours [4]. Review of a current echocardiogram will allow classification of the severity of the lesion, associated pathophysiologic changes such as left ventricular hypertrophy, and understanding of the patient's left ventricular diastolic and systolic function (wall motion and ejection fraction).

Review of his echocardiogram from 2 months ago reveals a left ventricular ejection fraction of 55–60%, left ventricular hypertrophy, and a moderate aortic stenosis with a mean gradient of 25 mmHg. What are your hemodynamic goals for the perioperative period?

In general, patients with stenotic valve lesions maintain cardiac output best with slow heart rhythms, adequate (but

not excessive) preload, and high-normal SVR ("slow and tight"). (This is in contrast to patients with regurgitant valve lesions, who do best with a faster heart rate, adequate preload, and low-normal SVR ["fast, full, and loose"]). In patients such as this one, with left ventricular hypertrophy and aortic stenosis, tachycardia and hypotension from peripheral vasodilation are particularly deleterious: the thick myocardial wall depends on adequate diastolic filling time and perfusion pressure to maintain adequate blood flow and oxygen delivery to the myocardium. For this patient, your goal will be to avoid tachycardia and vasodilation/hypotension, particularly during induction of anesthesia.

What medications should be used preoperatively, during induction, and for maintenance of anesthesia? What medications with you avoid?

Continuation of beta blockers and avoidance of vasodilating medications is important; the patient should receive his scheduled metoprolol but not his lisinopril prior to surgery. For induction of anesthesia, drugs that cause significant vasodilation (propofol) or tachycardia (ketamine) should be avoided or used judiciously; etomidate is a reasonable choice, particularly if a rapid sequence induction is indicated to minimize aspiration risk in an urgent surgery. Use of short-acting opioids (i.e. fentanyl) or short-acting beta blockers (i.e. esmolol) to block the sympathetic response to laryngoscopy/intubation and surgical stimulation will minimize tachycardia.

Will you take any special precautions during surgery?

Placement of a pre-induction arterial line allows continuous monitoring of blood pressure through induction, intubation, and surgery. Emergency drugs, such as phenylephrine, ephedrine, esmolol, glycopyrrolate, and epinephrine, should all be available for rapid control of hemodynamics. Use of higher doses of short-acting opioids such as fentanyl or remifentanil prevents tachycardia during intubation, but can

lead to hypotension during the period of low stimulation prior to incision; intermittent vasopressor dosing can help prevent this, as can a low-dose infusion of a vasopressor such as phenylephrine or norepinephrine. The anesthesiologist should pay particular attention to hemodynamic response to insufflation of carbon dioxide for laparoscopy. Slow insufflation of gas may prevent the bradycardia and hypotension from the vagal response to peritoneal stretch and attenuate the loss of preload from increased intraabdominal pressure. During emergence, treatment of tachycardia with short-acting beta agonists (i.e. esmolol) can help prevent episodes of increased myocardial oxygen demand/decreased oxygen delivery that can precipitate ischemia.

References & Suggested Further Reading

1. Stone ME, Salter B, Fischer A (2011) Perioperative management of patients with cardiac implantable electronic devices. Br J Anaesth 107(S1):i16–i26
2. Engelman DT, Ben Ali W, Williams JB, Perrault LP, Reddy VS, Arora RC et al (2019) Guidelines for perioperative care in cardiac surgery: enhanced recovery after surgery society recommendations. JAMA Surg 154(8):755–766
3. Ehrenfeld JM, Walsh JL, Sandberg WS (2008) Right and left sided Mallinckrodt double lumen tubes have identical clinical performance. Anesth Analg 106(6):1847–1852
4. Fleisher LA, Fleischmann KE, Auerbach AD, Barnason SA, Beckman JA, Bozkurt B et al (2014) 2014 ACC/AHA guideline on perioperative cardiovascular evaluation and management of patients undergoing noncardiac surgery: a report of the American College of Cardiology/American Heart Association Task Force on practice guidelines. J Am Coll Cardiol 64(22):e77–137
5. Gravlee GP, Shaw AD, Bartels K, Hensley FA (2018) Hensley's practical approach to cardiothoracic anesthesia, 6th edn. Lippincott Williams & Wilkins, Philadelphia

6. Kaplan JA, Augoustides JGT, Maneck GR Jr, Maus T, Reich DL (2018) Kaplan's cardiac anesthesia: for cardiac and noncardiac surgery, 7th edn. Elsevier, Philadelphia
7. Pardo MC, Miller RD (2018) Chap. 27, Chronic pulmonary disease and thoracic anesthesia. In: Basics of anesthesia, 7th edn. Elsevier, Inc., Philadelphia, pp 462–482
8. Furlow PW, Mathisen DJ (2018) Surgical anatomy of the trachea. Ann Cardiothorac Surg 7(2):255–260

Physiology & Anesthesia for Neurologic, ENT and Ophthalmologic Surgery

19

Joshua H. Atkins

Key Learning Objectives

- Learn about preoperative assessment and perioperative management of patients undergoing a broad range of neurosurgical procedures
- Understand key elements of neurophysiology and associated derangements as they directly impact choice of anesthetics and perioperative management
- Learn the properties of individual anesthetic agents and their effects on physiologic parameters
- Learn about preoperative assessment and perioperative management of patients undergoing a broad range of head and neck surgical procedures
- Appreciate how specific aspects of surgical procedures in ENT and Neurosurgery directly impact anesthetic planning

J. H. Atkins (✉)
Department of Anesthesiology and Critical Care, Perelman School of Medicine at the University of Pennsylvania, University of Pennsylvania Health System, Philadelphia, PA, USA
e-mail: joshua.atkins@pennmedicine.upenn.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_19

- Develop a structured approach to anesthesia assessment of patients who present for head and neck procedures
- Learn the basic approaches to regional and local anesthesia for common ophthalmologic surgical procedures

Neuroanesthesia - Physiology

The central tenets of neuroanesthesia are brain protection and optimization of surgical exposure. These are based on the physiology of cerebral autoregulation and associated reflexes as well as iatrogenic modulation of brain volume, intracranial pressure, cerebral blood flow and cerebral metabolic rate [1].

Intracranial Pressure (ICP)

The cranium is a closed space. ICP is determined by the combination of brain cellular volume (80%), cerebrospinal fluid (CSF) volume (10%) and blood volume (10%). Normal intracranial pressure is <10 mmHg. Cerebral blood flow (CBF) is a function of mean arterial blood pressure (MAP) and ICP or central venous pressure (CVP) and defined as CPP = MAP-ICP (or CVP). A cerebral perfusion pressure (CPP) of 55–70 mmHg is usually targeted, although in the presence of severe intracranial disease the target must be individualized to patient physiology but how to accomplish that remains an important research question.

Increase in brain mass (tumor, edema, traumatic brain injury), idiopathic overproduction of CSF or obstruction to outflow (e.g., tumor, hemorrhage/clot) or increased blood volume (↓venous drainage, ↑ arterial blood flow) all increase ICP. The normal physiologic response to increased ICP, in the absence of severe pathology, is diversion of CSF to the spinal canal.

As ICP continues to increase mental status decreases, focal neurologic signs (i.e., anisocoria, cranial nerve defects) present and herniation of brain contents occurs. Eventually manifesta-

tions of the Cushing's response (hypertension, bradycardia, irregular respiration) are present due to brainstem compression. These signs herald a neurosurgical emergency.

Management of ICP/brain volume is a critical part of anesthetic management for the neurosurgical patient. ICP can be measured by direct catheter insertion into a CSF containing space or via a surgically placed sub-arachnoid bolt. Interventions to reduce ICP include: (1) head elevation to 30 degrees, (2) optimization of jugular venous drainage, (3) direct drainage of CSF via a lumbar drain or intraventricular catheter, (4) hyperventilation (P_aCO_2 25–30 mmHg), (5) osmotic diuresis (mannitol, hypertonic saline), and (6) deep intravenous anesthesia (propofol infusion).

Cerebral Blood Flow

Under normal conditions cerebral blood flow is autoregulated in the range of MAP 50–150 mm Hg as shown in Fig. 19.1.

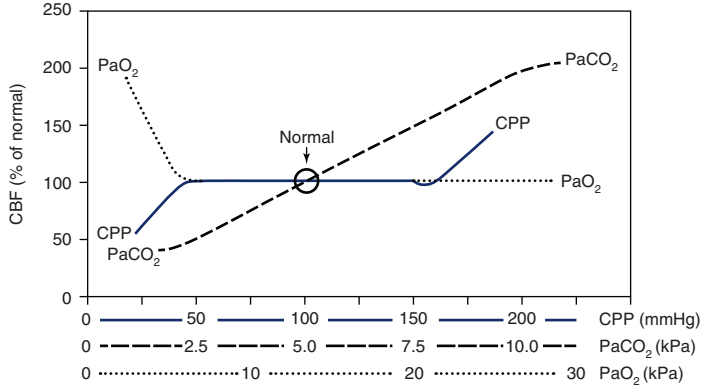


Fig. 19.1 Cerebral blood flow (CBF) is depicted as a function of cerebral perfusion pressure (CPP), arterial partial pressure of carbon dioxide ($PaCO_2$) and arterial oxygen partial pressure (PaO_2). (Carbon dioxide/CBF diagram is from: Gupta and Gelb "Essentials of Neuroanesthesia and NeuroIntensive Care, 2008, Saunders Fig. 3-2, p. 23. For permissions e-mail healthpermissions@elsevier.com)

Autoregulation is assumed to be disrupted in patients with chronic hypertension or pathologic conditions including traumatic brain injury and stroke or by inhaled anesthetic agents As cerebral metabolic rate increases blood flow increases proportionally and vice-versa. Cerebral blood flow also increases with rising arterial carbon dioxide and falling arterial oxygen. Controlling carbon dioxide by hyperventilation is an important consideration when increased cerebral blood flow is contributing to increased intracranial pressure.

Blood Brain Barrier (BBB)

Brain capillaries contain tight junctions that limit the passive diffusion of many substances into the brain tissue. The physiology of the BBB facilitates reduction of brain volume by osmotic agents such as mannitol and hypertonic saline, which are not freely permeable. Many pathologic states, including trauma, sepsis, and hemorrhage disrupt the BBB leading to brain edema that complicates management. There is no good way to clinically assess the integrity of the BBB.

Neuromonitoring

Neuroelectrophysiologic monitoring for surgical procedures on the brain and spine is increasing in scope and usage. The fundamental goal of these techniques is to avoid injury to functional pathways from either direct anatomic disruption or ischemia during surgical resection and manipulation.

Techniques include monitoring of EEG, descending motor pathways (e.g. motor evoked potentials (MEP) -corticospinal tract), ascending sensory pathways (e.g., somatosensory evoked potentials (SSEP) - dorsal column system), and cranial nerve function (e.g. visual, brain auditory evoked potentials (BAER) - auditory, or facial and spinal accessory nerve pathways), and local neuromuscular pathways (EMG). The positive and negative predictive value of changes (latency and amplitude) in the monitored

parameters varies based on the type and location of signal monitored, the anesthetic agents, blood pressure, temperature, and preoperative neurologic deficits. The modality selected for a specific case will depend on the proximity of the surgery to the pathway. In rare cases brain surgery can be performed awake to monitor speech and language. For the student, the important elements are to appreciate the use of neuromonitoring in selected cases, to know the basic tract(s) under surveillance, and to understand the general impact of anesthetic agents on these parameters (see table below).

It is key to maintain a steady state of anesthetic agents during monitoring and avoid bolus delivery of anesthetic agents while providing a stable depth of anesthesia throughout the monitoring period. Maintenance of steady blood pressure, blood glucose, and core body temperature also fall under the purview of anesthetic management during neuromonitoring.

Deep intra-operative neuromuscular blockade is contraindicated in any cases in which motor response (MEP) will be monitored. Cortically generated potentials of any kind are significantly depressed by inhaled potent agents, which should be avoided or used in sparingly during cortical monitoring. Spinal potentials and deeper brain potentials (e.g., auditory) are substantially more resilient to the effects of anesthetic agents and are compatible with a wider range of anesthetics. Benzodiazepines in anxiolytic doses, and most opioid agents in typical analgesic doses have little impact on monitored potentials.

Neurophysiology – Anesthetic Effects

Anesthetic agents almost universally decrease brain activity with the exceptions of ketamine and nitrous oxide when used alone (Table 19.1). For this reason, ketamine and nitrous oxide are often omitted from the anesthetic management of intracranial surgery. The decrease in brain activity with other agents (e.g., propofol) correlates with a decrease in global CMR. However, inhaled potent agents such as isoflurane will vasodilate the major intracerebral arteries resulting in an overall increase in cerebral blood flow and intracranial volume, which reflects an uncoupling of

Table 19.1 Effects of Anesthetic Agents on Cerebral Physiology [2, 3]

Agent	CBF	CMR	EP	Comments
Halogenated Potent Agents	↑	↓	↓↓	<0.5MAC generally suitable "luxury perfusion" uncoupling of CBF/CMR relationship
N_2O 60% (alone)	↑↑	↑	↔	
N_2O + Potent Agent	↑	↔	↓↓↓	effects ↑ with ↑ MAC potent agent
N_2O + Propofol	↔ (↓)	↔(↓)	↔	
Propofol	↓↓	↓↓	↔	
Etomidate	↓	↑	↑	
Ketamine (alone)	↑	↑	↑	generally contraindicated in neurosurgery
Ketamine + Propofol	↔	↔	?	propofol modifies effects of ketamine
Fentanyl/remifentanil/ sufentanil	↔	↔	↔	effects may occur in >10 mcg/kg bolus
Dexmedetomidine	↓	↓	↔	EP effects may occur at higher doses
Midazolam/ Remimazolam	↔	↓	↔	may suppress in >0.2 mg/kg bolus dose

CMR with CBF and excess perfusion. Inhaled agents are relatively contraindicated in situations of increased ICP or when increased brain volume impedes surgical access to the anatomy of interest. In contrast, the intravenous agents propofol and thiopental decrease both CMR and CBF (i.e., they maintain the normally coupled relationship). The use of barbiturates has declined substantially. Infusions of these agents may be beneficial in the management of patients with increased ICP or to facilitate surgical exposure in the "tight" brain. Ketamine may be used in conjunction with benzodiazepines or propofol, especially when managing a patient with hypotension and ICP since propofol alone commonly induces hypotension or cardiac depression.

Other agents commonly used in balanced anesthesia include opioids and benzodiazepines. Generally speaking, these agents have minimal impact on CMR or CBF and are commonly used as part of a balanced anesthetic.

Neurosurgical Procedures – Anesthetic Management

General Goals

The goals for the management of a neurosurgical patient are similar across the spectrum of patient disease. Attainment of these goals relies on a thorough appreciation of basic neurophysiology, understanding of the effects of individual anesthetic agents on brain function, and clear peri-operative communication with the neurosurgical team.

Key Features of a Neuroanesthetic

1. Neuroprotection
   (a) optimization of CBF/CMR balance
   (b) control of ICP
   (c) temperature regulation
2. Provision of optimal operating conditions, including neuromonitoring and "relaxed" brain
3. Maintenance of euglycemia and electroyte balance
4. Prompt emergence to facilitate neurologic assessment

Craniotomy

Preoperative Considerations

Why is the surgery being done? Is the targeted pathology related to (1) tumor, (2) neurovascular malformation (aneurysm/AVM), (3) traumatic brain injury with intractable intracranial hypertension, (4) intracranial hemorrhage (epidural, subdural, intracerebral), or (5) seizure disorder? Will neuromonitoring be employed?

A detailed neurologic exam must be performed with attention to recent signs and symptoms such as mental status, seizures, focal deficits, signs of increased ICP. Available neuroimaging studies should be reviewed, and any procedures noted (e.g., embolization of AVM or tumor, placement of intraventricular catheter or tissue oxygen monitor). Current medications (esp. blood

pressure agents, anticonvulsants, steroids, sedatives and opioids) should be reviewed and time of last dose noted. Anticonvulsants should be maintained throughout the perioperative period. A type and screen but not necessarily crossed blood should be available for most procedures.

Intra-Operative Considerations

General endotracheal anesthesia is indicated for most intracranial procedures except for the "awake craniotomy" for epilepsy or resection of a lesion in the motor or speech cortex. Invasive monitoring is indicated for all but the most limited neurosurgical procedures (e.g., stereotactic biopsy or burr hole drainage). An arterial line will facilitate close management of blood pressure, carbon dioxide, serum osmolality, hemoglobin, and oxygenation. Central venous access should be considered based on likelihood of high-volume blood loss (e.g., invasive cancer, AVM resection) or air embolus (sitting position). Positioning is an important consideration. Supine, sitting, prone, lateral park-bench and others are possible and can have significant impact on planning, placemen of intravenous lines, and monitoring. Maintenance with intravenous or inhaled agents should be individualized to the patient and the proposed surgical approach. Sometimes "brain relaxation" is necessary to allow the tumor or vascular malformation to be exposed and accessed from the surrounding brain [4]. Opioids should be used judiciously; fentanyl, sufentanil, and hydromorphone are most commonly employed. The most stimulating periods of surgery are head pinning, skin incision, and dural opening. Additional opioids are rarely required in significant doses after dural opening. Benzodiazepines should be used sparingly to facilitate rapid emergence and post-operative neurologic evaluation. Remimazolam is a newer ultra-short acting benzodiazepine that may find a role as an adjunct in neuroanesthesia. Hypo-osmolar agents (e.g. Lactated Ringers) should generally be avoided during fluid resuscitation. Large volumes of normal saline, however, may produce a non-anion gap metabolic acidosis, which must be considered in assessment of arterial blood gases.

Rapid emergence and extubation is feasible after most neurosurgical procedures. Exceptions include patients with profoundly decreased mental status prior to surgery, significant intra-operative complications, acute traumatic brain injury, marginal surgical hemostasis with high likelihood for re-exploration, and procedures involving critical neural structures of the posterior fossa (medullary respiratory centers, C.N. IX, X, XII). Post-procedure ICU monitoring, primarily for continuous neurologic assessment and rapid detection of changes, is standard for the vast majority of intracranial procedures.

Neurovascular Surgery: Aneurysm Clipping/AVM Resection

These procedures are technically challenging, high-risk interventions with unique considerations for anesthetic management. The complexity of the dissection, the risk of rupture, and the surgeon's plan for CSF drainage, burst-suppression, deliberate hypotension, deep hypothermic circulatory arrest, temporary clipping, and intraoperative angiography should all be outlined in detail during the pre-operative preparations.

Arteriovenous malformations are abnormal collections of veins and arteries with convoluted vessel contributions that lack capillaries. These lesions may feed functional cortex, which may be studied prior to surgery by selective barbiturate injection in the awake patient. An AVM may be selectively embolized in the radiology suite pre-operatively to reduce bleeding.

Blood pressure control is of central importance. Acute hypertension prior to clipping can lead to catastrophic aneurysmal rupture. AVM's, by nature of the anatomy involved, are generally much less prone to rupture than aneurysms. Induction/intubation, pinning, and incision are times of high risk for this complication. A smooth-controlled induction to a deep plane of anesthesia with complete muscle relaxation, generous opioid administration, glottic topicalization, and brief laryngoscopy will contribute to reliable attainment of these goals. Local anesthetic without epinephrine may be instilled at the pin and incision sites prior to instrumenta-

tion. Hypertension should be treated immediately with additional intravenous hypnotic agents, rapidly acting vasodilators (e.g., nitroprusside/nicardipine) and prompt cessation of stimulation. Aneurysm rupture is a catastrophic complication. Blood loss can be substantial and sudden. Increasingly intraoperative angiograms are performed some using intravenous dyes such indocyanine green.

Neurosurgical Anesthesia Controversies

For the advanced student these key questions (with no clear answers) serve as excellent starting points for reading on current topics and intra-operative discussion with both residents and faculty. References are provided for further reading and to stimulate discussion.

(a) What is the optimal blood pressure for an individual patient?
   See Brady, KM. Personalizing the Definition of Hypotension to Protect the Brain. Anesthesiology 2020;132:170–9
(b) Is deliberate hypothermia or EEG burst suppression a useful method of neuroprotection during neurovascular surgery or after traumatic brain injury?
   See Baughman VL. Brain protection during neurosurgery. Anesthesiol Clin North America 2002;20 (2):315–27.
(c) What exactly is brain 'relaxation'?
   See Meng, L. Definition, evaluation, and management of brain relaxation during craniotomy. Brit. J. Anesth. 2016;116 (6):759–69.
(d) Is hypertonic saline better than mannitol for ICP management?
   See Diringer MN, Zazulia AR. Osmotic therapy: fact and fiction. Neurocrit Care 2004; 1 (2):219–233.
(e) Is there an advantage of sedation versus general anesthesia for interventional stroke procedures?

See Novarro, JC. Anesthesia for endovascular therapy for acute ischemic stroke in adults. UptoDate (uptodate.com/contents/anesthesia-for-endovascular-therapy-for-acute-ischemic-stroke-in-adults)

Neurologic Disease and Anesthesia: Special Considerations [5]

Myasthenia Gravis (MG)

Etiology: autoimmune antibodies against nicotinic cholinergic receptors

Symptoms/Signs: laryngeal weakness → dysphagia, dysarthria; extraocular muscle weakness → diplopia, ptosis; skeletal muscle weakness → worsens with activity

- symptoms can be worsened by surgery, infection, pregnancy

Treatments: anticholinesterases, steroids, plasmapheresis, thymectomy

Risk Factors for Postoperative Respiratory Failure
Coexisting lung disease Vital capacity < 2.9 L
Pyridostigmine dose >750 mg/day Poorly controlled disease
Disease duration >6 years

Preoperative Considerations:

- Commonly present for thymectomy
- Assess degree of weakness & duration of symptoms
  - Maintain pre-op medications if severe baseline symptoms
  - Hold pre-op medications if mild symptoms
- Optimize patient prior to surgery, maintain home anticholinesterase therapy
- Consider PFTs, EKG (can see myocardial changes), electrolytes

- Anticholinesterase overdose → *cholinergic crisis* → further weakness
  - Diagnosis: worsening of symptoms with edrophonium (10 mg)
  - Treatment: anticholinergic administration (i.e., atropine)

Anesthetic Management:

- Minimize sedatives / respiratory depressants; consider regional anesthesia techniques
- Consider rapid sequence induction (patients at ↑ risk of aspiration)
- Consider Pre-induction and pre-extubation negative inspiratory force
  - Adequate is considered >-25 cm H_20
- Limit muscle relaxants if possible & measure baseline ToF (consider quantitative ToF)
  - Use suggamadex preferentially for reversal
- Delay extubation until return to baseline muscle strength
- Use caution when using neostigmine (↑ risk of cholinergic crisis)

Eaton-Lambert Syndrome (Table 19.2)

Etiology: ↑ release of acetylcholine due to Ca channels antibodies**;** assoc. with lung ca.

Table 19.2 Key clinical features of Eaton Lambert Syndrome and comparison with Myasthenia Gravis

	Eaton-Lambert Syndrome	Myasthenia Gravis
Symptoms/ Signs	Proximal limb weakness Exercise improves strength Diminished reflexes	Extraocular, bulbar & facial weakness Activity worsens symptoms Normal reflexes
Coexisting disease	Lung carcinoma	Thymoma, autoimmune dz
Response to muscle relaxants	Sensitive to both depolarizing & non-depolarizing drugs Minimal response to anticholinesterases	Untreated pts sensitive to non-depolarizing drugs & resistant to depolarizing drugs Improvement with anticholinesterases

Multiple Sclerosis

Etiology: CNS disorder → demyelinated plaques

Treatment: steroids, interferon, baclofen, dantrolene

Symptoms: visual disturbances, limb weakness, paralysis, respiratory failure, bulbar palsy

Anesthetic Considerations:

- ↑ risk of aspiration & ↓ airway reflexes; risk of postop respiratory failure
- neuraxial blockade (spinal) is associated with worsening symptoms; epidurals are *not* contraindicated but thorough patient education should be undertaken
- regional or general anesthesia not assoc. with worsening symptoms

Guillain-Barre Syndrome

Etiology: immune-related progressive neuron demyelination → paralysis

Symptoms: patients may require ventilatory support, ↑ aspiration risk, autonomic dysfx

Anesthetic considerations: consider RSI, avoid succinylcholine, minimize muscle relaxants & opioids

Neuroleptic Malignant Syndrome (NMS)

Etiology: derangement of dopaminergic receptors in hypothalamus; assoc. with psychotropic drug use (phenothiazines, butyrophenones)

Anesthetic Management:

- discontinue neuroleptic meds, control temp., hydrate
- Treatment options: dantrolene, bromocriptine, amantadine

NMS vs. Malignant Hyperthermia

- NMS has slower onset, muscle rigidity is a central, not peripheral, effect

Parkinson's Disease

Etiology: loss of dopaminergic fibers ➔ unopposed acetylcholine activity

Treatments: levodopa, anticholinergics, antihistamines, MAO inhibitors

Anesthetic Management:

- ↑ risk of aspiration, consider RSI
- avoid dopamine and acetylcholine antagonists (droperidol, promethazine, prochlorperazine, metoclopramide, scopolamine, high dose glycopyrrolate)
- May see dysrhythmias & intravascular volume depletion
- Baseline ToF prior to dosing of NMB
- Unmasking of Parkinson like symptoms is reported on emergence

Epilepsy

- Most anesthetics are anticonvulsants
- Patients on chronic anticonvulsants should have therapeutic drug levels maintained throughout the perioperative period
- Typical seizure manifestations, pre-disposing factors, and frequency should be noted during the pre-operative assessment
- Ketamine and etomidate lower the seizure threshold and should be used with caution or avoided in patients with a seizure disorder
- Large bolus doses of some opioids may precipitate seizure activity when given in isolation
- In high-risk individuals use of processed EEG to detect an intraoperative seizure

- Seizure and anticonvulsant management most commonly occurs with neurosurgical, pre-eclamptic, and ECT patients
- Anticonvulsants modulate the pharmacokinetics/dynamics of anesthetics
  - Phenytoin/barbiturates induce hepatic enzymes
  - Acute phenytoin dosing potentiates non-depolarizing NMB
  - Chronic phenytoin shortens duration of NMB
- Acute seizure
  - Airway protection (airway support, suction and intubation)
  - Intravenous bolus of propofol, midazolam, thiopental
  - Phenytoin, levetiracetam, or Mg^{++} (eclampsia) load I.V.
    - Caution: rapid bolus of phenytoin can result in severe hypotension, dysrhythmia, and cardiovascular collapse

Otolaryngology (ENT) – Anesthetic Approach

ENT procedures have extraordinary variation from the relatively simple and straightforward (sinus surgery) to the technically complex and challenging (resection of a glottic lesion). Anesthesia team familiarity with the key aspects of the procedure will facilitate planning and informative discussion [6]. A common theme is the notion of the shared airway. Detailed communication with the surgical team in the pre-operative and intra-operative periods is imperative along with an appreciation for both the lack of access to the airway and the possibility of surgical disruption of the airway [7].

Specialized Equipment

ENT surgery provides exposure to a variety of specialized airway and surgical equipment. This includes specialized endotracheal tubes (e.g., nasal and oral RAE, reinforced, laser, NIMS, MLT) that generally afford the operative team improved access, a more secure airway, or special monitoring capability. Procedures on the larynx or trachea may utilize unusual oxygenation strategies such as jet ventilation or high-flow nasal oxygenation (HFNO) and laser technologies for lesion ablation. Sinus surgery increasingly

utilizes real time CT-image guidance and direct laryngoscopy utilizes specialized surgical laryngoscopes and robotics. Early familiarity with the available anesthesia and surgical equipment alike will facilitate anesthetic planning.

Preoperative Planning

The goals and indication for the planned procedure should be clearly defined. An algorithm for operative planning for ENT surgery patient is presented in Fig. 19.2. Many ENT procedures are performed as same-day ambulatory surgery yet come with the high risk of post-operative nausea and vomiting or potential airway compromise from opioid-induced respiratory depression. Care should be taken to risk stratify patients and adjust anesthetics appropriately to enhance the success of same day procedures

A feature relatively specific to ENT anesthesia is the increased likelihood of an anticipated difficult airway. This is especially true in those patients who present with lesions of the oropharynx, trachea, thyroid, those with severe obstructive sleep apnea, and those who have abnormal anatomy due to previous surgery or radiation of the head or neck. These patients require special consideration more so than other "routine" ENT procedures including neck dissection, sinus, and inner ear surgery.

A thorough pre-operative assessment should include review of surgeon clinic notes, nasopharyngeal laryngoscopy (NPL) reports

Key Pre-operative questions: (8)

1. Same Day Surgery? Sinus, most inner ear, tonsillectomy, MDL
   Yes: See ambulatory surgery chapter, enhanced recovery planning
2. Airway Surgery or known airway pathology? MDL, Oral Robotic Surgery, OSA Surgery, radiation
   Yes : Conversation with surgeon, NPL exam, difficult airway preparations, awake trach, non-ETT oxygenation strategies, total intravenous anesthesia (TIVA)
3. Neuromonitoring? Parotid (VII), Neck Dissection (VII, XI), Thyroid (X-RLN), Ear (VII/VIII)
   Yes: Avoid neuromuscular blockade
4. Elevated PONV Risk? Multimodal, Highest risk consider adding scopolamine patch/aprepitant (NK1), TIVA
5. Respiratory depression risk? OSA, Obesity, Airway Surgery
   Yes: Consider post-operative SpO_2/CO_2 monitoring, Opioid Sparing Plan: acetaminophen, lidocaine, blocks, ketamine, NSAID
6. Special purpose ETT? Robotic, laser resection, thyroid, oral, airway surgery
   Yes: Discuss with surgeon: wire-reinforced, laser, R.A.E., nasal, MLT, NIMS
7. Elevated fire risk? Laser, airway, tracheostomy, thyroid (if sedation)
   Yes: Close communication, lower FiO_2, saline pledgets, Air/O_2 blender if sedation
8. Tracheostomy?
   Yes: Indication, airway records, vent settings, blood gas, backup intubation plan, ETT balloon management

Fig. 19.2 Operative Planning for ENT Surgery

and a discussion of both concerning features and the operative plan with the surgeon. The patient should be queried regarding signs or symptoms of airway obstruction (positional dyspnea, cough, stridor, dysphagia, hoarseness, wheezing) or a diagnosis of obstructive sleep apnea. Radiologic studies, and particularly 3D, multi-planer CT reconstructions of the airway may be performed in some centers. Spirometry will commonly show evidence of obstruction but is rarely quantitative. Warning signs of impending severe obstruction include signs and symptoms include inability to lie flat, inability to produce a strong cough, stridor or dyspnea at rest, sialorrhea, and baseline hypoxemia. Awake, sedated fiberoptic intubation or at least awake fiberoptic examination of the airway should always be considered in the management of a tenuous airway [8, 9]. Consideration may be given to the need for awake tracheostomy under local block as dynamic airway changes after induction of anesthesia, even with spontaneous ventilation can never be excluded.

Intra-Operative Issues

General anesthesia for ENT procedures can be maintained with a variety of techniques. Total intravenous anesthesia (TIVA) may be considered in procedures with delicate hemostasis (sinus surgery, tonsillectomy, inner ear surgery) or high risk of PONV as some data suggest that TIVA is associated with decreased bleeding, decreased coughing at emergence, and reduced rate of PONV. TIVA should also be considered in cases where periodic interruption of ventilation is likely to be required or jet ventilation employed (e.g. laryngotracheal surgery, tracheal stenting). An infusion of propofol and an opioid (fentanyl,sufentanil,remifentanil) is the most common approach.

The surgical airway is almost always rotated away from the anesthesia team and is generally inaccessible after surgical draping. Extreme neck extension, rotation, or flexion for surgical positioning can result in extubation or endobronchial intubation, respectively. For this reason, careful attention to positioning is critical in head and neck surgery. This includes attention to arms

and intravenous lines when the arms are tucked, adequate slack on the breathing circuit, and assessment of the head to avoid overextension.

As in certain neurosurgical procedures, nerve monitoring has a role in ENT surgery when the facial, acoustic, and recurrent laryngeal nerves are at risk. The procedures include resection of acoustic neuroma, mastoidectomy, tympanoplasty, parotidectomy, and thyroidectomy. A specialized endotracheal tube with electrodes located at the vocal cords (NIMS) may be used to monitor vocal cord function. Nerve monitoring for these procedures precludes the use of intra-operative muscle relaxation, but due to the high fidelity of EMG signals there is rarely any need to further adjust the anesthetic management.

In the absence of pre-operative anemia, blood loss rarely meets criteria for transfusion unless unexpected intrusion of a major vessel occurs during neck dissection.

Neck Dissection

Neck dissection is a common procedure associated with a head/neck tumor and is performed for the removal/staging of lymph nodes. This procedure is often lengthy with concern for hypothermia. Spontaneous ventilation is relatively contraindicated due to possible air embolus with surgical trespass on neck veins. General endotracheal anesthesia is standard approach. Surgeons may desire to monitor the spinal accessory nerve and the marginal mandibular branch of the facial nerve during fine dissection thus limiting the use of neuromuscular blocking agents, while gross dissection around large neck muscles may benefit from muscle relaxation. Therefore, coordination with regard to dosage and timing of neuromuscular blockade should occur. Frequent manipulation of the head during the procedure often leads to sudden circuit disconnect or tube malposition (main stem intubation with flexion or cuff herniation above the glottic with extension) and kinking. In rare situations, pneumothorax or air embolus can occur. These possibilities should be considered immediately if ventilator fault alarms sound or hypoxemia develops during a neck dissection.

Endoscopic Sinus Surgery (FESS)

This is a common procedure performed for chronic sinusitis but also for severe epistaxis, tumor resections of the anterior skull base, pituitary, and sinus cavities, and repair of CSF leaks. Most surgeons use CT image guidance for the procedure and rotate the head away from the anesthesia machine. Most patients who present for these procedures have limited co-morbidities and many are done on an outpatient basis. One should be aware, however, of the physiologic consequence of pituitary tumors and their removal (acromegaly, diabetes insipidus, thyroid dysregulation) if this is the indication for surgery.

A transsphenoidal approach to neurosurgical procedures involving the skull base and pituitary has become popular due to decreased surgical morbidity. These procedures are combined neurosurgical/ENT team procedures and are generally more invasive and more complex than routine sinus surgery. Steroid repletion may be necessary around the time of surgery involving the pituitary, and invasive arterial monitoring may be indicated, especially for perioperative electrolyte monitoring.

The anesthetic approach for sinus-related surgery typically involves general endotracheal anesthesia with non-invasive monitoring and single intravenous access. Post-operative pain is usually mild and blood loss is typically modest. In complex cases of tumor resection or epistaxis treatment, large-bore IV access should be obtained and blood products available. A lumbar drain, to facilitate CSF drainage and fluorescein dye injection, may be requested. Post-operative pain is usually mild to moderate and avoidance of PONV is important.

Thorough suctioning of the oropharynx prior to extubation is critical as large volumes of oral secretions may accumulate. Some elect to pass an orogastric tube to evacuate blood and secretions prior to extubation. In combined neurosurgical cases, a CSF leak may be created during the procedure requiring extreme attention to the avoidance of valsava during emergence. Likewise, placement of nasal trumpets or mask ventilation with positive pressure after any sinus procedure should be done only after consultation with the surgical team and with extreme caution.

Inner Ear Surgery

Chronic mastoiditis, sensorinueral hearing loss, and otosclerosis are all common indications for inner-ear surgery. Procedures include tympanoplasty, mastoidectomy, stapedectomy, and cochlear implant. The procedures are routinely performed under general anesthesia with an LMA or endotracheal tube, although stapedectomy can be safely performed with sedation in selected patients. There is rarely significant blood loss and post-operative pain is usually minor. Intra-operative monitoring of the facial nerve is standard and requires avoidance of muscle relaxation during the intra-operative period. A major problem is post-operative nausea and vomiting which requires aggressive multi-modal prophylaxis: a serotonin 5HT-3 antagonist, dexamethasone, scopolamine patch, aprepitant (NK-1 antagonist), and polyantagomists (promethazine) are commonly employed. Post-operative pain is usually mild to moderate and can often be managed without longer acting opioids.

Airway Surgery

Surgery to diagnose and treat airway disease (vocal cord polyp, oral cancer, laryngeal mas) is a mainstay of ENT practice. More recently, transoral robotic surgery (TORS) has become a mainstream of treatment for cancers of the oropharynx. Patients with oral lesions tend to have multiple medical conditions, a long history of smoking or heavy alcohol consumption, and at least the potential for a difficult airway. As the prevalence of obstructive sleep apnea (OSA) has increased in the global population, these patients are increasingly presenting to the OR. Novel therapies such as hyoglossal nerve stimulators are now becoming common and the surgical procedure for insertion is relatively limited and frequently performed on an ambulatory basis. Patients presenting for airway surgery for cancer, other lesions (e.g. stenosis), or OSA require comprehensive discussion and planning with the surgeons.

Some specific considerations are detailed below. Post-operative intubation and ventilation may be necessary in patients with significant residual airway disease, or procedures in which significant surgery involving the airway may predispose to swelling, recurrent laryngeal nerve injury, or bleeding with concomitant airway compromise. Otherwise, inpatient monitoring with continuous oximetry or capnometry and opioid-sparing approaches should be considered.

1. Tonsillectomy (Most common ENT procedure)
   (a) Frequently associated with severe OSA
   (b) Usually employ oral R.A.E. tube for midline position
   (c) Elevated risk of airway fire
   (d) Delicate hemostastis, risk of post-operative bleed early and late
      (i) Smooth emergence to avoid hypertension, hypervigilance of PONV; NSAID use is controversial
2. Micro Direct Laryngoscopy (MDL) [10]
   (a) Examination of the pharynx/larynx under direct vision for interventional procedures (e.g. lesion resection or biopsy); typically a <30 min procedure
   (b) General anesthesia with jet ventilation, small ETT (size 4–6), intermittent apnea with extubation/re-intubation, or Transnasal Humidified Hi-Velocity Exchange (THRIVE) using hi-flow nasal oxygen.
   (c) Total intravenous anesthesia preferred to potent agents
      (i) +/− muscle relaxation (short-acting) as needed for visualization
   (d) Surgeon often present at time of induction
   (e) Minimal post-operative pain
3. Tracheostomy
   (a) For obstructive lesion or respiratory failure
   (b) Usually critically ill or life-threatening airway compromise
      (i) Thorough pre-operative medical evaluation
      (ii) Understand previous airway management & assess risk

(c) Coordinate airway management (e.g. tube manipulation, FiO_2) with the surgeon
(d) Consider special ventilation requirements (APRV, high PEEP)
(e) Minimal sedation for emergent awake tracheostomy
    (i) Use air-oxygen blender for high fire risk

4. Laser surgery [11]
   (a) Usually performed at time of MDL for mass/papilloma/web
   (b) Risk of fire: use precautions (FiO_2 ~ 21%, avoid N_2O, use a laser tube with methylene blue indicator, use saline soaked pledgets)
   (c) Eye protection (laser goggles) for providers and patient

Ophthalmology

The majority of ophthalmologic procedures are done on an outpatient, elective basis. However, the patient population varies widely from pediatric strabismus surgery to elderly patients with multiple co-morbidities for cataract surgery. Procedures generally require a cooperative patient and an immobile globe.

Intraocular pressure (IOP) is akin to ICP and is a primary physiologic consideration in ophthalmologic surgery, particularly as concerns direct injury to the globe and glaucoma. The principles of management are similar to neurosurgery. IOP may be increased by severe hypertension, valsalva, coughing, hypercapnia, succinylcholine induced fasciculations, and injection of fluid/anesthetic into the orbit.

Numerous procedures such as Lasik® and cataract surgery are conducted with sedation accompanied by local infiltration or block. Others, including vitrectomy and strabismus repair invariably require general anesthesia. Importantly, choice of anesthetic is often influenced by co-existing conditions (e.g. inability to lay flat/still, neurologic disease) and the invasiveness of the procedure.

Many approaches to sedation are compatible with patient comfort. A bolus of hypnotic agent such a propofol, etomidate, or ketamine will facilitate block and instillation of local anesthetic. Henceforth anesthetic requirements are minimal and often giving 'less is more'. Importantly, the head of the patient will be fully covered and inaccessible once surgery has commenced under the operating microscope. Use of nasal cannula with capnographic monitoring capability is optimal.

Many ophthalmologists are accustomed to placing a retrobulbar block, peribulbar block or Sub-Tenon's injection. The choice of block is largely based on surgeon preference and experience with peribulbar and Sub-Tenon's injections carrying less risk of optic nerve injury or bleeding but requiring larger volumes with less reliable akinesia. Blocks are often accompanied by instillation of local anesthetic in the conjunctiva. In some cases this local anesthesia is sufficient for the procedure (e.g. simple cataract).

For the retrobulbar block (Fig. 19.3), a 25G sharp needle (25 mm length) is used to inject several milliliters of a mixture of

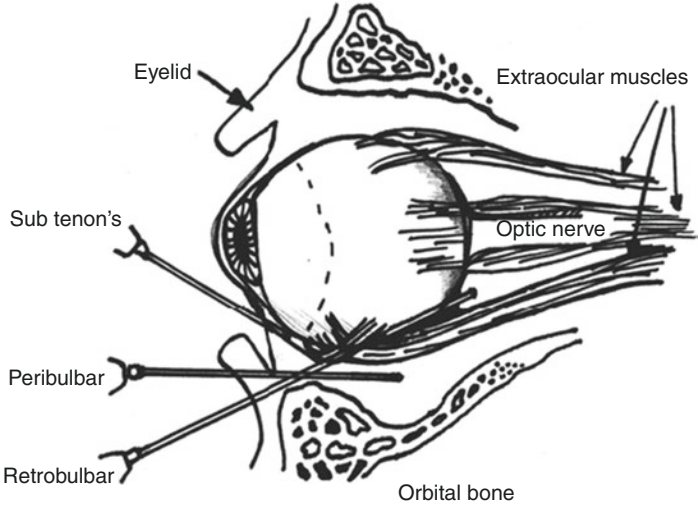


Fig. 19.3 The typical needle trajectory used to perform Sub-Tenon's, peribulbar, and retrobulbar blocks is depicted [12]

bupivicaine 0.5% with lidocaine 2% with hyaluronidase to facilitate diffusion and penetration. Epinephrine is avoided in most patients on the presumption of exacerbation of cardiac disease or risk of optic ischemia in particularly with regard to analgesia and globe immobility. However, anesthesiologists must be able to recognize and treat the potential complications associated with such blocks. These include subarachnoid injection (apnea), intravascular injection (seizure), intraneural injection (severe pain, blindness), and globe rupture/bleeding or increased IOP (proptosis, agitation, hemorrhage).

The oculo-cardiac reflex is an additional consideration. Mediated by the ciliary branches of V1 and the vagus nerve, the reflex causes a profound bradycardia, and occasionally arrhythmia or asystole, in response to manipulation of the globe or pressure within the orbit. The reflex is present even after enucleation. The resultant bradycardia can be treated with immediate cessation of stimulus, administration of atropine, deepening of general anesthesia, and in some cases infiltration of additional local anesthetic. The reflex is extremely common in pediatric strabismus surgery and less so during procedures conducted under local bloc.

Procedures on the eye increase the risk of post-operative nausea and vomiting and aggressive prophylaxis is recommended.

Case Discussion: Outpatient Thyroid Surgery

A 52-year-old woman with a moderate size thyroid goiter presents for same day thyroidectomy. Her past medical history includes well-controlled hypertension, moderate OSA on CPAP with which she is compliant, and Grave's disease. She takes daily lisinopril 10 mg and methimazole which she has taken the evening before surgery. She has no known drug allergies and last had anesthesia for a tonsillectomy at age 26 with no reported problems. She is 160 cm tall and weighs 59 kg with a BMI of 23. Her vital signs in the preoperative area are BP 132/69, HR 72, RR 12, SpO2 99% on room air and she has an 18G intravenous line in place.

What are considerations for pre-operative assessment? It is imperative to know if the patient is clinically euthyroid. Hypo- and hyperthyroid states can complicate perioperative management and increase risk for an otherwise non-urgent procedure. Thyroid state is evaluated by TSH and free T3/T4 levels but can also be assessed from clinical signs and symptoms. The next consideration is the assessment of the impact of the goiter on the airway. This can be assessed radiographically by examining the CT scan. It is important for anesthesiologists to become accustomed to reviewing relevant films. A joint review with the surgical team can be enlightening and helpful to clarify specific issues. In addition to radiographic findings, ENT consultation for a nasopharyngolaryngoscopy (NPL) exam can be considered if there is a high concern for airway impingement by the goiter. A bedside clinical assessment is also informative. This includes looking for overt signs of respiratory distress. It is also helpful to ask the patient if they can lie flat, if there are any new symptoms of "asthma", and if the patient can produce a strong cough. Airway compromise can frequently be misdiagnosed as "asthma". The ability to lie flat and produce a cough is a reassuring finding.

Why is the patient hoarse and what are the clinical implications? The recurrent laryngeal nerve, a branch of the vagus nerve, runs through the thyroid gland. Hoarseness is a common presenting symptom of thyroid disease. This information is important because one of the more serious complications of thyroid surgery is injury to the recurrent laryngeal nerve. This presents as severe voice impairment after surgery if there is unilateral or potentially severe airway compromise requiring intubation or tracheostomy if there is bilateral damage. For this reason the vast majority of thyroid surgeons employ neuromonitoring of the recurrent laryngeal nerve during surgery. For the anesthesiologist this entails (1) use of a NIMS tube to which sensing electrodes have been applied (2) recommended use of videolar-

yngoscopy to place the tube so that the electrode placement at the level of the cords can be confirmed by the surgical and anesthesia teams, and (3) avoidance of neuromuscular blockade. If the patient is deemed a high-risk intubation and a fiberoptic approach is taken, this will require a separate assessment of electrode placement after intubation.

Given the reassuring information about the airway what are important considerations to the operative management? The case is scheduled for a same-day discharge. Post-operative vomiting and the associated Valsalva can disrupt delicate hemostasis after thyroid surgery and cause hematoma formation. A post-thyroidectomy hematoma is a surgical emergency. As discussed in the chapter on Ambulatory Surgery, a multimodal PONV prophylaxis plan is imperative. Total intravenous anesthesia would be helpful to reduce PONV and dampen emergence-related coughing that is more frequently associated with inhalation anesthetics. Pain after thyroidectomy is usually mild-to-moderate. An opioid-sparing approach would be beneficial given both ambulatory nature of the surgery and the OSA which is likely due to anatomical features of the patient's airway as the patient is not obese. Pre-operative acetaminophen and perioperative NSAID with the use of intermediate or long-acting local anesthetic can be considered.

The patient is desaturating in the PACU after a relatively straightforward procedure, what do you do? Desaturation after surgery and anesthesia can have many causes and needs to be assessed urgently. Common causes include airway obstruction from OSA, opioid-induced respiratory depression, atelectasis and wheezing. In this patient it is critical to differentiate immediately between obstruction and breathing without obstruction. Airway obstruction in the thyroid patient that is unrelated to OSA is a surgical emergency and can be secondary to either bilateral recurrent laryngeal nerve injury, hypocalcemia due to unintended total parathyroidectomy, or hematoma from

bleeding resulting in airway compromise. The surgical teams should be alerted quickly and emergency airway equipment and surgical instruments needed to decompress the hematoma should be made immediately available at the bedside.

References

1. Brambrink AM, Kirsch JR (eds) (2011) Essentials of neurosurgical anesthesia and critical care. Springer, New York
2. Banoub M, Tetzlaff JE, Schubert A (2003) Pharmacologic and physiologic influences affecting sensory evoked potentials: implications for perioperative monitoring. Anesthesiology 99(3):716–737
3. Gupta A, Gelb A, Duane D, Adapa R (eds) (2018) Gupta and Gelb's essentials of neuroanesthesia and neurointensive care, 2nd edn. Cambridge University Press
4. Li J, Gelb AW, Flexman AM, Ji F, Meng L (2016) Definition, evaluation, and management of brain relaxation during craniotomy. Br J Anaesth 116(6):759–769
5. Stoelting RK, Dierdorf RF (2004) Anesthesia and co-existing disease, 4th edn. Elsevier Churchill Livingston
6. Jaffe RA (ed) (2014) Anesthesiologist's manual of surgical procedures, 5th edn. Wolters Kluwer, Philadelphia
7. Atkins, JH, Mandel JE (eds) Current topics in anesthesia for head and neck surgery, Anesthesiol Clin 28(3)
8. Moorthy SS, Gupta S, Laurent B, Weisberger EC (2005) Management of airway in patients with laryngeal tumors. J Clin Anesth 17(8):604–609
9. Pearce W (ed) (2020) Approach to the difficult airway. Operative techniques in otolaryngology 3(1)
10. Werkhaven JA (2004) Microlaryngoscopy-airway management with anaesthetic techniques for CO(2) laser. Paediatr Anaesth 14(1):90–94
11. Roy S, Smith LP (2015) Surgical fires in laser laryngeal surgery: are we safe enough? Otolaryngol Head Neck Surg 152(1):67–67
12. Mani J, Brodsky MA (2017) Anesthesia for ophthalmologic surgery. In: Goudra B, Singh P (eds) Out of operating room anesthesia. Springer, Cham. https://doi.org/10.1007/978-3-319-39150-2_24

Obstetric Anesthesia

20

Vesela Kovacheva, Jacob Schreiner, and Meredith A. Albrecht

Key Learning Objectives

- Learn the physiologic changes associated with pregnancy
- Know the various methods of pain control available during labor
- Understand the anesthetic management of the pregnant patient

V. Kovacheva (✉)
Department of Anesthesiology, Perioperative and Pain Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA
e-mail: vkovacheva@bwh.harvard.edu

J. Schreiner
Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: jschreiner@mcw.edu

M. A. Albrecht
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: maalbrecht@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_20

Obstetric challenges for the anesthesiologist include simultaneous care of the mother and fetus, dire emergencies, and complex diseases. In the course of battling these challenges, clinicians are immersed in their patient's life-changing experiences. For this reason, obstetric anesthesia is considered by many to be one of the most rewarding anesthetic subspecialties.

Normal Physiologic Changes of Pregnancy

In order to provide safe and effective obstetric anesthesia, you must understand maternal physiology. Pregnancy represents a state of profound physiologic adaptation. Some adaptations become apparent in the first trimester and many persist well after delivery. Every organ system is affected. Table 20.1 summarizes some of the important changes.

Table 20.1 Summary of physiologic changes of pregnancy at term

Variable	Increase or Decrease
Oxygen consumption	↑
Cardiac output and stroke volume	↑
Systemic vascular resistance	↓
Blood pressure	↓
Minute ventilation	↑
$PaCO_2$	↓
Functional residual capacity	↓
Total blood volume	↑
Hematocrit	↓
Serum creatinine	↓

Cardiovascular

During pregnancy, **maternal oxygen requirements and metabolism steadily increase** and the cardiovascular system must adapt to meet these increased demands. Cardiac output escalates throughout pregnancy, due to increased stroke volume and elevated heart rate. Central venous and pulmonary artery occlusion pressures are unchanged. During labor, uterine contractions cause a cyclical increase in cardiac preload, further augmenting cardiac output. Systemic vascular resistance and mean arterial pressure decrease early in pregnancy and return to baseline at term.

In the supine position, the gravid uterus readily compresses the inferior vena cava. The aorta is affected to a lesser extent. This **aortocaval compression** impedes venous return and can lead to decreased cardiac output, hypotension, and decreased uterine perfusion. This syndrome, called the supine hypotensive syndrome, may occur as early as **20 weeks gestation** and is exacerbated by conditions that increase uterine size – such as macrosomia (large fetus) and multiple gestation. The lateral decubitus, knee-chest, and left uterine displacement positions help to avoid the detrimental effects of aortocaval compression.

Respiratory

Tidal volume increases during pregnancy. Respiratory rate is also increased, but less profoundly. The increased minute ventilation leads to a **compensated respiratory alkalosis**, a fact that is especially important to remember when initiating mechanical ventilation.

A number of physiologic changes place the obstetric patient at increased **risk** for airway complications including **failed endotracheal intubation** and **pulmonary aspiration**. Increased oxygen consumption and decreased functional residual capacity (FRC) lead to rapid development of hypoxemia during periods of apnea. Parturients (pregnant patients) are at an increased risk for difficult and failed intubation because the airway becomes less favorable during pregnancy and even labor. At term, mucosal engorgement frequently afflicts the upper and lower airway, mandating gentle laryngoscopy, smaller endotracheal tubes, and

avoidance of nasal airways. In the supine position, the enlarged breasts of pregnant females at term are upwardly displaced and laryngoscopes with short handles may be used to aid intubation.

Central Nervous System

The parturient is more sensitive to both inhalational and local anesthetics, an effect that has been attributed to increased progesterone. Endogenous endorphins may also play a role in mediating this effect, especially during the peripartum period. The minimal alveolar concentration (MAC) for volatile anesthetics declines throughout pregnancy. Hormonally-mediated changes may also increase neuronal sensitivity to local anesthetic agents. In addition, the gravid uterus causes distention of the epidural veins which is thought to decrease the local anestethic dose requirements for neuraxial blockade.

Hematologic

Total blood volume increases significantly (≈45%) during pregnancy. **Dilutional anemia** occurs because plasma volume increases more than red cell mass. The blood loss associated with a typical vaginal delivery (500 cc) or cesarean section (1000 cc) is usually well tolerated as a result of these changes. Other notable hematologic changes include leukocystosis, increased serum clotting factors, and an occasional mild decrease in platelet count. Parturients become **relatively hypercoagulable**, which is advantageous during acute obstetric blood loss. Unfortunately, the hypercoagulable state predisposes these patients to deep venous thrombosis, pulmonary emboli, and other thromboembolic events.

Gastrointestinal

The obstetric patient is at **increased risk for aspiration** of gastric contents because of:

- Impaired esophageal and intestinal motility
- Stomach conformation and position changes
- Decreased lower esophageal sphincter tone
- Delayed gastric emptying during labor

Prophylactic measures aimed at reducing the risk of aspiration pneumonitis are generally focused on modifying these risk factors. The most important prophylactic measure is the **avoidance of solid food during labor**. Other measures should be considered prior to surgery. Many routinely administer oral sodium citrate, a non-particulate antacid. Sodium citrate quickly buffers existing stomach acid, but at the expense of increasing gastric volume and possibly causing nausea. The buffering capacity of sodium citrate is time-limited, and it should therefore not be administered far in advance of surgery. H_2-receptor antagonists or proton-pump inhibitors can be used, but their beneficial effects are likely delayed. Metoclopramide increases gastric emptying and lower esophageal sphincter tone and is advocated by some practitioners. The possibility of extrapyramidal reactions is a major drawback to its routine use.

Renal

Renal blood flow and glomerular filtration rate increase markedly during pregnancy. As a result, the obstetric patient's creatinine should be less than her non-pregnant value. Additionally, total body water increases by ≈30%. Increased glomerular permeability to proteins may lead to a mild proteinuria during pregnancy.

Musculoskeletal

As the gestation progresses, the lumbar spine becomes increasingly lordotic. Lordosis hampers the interlaminar approach for the lumbar spinals and epidurals. Although less feasible with advancing uterine size, good positioning helps to offset the undesirable effects of lordosis. Ligaments tend to become more lax near term

as the body prepares for vaginal delivery. Many operators have noted that the ligamentum flavum has a more spongy texture at term when compared to the non-pregnant state.

Uteroplacental Blood Flow

By the end of the third trimester, uterine blood flow may represent up to 12% of cardiac output. Perfusion of the uterus is adversely affected by decreased uterine arterial pressure (hypovolemia, aortic compression), increased uterine venous pressure (vena cava compression), and increased uterine vascular resistance (uterine contractions, severe preeclampsia). Derangement of these variables may adversely affect fetal oxygen delivery.

Exogenous vasoconstrictors can also adversely affect uterine perfusion. Recent studies have shown that phenylephrine (direct α- agonist) is superior to ephredrine (indirect α- and β-agonist) for the treatment of hypotension following neuraxial block for cesarean section, as evidenced by better hemodynamic control and more favorable umbilical cord gases.

Maternal Fetal Exchange

Blood from the maternal uterine spiral arteries bathes fetal villi capillaries within the maternal intervillous spaces of the placenta. Since placental exchange occurs across a membrane, it is dependent on diffusion, bulk flow, and active mechanisms. Oxygen and carbon dioxide diffuse readily across the placenta. Unloading of maternal oxygen is facilitated by a **rightward shift in the oxyhemoglobin dissociation curve**. Fetal oxygen transfer is further bolstered by fetal hemoglobin's high affinity for oxygen (leftward shift of the oxyhemoglobin dissociation curve compared to adult hemoglobin).

The maternal-to-fetal transfer of drugs is a complex topic. In general, molecules that are small and lipophilic (e.g., most anesthetics) cross the placenta easily, while large, hydrophilic molecules that are protein-bound diffuse poorly (e.g., neuromuscular blocking drugs, insulin). Some drugs, for example, local anesthetics may accumulate in the fetus through so-called **ion-trapping**.

This occurs when local anesthetics (which are non-ionized weak bases) cross into the relatively acidotic fetus and become ionized and are then unable to defuse back to the maternal circulation or are "trapped".

Intrapartum Fetal Evaluation

The goal of intrapartum fetal evaluation is to detect early fetal distress and initiate interventions (e.g., change maternal position, tocolysis, or perform a cesarean section) to prevent adverse neonatal outcome. Continuous fetal heart rate (FHR) monitoring is very widely used to guide clinical decisions despite association with increased incidence of instrumental/operative delivery and scarce evidence of its efficacy. When analyzing FHR racing, the following features are of greatest importance in relevance to the uterine contractions: baseline FHR, variability, accelerations and decelerations. The normal, baseline (FHR) is between 120 and 160 beats per minute (Fig. 20.1). FHR variability is the fluctuation above and below the baseline over time and its presence is reassuring. Accelerations are brief, short increases of FHR above the baseline that are usually accompanied by fetal movement and signal fetal wellbeing.

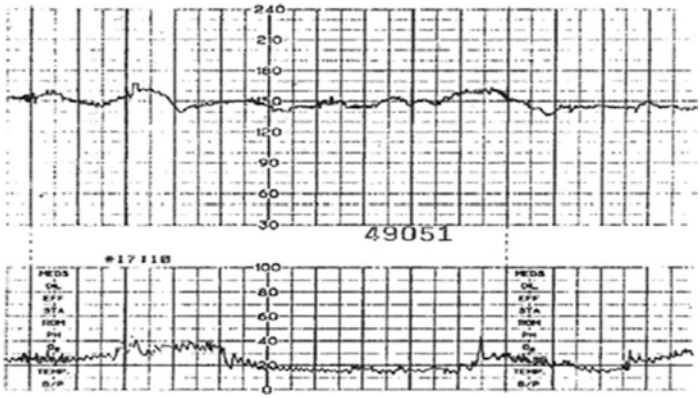


Fig. 20.1 Normal fetal heart rate pattern. The heart rate (140 beats/min) variability is normal. There are no periodic changes. (From Ref. [5]. Used with permission)

Decelerations are a periodic slowing of FHR. Three principal deceleration patterns have been described according to their relationship to uterine contraction: *early, late, and variable decelerations* (Figs. 20.2, 20.3, and 20.4).

Increased vagal activity due to fetal head compression is associated with early decelerations. Early decelerations begin soon after uterine contraction, tend to have a uniform shape, and do not herald fetal hypoxia. Late decelerations represent uteroplacental insufficiency, that is, insufficient fetal oxygen delivery during

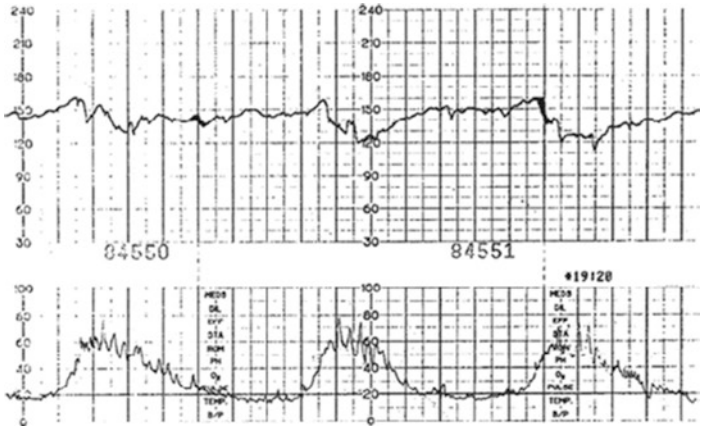


Fig. 20.2 Early decelerations. (From Datta [5]. Used with permission)

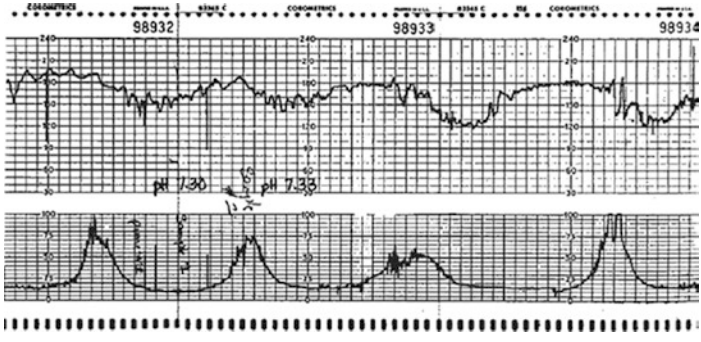


Fig. 20.3 Late decelerations, with decreased variability of the fetal heart rate (FHR) between contractions. (From Datta [5]. Used with permission)

uterine contraction. Variable decelerations are typically due to umbilical cord compression and have a variable relationship to uterine contraction.

Based on these characteristics, FHR tracings are classified into 3 categories (Table 20.2).

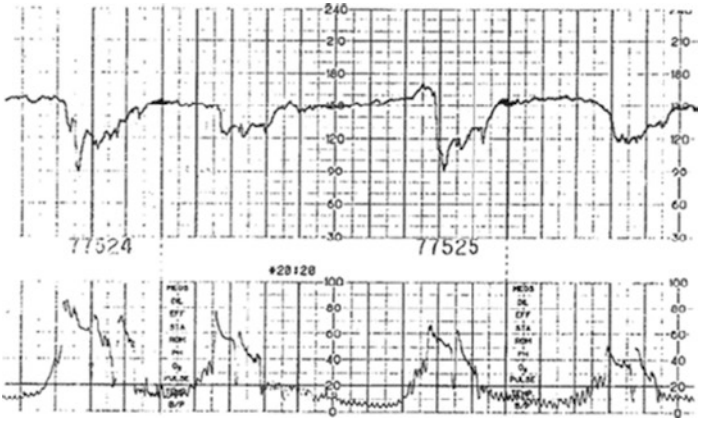


Fig. 20.4 Mild to moderate variable decelerations with pushing during the second stage of labor. (From Datta [5]. Used with permission)

Table 20.2 Three tier system for categorization of FHR patterns

	Cat I	Cat II	Cat III
Fetal acid-base status	Likely normal	Unable to determine	May be abnormal
Examples:	*Baseline FHR* 110–160 Accelerations No late or variable decelerations	All tracings not classified in cat I or III	Absent baseline variability and recurrent late or variable decelerations Fetal bradycardia
Management	Continue routine care	Considet further fetal and maternal evaluation	Prompt attempts to resolve Consider oxygen, terbutaline if appropriate Consider expediting delivery

Neonatal Evaluation

Biophysical Profile Another technique to examine fetal well-being involves a prenatal ultrasound evaluation and a non-stress test (NST) with the fetus scored based on the fetal heart rate, breathing, movement, tone and amniotic fluid volume. It is used to help make decisions when to induce labor early.

The Apgar Score Once the fetus has been delivered, the Apgar Score (Table 20.3) can be used to evaluate its well-being. Named after Virginia Apgar (an anesthesiologist who developed the system in the 1950s), the score is made up of five criteria each on a scale of 0–2. The five scores are then summed to provide a single total Apgar Score of the newborn. The score ranges from 0 to 10, with 7–10 generally considered normal.

Table 20.3 Apgar score

	0 points	1 point	2 points
Appearance	Completely blue	Extremities blue	Pink
Pulse	Absent	<100 bpm	>100 bpm
Grimace	No response to stimulation	Grimaces when stimulated	Pulls away when stimulated
Activity	None	Some flexion	Moving actively
Respiration	None	Weak	Good

Anesthesia for Vaginal Delivery

The coordinated uterine movements and cervical dilation cause significant discomfort commonly known as labor pain. Labor itself can be divided into three stages:

- the **first stage** of labor begins with contractions and ends with complete cervical dilatation
- the **second stage** of labor begins with full cervical dilation and ends when the fetus is delivered
- the **third stage** of labor begins with the delivery of the fetus and ends with delivery of the placenta

The majority of pain during the latent phase of labor is visceral in quality and uterine in origin. During the first stage of labor, pain is due to cervical dilatation and uterine contractions. The pain pathway involves visceral afferents that enter the spinal cord at T10-L1. As labor progresses to second stage, it is increasingly accompanied by somatic pain, which reaches the spinal cord via pudental afferents (S2–S4). Figure 20.5 depicts pain pathways in the parturient.

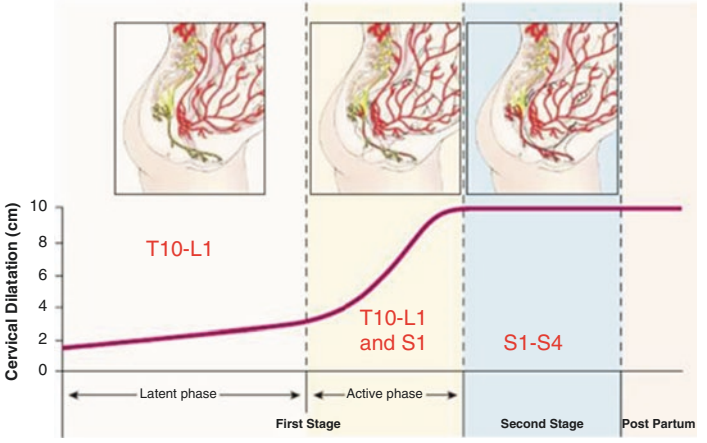


Fig. 20.5 Pain pathways for the first and second stages of labor. (From NEJM[7] Used with permission)

Non-pharmacologic Options for Labor Pain

The pain associated with vaginal delivery can be mitigated by a variety of techniques. Supraspinal modulation of pain may underlie the effectiveness of techniques, such as the Lamaze technique of breathing and relaxation. Other non-pharmacologic pain management techniques include childbirth education, biofeedback, aromatherapy, yoga, hypnosis, acupuncture, hydrotherapy, and massage

Systemic Medications for Labor Pain

Systemic (intravenous) analgesia with opioids such as morphine, fentanyl, hydromorphone, and remifentanil as well as mixed agonist-antagonist opioids (e.g., butorphanol, nalbuphine) are used as either intermittent bolus doses or patient-controlled analgesia (PCA) The main disadvantage of systemic opioids is that they can cause **respiratory depression** in the fetus and the mother. Inhaled nitrous oxide is an alternative, albeit not very potent, analgesic which has minimal side effects on the mother and fetus.

Neuraxial Anesthesia

Though far from ideal (see Table 20.4), neuraxial analgesia (lumbar epidural) is often the best pharmacotherapeutic solution to the pain of childbirth. Most consider lumbar epidural analgesia to be the gold standard for labor analgesia. It is effective for both first and second stages of labor.

Table 20.4 Qualities of an ideal pharmacotherapeutic technique for labor analgesia

Attribute
Efficacious and reliable
Duration of action coincides with duration of labor
No contraindications
No side effects (pruritus, nausea, hypotension, urinary retention)
No complications (nerve injury, high block, epidural hematoma/abscess)
Produces sensory blockade without motor weakness
Does not interfere with or prolong labor
No increased risk of operative delivery
Flexible as the situation changes (vaginal vs. operative vs. cesarean delivery)
Low cost and low resources needed

Epidural Analgesia

Continuous lumbar epidural analgesia (see Chap. 13, Regional Anesthesia) is often employed for labor analgesia, with patient-controlled epidural analgesia (PCEA) or programmed intermittent epidural boluses (PIEB). PCEA and PIEB have both been shown to improve analgesia, reduce the amount of medication used, and decrease the number of provider interventions. The contemporary use of dilute local anesthetics solutions with small doses of epidural opioids provides effective analgesia with minimal motor block and low risk of opioid-related respiratory depression. Dilute local anesthetics are also associated with a lower risk of operative delivery. Main side effects of the labor epidural include **hypotension, motor blockade**, and a risk of intravascular or intrathecal local anesthetic injection.

Needle placement in the laboring parturient can be challenging due to ongoing discomfort and increased lordosis. When identifying the epidural space, one must be aware that increases in intraabdominal pressure can transmit to the epidural space. **Unintentional dural puncture**. may result if the needle is advanced indiscriminately during a period of high intraabdominal pressure, as often occurs with uterine contractions.

Combined Spinal-Epidural Analgesia

Combined spinal-epidural analgesia (CSE) has become increasingly popular for labor analgesia. When properly utilized, the technique appears to have a safety profile similar to continuous lumbar epidural analgesia. The principal advantage of the technique is rapid onset of analgesia due to intrathecal injection of opioid and/or local anesthetic. Unfortunately, the technique is sometimes associated with transient fetal bradycardia.

To perform a combined spinal epidural block, the epidural space is identified with loss of resistance in the low lumbar region. Once the epidural needle is properly positioned in the epidural space, it is stabilized. A long, small-gauge, pencil-point spinal needle is inserted through the epidural needle until a "pop" is detected. CSF is identified, and the desired medications are administered intrathecally. Upon removal of the spinal needle, an epidural catheter is threaded into the epidural space.

Dural Puncture Epidural

The technique involves a similar process as the CSE but no medication is inserted into the intrathecal space. This modification of the technique is associated with less side effects than a CSE (puritis, hypotension, fetal bradycardia), increased sacral coverage and less one-sided blocks compared to an epidural, and less intervensions by anesthesia personnel compared to both CSE and epidural. Its onset time is between a traditional epidural and a CSE. (See Fig. 20.6)

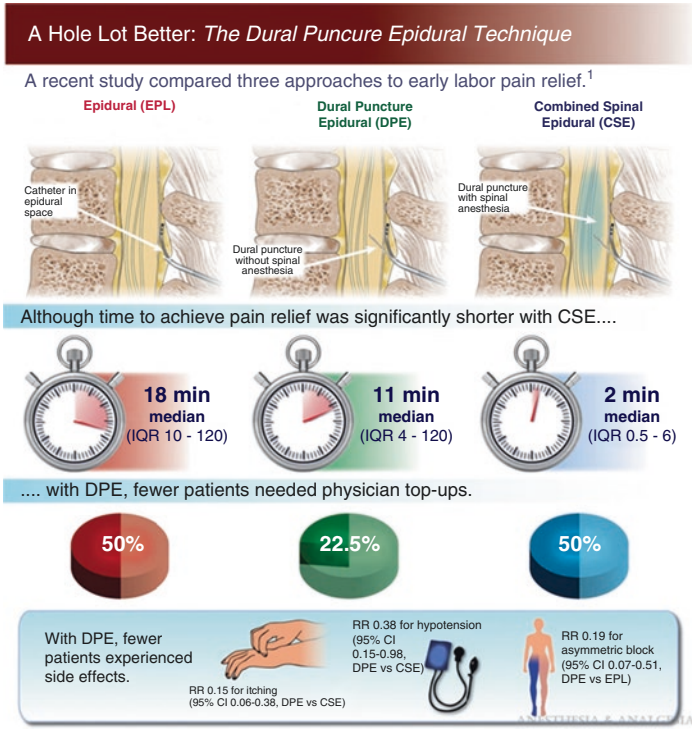


Fig. 20.6 Comparison of different neuraxial techniques for labor analgesia. (From Anesth Analg. 2017;124(2):375. Used with permission)

Continuous Spinal Analgesia

Continuous spinal analgesia, planned or unplanned, is highly effective for labor analgesia. An intrathecal catheter permits rapid achievement of surgical anesthesia, should it become necessary. Unfortunately, standard-sized catheters must be placed through large bore needles, leading to an unacceptable incidence of **post-dural puncture headache** (PDPH).

Neurologic Complications of the Neuraxial Techniques

The most common complication after neuraxial techniques is post-dural puncture headache. It manifests as positional headache which is worse with the patient sitting or standing and improves with the patient in recumbent position. It is commonly managed symptomatically; in severe or prolonged cases, it may be necessary to perform an epidural blood patch. The latter is a procedure in which a small amount of the patient's own blood is injected epidurally. Other rare but very serious complications include trauma to the nerve roots and spinal cord, infection and hematoma. The management of those patients requires prompt evaluation of any neurologic symptoms, early imaging and treatment. In cases of emergencies associated with spinal cord compression by either hematoma or abscess, the patient may need surgery to avoid permanent neurologic damage. Team communication, patient follow up and timely intervention are essential for best outcome.

Common Myths Regarding Neuraxial Analgesia

Over the years, many problems have been attributed to epidural analgesia for labor. Most assumptions have been determined to be false. Historical differences in epidural management and difficulties in study design have hampered the battle.

Old data, now refuted, appeared to show that epidural analgesia impairs neonatal well-being and increases the risk of cesarean section. Backache and neuropathy are also frequently blamed on neuraxial blocks. Many obstetric patients are afflicted by either condition whether or not they have had a neuraxial block. It is important to remember that obstetric trauma can injure the lumbosacral trunk. The neurologic exam may help to distinguish obstetric trauma from regional block needle trauma. A deficit is more likely due to obstetric trauma if it corresponds to the distribution

of a peripheral nerve, whereas a dermatomal distribution may be more likely the result of a neuraxial block.

Though often debated, **it is not clear whether or not epidural analgesia prolongs labor**. Epidural analgesia was historically avoided in early labor for fear of prolonging it. Fortunately for laboring women, this practice has been largely abandoned.

Anesthesia for Cesarean Section

Cesarean section is most commonly performed under neuraxial anesthesia. Though rarely necessary, the operation can be performed under local anesthesia. When choosing the anesthetic, one must consider a number of factors, particularly indication for cesarean, case urgency, and maternal-fetal well-being. Common indications for cesarean section include fetal distress, risk of maternal hemorrhage, dystocia (abnormal labor), and impending maternal death. The qualities of an ideal anesthetic for cesarean section are listed in Table 20.5. Neuraxial anesthesia, though not ideal, usually represents the best option.

Table 20.5 Qualities of an ideal anesthetic for cesarean section

Efficacious and reliable
Can be achieved instantaneously
Duration of action coincides with duration of surgery
Avoids aspiration of gastric contents
Avoids airway manipulation (negates the risk of difficult intubation)
Allows maternal participation in delivery
Conducive to family member presence in operating room
Does not interfere with neonatal well-being
Allows for stable hemodynamics
Does not interfere with hemostasis
No complications or unwanted side effects
No contraindications/no technical failures
Alleviates post-operative pain

Spinal Anesthesia

Single-shot spinal anesthesia produces rapid, reliable surgical anesthesia with a fairly predictable duration. Because peritoneal traction occurs, a T4 sensory level is considered ideal for most patients. Vagal afferents may explain the sensation of visceral discomfort even though the block appears to be "adequate." **Prior to surgical incision**, the presence of surgical anesthesia must be verified with objective testing (e.g., pin-prick). Prolonged operations (greater than 90 min) are often best managed with a continuous technique (e.g., combined-spinal epidural, continuous epidural, continuous spinal).

Intrathecal injection of small doses of lipophilic opioids (e.g., fentanyl) may help to alleviate some of the visceral discomforts of a cesarean section. Intrathecal morphine can provide good postoperative analgesia, though pruritus, nausea, and respiratory depression limit the enthusiasm of some practitioners for this technique.

Preemptive bolus administration of intravenous fluid and/or a phenylephrine infusion may help reduce the hemodynamic consequences of spinal anesthesia. Maintanence of proper left uterine displacement or a phenyleprine infusion helps avoid hypotension and patient nausea and vomiting due to hypotension. If hypotension occurs, it must be treated aggressively with intravenous fluid and phenylephrine.

Bradycardia will typically manifest when the block reaches a high thoracic level (T4). Bradycardia and hypotension unresponsive to initial resuscitative attempts must be promptly treated with epinephrine. Respiratory compromise may occur with a high spinal (greater than T4 level).

Epidural Anesthesia

In contrast to spinal anesthesia, epidural anesthesia affords a **more gradual onset** of hemodynamic changes that may be preferable in some scenarios. Unfortunately, epidural anesthesia is less profound, frequently patchy or unilateral, requires high doses of local anesthetic, and takes more time to establish.

For safety and convenience, epidural anesthesia is usually established via intermittent bolus of an indwelling epidural catheter. With a lumbar epidural, 15–25 mL of local anesthetic (0.5% Bupivacaine, 1.5–2% Lidocaine, 3% Chloroprocaine) is typically required to achieve surgical anesthesia. If patients are appropriately monitored, epidural morphine may be included for post-operative pain. Epinephrine is often added to epidural local anesthetics to decrease systemic absorption and lengthen duration.

A test dose of local anesthetic and epinephrine helps exclude subarachnoid and intravenous administration and is appropriate prior to epidural dosing. Chloroprocaine has a quick onset and is rapidly metabolized by plasma esterases. As such, chloroprocaine offers **some protection against systemic toxicity**. It is an excellent choice when epidural anesthesia must be induced quickly, such as during fetal distress in a patient with an existing epidural catheter.

Existing labor epidurals that are symmetric and have been controlling labor pain well can be used for surgical anesthesia after bolus dosage with concentrated local anesthetic. Epidural anesthesia is less profound when compared to spinal anesthesia. As with all regional anesthetics, objective testing of block quality must precede surgical incision. Should epidural anesthesia become inadequate during the operation, intravenous supplementation may be helpful (e.g., intravenous opioids, ketamine). Protective airway reflexes must remain intact, however. If the patient requires more than light sedation, general anesthesia should be induced and the airway should be secured. Risk factors for the failure of conversion of labor analgesia to surgical anesthesia include: urgency of the C-section, lack of an obstetric anesthesia specialist, and prior anesthesia clinician boluses for breakthrough pain during labor.

General Anesthesia

Parturients are considered to be at higher risk for **failed endotracheal intubation** and **aspiration of gastric contents**. As a result, general anesthesia is reserved for emergency cases or for those with contraindications to regional anesthesia. If a difficult airway

is anticipated, neuraxial anesthesia or awake fiberoptic intubation may be appropriate.

Prior to induction of general anesthesia, one should administer a nonparticulate antacid and consider the administration of metoclopramide and/or an H_2 receptor antagonist. In an effort to minimize fetal depression, general anesthesia is not induced until the patient is draped and the obstetrician is ready to operate.

Since parturients desaturate rapidly, the importance of preoxygenation cannot be overstated. As always, left uterine displacement must be maintained. After adequate preoxygenation, a rapid sequence intubation is performed, most commonly with propofol and succinylcholine. Cricoid pressure is applied by an assistant **until the endotracheal tube position is confirmed**. Prior to delivery, anesthesia is typically maintained with a volatile anesthetic. Some advocate the use of 100% oxygen prior to delivery, particularly in the setting of fetal distress. Oxytocin is routinely administered after fetal delivery to promote uterine contracture.

After delivery, the goal is to minimize volatile anesthetic concentration because higher volatile anesthetic concentrations can lead to inferior uterine tone. At this stage in the operation, supplemental opioids and nitrous oxide help to achieve an acceptable depth of anesthesia. It is wise to administer prophylactic antiemetics and empty the stomach with an orogastric tube prior to emergence. As with all patients who are considered to be a "full-stomach," the trachea must remain intubated until the patient is awake and able to protect her airway. The post-operative analgesic plan should aim to maximize the non-opioid approaches such as acetaminophen, ketorolac and regional blocks, for example transversus abdominus plane block (TAP).

Severe Maternal Morbidity

Antepartum/Postpartum Hemorrhage

Obstetric hemorrhage **is the leading cause of maternal morbidity and mortality worldwide**. The most important conditions associated with antepartum hemorrhage are:

- *Placenta previa* exists when the placenta is located close to the internal cervical os. Typically, the hemorrhage presents as painless vaginal bleeding.
- *Abruptio placentae* is an abnormal separation of the placenta from the uterine wall before the delivery of the fetus and is accompanied by changes in the FHT. Vaginal bleeding usually occurs with abruptio placentae, though significant hemorrhage can be concealed within the uterus.
- *Uterine rupture* is the feared complication of vaginal birth after cesarean section (VBAC), but it also occurs in patients without obvious risk factors. Uterine rupture may present with hypotension, fetal distress, and continuous abdominal pain (e.g., severe pain unrelieved by epidural analgesia). Significant hemorrhage may be concealed within the abdomen.
- *Vasa previa* is found when fetal blood vessels are close to the internal cervical os. Even though the bleeding is usually not severe, the risk for fetal mortality necessitates cesarean delivery.

The most common causes of significant post-partum hemorrhage include **uterine atony and retained placenta**. Uterine massage and intravenous oxytocin help to prevent uterine atony post-partum. Uterine tone can be improved with secondary agents like methylergonovine, carboprost and misoprostol. Adding tranexamic acid is likely to decrease blood loss and transfusion requirements. Manual uterine exploration is usually indicated in the setting of a retained placenta. General anesthesia or regional anesthesia may be appropriate, depending on the clinical scenario. Intravenous nitroglycerin and/or volatile anesthetics facilitate manual exploration via uterine relaxation. *Placenta accreta* occurs when the placenta invades deeply within the uterine wall, and may place the patient at risk for severe hemorrhage and cesarean hysterectomy. Vaginal and cervical lacerations can occur during delivery and may rarely cause overt hemorrhage requiring operative intervention.

When obstetric hemorrhage necessitates surgical management, general anesthesia is often considered, especially if emergency or severe hemorrhage. Ketamine and etomidate cause less hemodynamic depression as compared to propofol, making them good

intravenous induction agents for this setting. Large bore intravenous access, blood products, and fluid warming devices are obvious, life-saving necessities. Protocol-driven, team approaches are likely to result in the best patient outcomes.

Maternal Hypertensive Disorders

Hypertensive disorders of pregnancy are a leading cause of maternal mortality especially in developed nations. There are four main categories: Preeclampsia/eclampsia/HELLP syndrome (hemolysis, elevated liver enzymes, low platelets), gestational hypertension, chronic hypertension, and preeclampsia superimposed on chronic hypertension.

Gestational hypertension is hypertension without proteinuria or other signs/symptoms of preeclampisa that develops after 20 weeks (wks.) of gestational age (GA). About 10–25% of patients with gestational hypertension will develop preeclampsia.

Preeclampsia refers to the new onset of hypertension and proteinuria or the new onset of hypertension and significant end-organ dysfunction (with or without proteinuria). It typically develops after 20 weeks of gestation in a previously normotensive woman (systolic blood pressure (SBP) > 140 mmHg or diastolic blood pressure (DBP) > 90 mmHg. It may also develop postpartum. Severe hypertension (SBP > 160 mmHg or DBP > 110 mmHg) or signs/symptoms of significant end-organ injury represent the severe end of the disease. Severe preeclampsia is the presence of any of the following: severe range blood pressure (SBP > 160 mmHg or DBP > 110 mmHg), thrombocytopenia (platelet count <100 k), impaired liver function or persistent right upper quadrant pain, development of renal insufficiency (creatine >1.1 or a doubling of creatine in patients with preexisting kidney disease), pulmonary edema, and persistent cerebral or visual disturbances. Preeclampsia can develop into eclampsia (generalized seizures develop with no other possible cause). Preeclampsia can also develop into HELLP syndrome (hemolysis, elevated liver enzymes, and a lower platelet count). The treatment for preeclampsia is delivery. However, the timing of the delivery will

depend of the severity of the symptoms and the gestational age and development of the fetus.

Chronic hypertension in a hypertension that proceeds pregnancy or is present prior to 20 wks GA.

Preeclampsia superimposed upon chronic hypertension is a prior well controlled chronic hypertensive parturient develops worsening or resistant hypertension, new onset proteinuria or worsening proteinuria, and/or significant organ dysfunction after 20 wks. GA.

Case Study

A 30-year-old otherwise healthy woman presents at 39 weeks gestation with elevated blood pressure for induction of labor. You are consulted when she is 4 cm dilated, contracting regularly, and requesting labor analgesia.

What other information will you seek during your preoperative interview?

Besides routine information on comorbidities, NPO status, and obstetric and anesthetic history, you should learn more about the high blood pressure, which may be a sign of preeclampsia. If this diagnosis is suspected, it is prudent to check her laboratory studies, particularly the platelet count, before administering neuraxial analgesia. Her obstetric history is helpful in deciding if she is likely to deliver rapidly (for example, if she is multiparous, with ruptured membranes, and at 8 cm dilation) or more slowly (a nulliparous patient with intact membranes at 4 cm). It is also important to assess the fetal heart rate tracing (FHR) or consult with the obstetrician or obstetric nurse about the status of the baby. This information may guide your selection of analgesic technique.

Your preop shows that she is pregnant with her first child and has intact membranes. Her platelet count is 165×10^9/L. Other laboratory studies are negative. Her previous medical history is negative and her anesthetic history

is unremarkable. Her blood pressure on admission was 150/90 and has remained stable. The FHR shows a reassuring pattern.

What is your anesthetic plan?

This appears to be a healthy patient with mild gestational hypertension. She is a candidate for epidural, dural pucture epidural or combined spinal-epidural analgesia. Since her hypertension may be a risk factor for cesarean section, some anesthesiologists may prefer conventional epidural analgesia, in order to be certain that the catheter is functioning well (the CSE technique uses intrathecal opioids for the first 90 min or so, potentially masking an inadequate epidural catheter).

You select epidural analgesia.

Describe the technique and your initial choice of drugs.

The patient is positioned after applying standard monitors (pulse oximeter and NIBP) either sitting on the edge of the bed or lateral, with knees and hips flexed. The lower back is prepped and sterily draped and the L3–4 (or L4–5 or L2–3) interspace is infiltrated with 1% lidocaine. The epidural needle is inserted into the ligament with a slight cephalad angulation and then advanced slowly while checking for resistance to injection of saline or air in a syringe attached to the needle. When a loss of resistance is encountered (typically 4–7 cm from the skin), the catheter is threaded through the needle 3–5 cm into the epidural space, using the marks on the catheter and needle as a guide to depth, and secured with a sterile dressing and tape. A test dose of local anesthetic (with or without 1:200,000 epinephrine) is injected and the patient is asked for signs of intravascular injection (lightheadedness, tinnitus, perioral numbness) or intrathecal injection (immediate onset of profound numbness in the lower extremities). If negative, a loading dose of local anesthetic, often bupivacaine 0.0625–0.125%, often mixed with 2 mcg/ml fentanyl, is injected *in divided doses*, periodically checking again for signs of intravascular or intrathecal injection.

How will you maintain analgesia once established?

Although there are numerous regimens, programmed intermittent epidural boluses (PIEB) is very popular. An intermittent bolus of 9 ml epidural mix delivered every 45 min, is a typical protocol. The patient is instructed to push a demand button if pain ensues and to have the anesthesiologist paged if relief does not occur after one or two demand doses. Periodic checks of the patient's comfort and vital signs, the pump, and the FHR should continue even if you are not called!

After 3 h, you are paged because the patient is experiencing discomfort in the perineal area. She has tried pushing the PCEA button.

How would you respond?

Sacral pain and the urge to push often herald the beginning of the second stage of labor. Review of the most recent cervical exam with the obstetric nurse can help clarify the situation. A "top-up" dose of local anesthetic (5–10 ml of 0.125–0.25% bupivacaine and/or fentanyl (50–100 mcg), usually given with the back of the bed raised, is often effective. The patient has reached full cervical dilation and begins pushing. Shortly thereafter, you are paged urgently because of decelerations noted on the FHR tracing.

What are your immediate steps?

First, assess the patient's block and vital signs. Sometimes, hypotension following an additional dose of local anesthetic may precipitate FHR changes. If the BP has declined, give phenylephrine, 60 mcg, or ephedrine, 5–10 mg, and increase the rate of fluid administration. Put an oxygen mask on the patient and ensure that she is not positioned flat on her back (to avoid aorto-caval compression by the gravid uterus).

Vital signs are normal and the patient is comfortable, but the FHR tracing does not improve. The obstetrician wishes to perform a cesarean section.

How do you extend the epidural block for the operation?

Depending on the urgency of the situation, you administer lidocaine 2% with epinephrine or chloroprocaine, 3%, 10–20 ml in divided doses. Chloroprocaine has a faster onset and is useful in emergent situations. The goal is to obtain a T4 level (numbness to the level of the nipples) within a few minutes. Vital signs should be monitored during administration, and fluids and phenylephrine are given for hypotension. Fentanyl 50–100 mcg is another useful adjunct to augment a lidocaine block and longer activing neuraxial opioids like morphine or hydromorphone,should be administered for post-oprative analgesia.

Suggested Further Reading

1. Alfirevic Z, Devane D, Gyte GM (2006) Continuous cardiotocography (CTG) as a form of electronic fetal monitoring (EFM) for fetal assessment during labor. Cochrane Database Syst Rev (3):CD006066
2. Brown WU Jr, Bell GC, Alper MH (1976) Acidosis, local anesthetics, and the newborn. Obstet Gynecol 48(1):27–30
3. Chau A et al (2017) Dural puncture epidural technique improves labor analgesia quality with fewer side effects compared with epidural and combined spinal epidural techniques: a radomized linical trial. Anesth Analg 124(2):560–569
4. Clark SL, Cotton DB, Lee W et al (1989) Central hemodynamic assessment of normal term pregnancy. Am J Obstet Gynecol 161(6 Pt 1):1439–1442
5. Datta S (2004) Anesthetic and obstetric management of high-risk pregnancy, 3rd edn. Springer, New York
6. Datta S (2010) Obstetric anesthesia handbook, 5th edn. Springer, New York
7. Eltzschig H, Lieberman E, Camann W (2003) Regional anesthesia and analgesia for labor and delivery. NEJM 348(4):319–332
8. Gin T, Chan MT (1994) Decreased minimum alveolar concentration of isoflurane in pregnant humans. Anesthesiology 81(4):829–832
9. Kinsella SM, Lohmann G (1994) Supine hypotensive syndrome. Obstet Gynecol 83(5 Pt 1):774–788
10. Kodali BS, Chandrasekhar S, Bulich LN et al (2008) Airway changes during labor. Anesthesiology 108(3):357–362

11. Leighton BL (2009) Why obstetric anesthesiologists get sued. Anesthesiology 110:8–9
12. Mendelson CL (1946) The aspiration of stomach contents into the lungs during obstetric anesthesia. Am J Obstet Gynecol 52:191–205
13. Ngan Kee WD, Khaw KS, Lau TK et al (2008) Randomised double-blind comparison of phenylephrine vs ephedrine for maintaining blood pressure during spinal anaesthesia for non-elective Caesarean section. Anaesthesia 63(12):1319–1326
14. Pollard JB (2001) Cardiac arrest during spinal anesthesia: common mechanisms and strategies for prevention. Anesth Analg 92(1):252–256
15. Reynold F (2008) Obstetric problems? Blame the epidural! Reg Anesth Pain Med 33(5):472–476
16. Thaler I, Manor D, Itskovitz J et al (1990) Changes in uterine blood flow during human pregnancy. Am J Obstet Gynecol 162(1):121–125

Physiology and Anesthesia for General and Bariatric Surgery

21

Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xxvii are reviewed before reading this chapter.

Key Learning Objectives

- Learn the pathophysiology of obesity and endocrine disorders
- Understand the anesthetic considerations for bariatric surgery and common general surgical procedures
- Learn about physiologic considerations that occur during laparoscopy

Obesity

Obesity is a growing problem in the United States and around the world. Over one billion overweight or obese people exist in the world. Seventy-three percent of United States adults are

J. M. Ehrenfeld (✉)
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: jehrenfeld@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_21

Table 21.1 Classification of obesity

Obesity class	BMI	Health risk
Class I (overweight)	25–30	Low
Class II (obese)	30–35	Moderate
Class III (severely obese)	35–40	High
Class IV (morbidly obese)	>40	Very high

overweight and 42% are obese. Over 300,000 US deaths a year are associated with obesity.

Obesity is the accumulation of extra fatty tissue in the body (more than 25% of body weight for men and more than 35% for women) and is classified based on the body mass index (BMI) as shown in Table 21.1. BMI is calculated as weight (in kg) divided by square of body height (in m^2). Normal BMI is 20–25. BMI of 25–30 is considered overweight (class I obesity), BMI of 30–35 is considered obese (class II obesity), BMI of 35–40 is considered severely obese (class III obesity), and BMI over 40 is considered morbidly obese (class IV obesity). BMI has its limitation and may not be an accurate way of assessing obesity in body builders.

There are two types of obesity: "central-android" type, which is more common in men and "peripheral-gynecoid" type more common in women. The former is also known as apple-shape obesity and the latter is known as pear-shape obesity. It is important to measure abdominal circumference in addition to BMI. Central obesity (waist measurement more than 40 in. for men and more than 35 in. for women) is associated with the respiratory and cardiac co-morbidities. Waist-to-hip ratio (WHR) >0.95 for men and >0.8 for women has been shown to confer higher risk of complications.

Physiologic Changes Associated with Obesity

Cardiovascular System

Obesity is an independent risk factor for cardiovascular disease. Since adipose tissue needs perfusion, total blood volume and

stroke volume will increase to perfuse additional body fat. Cardiac output (C.O.) increases by 0.1 L/min for each 1 kg addition in body weight.

Gradual accumulation of fat between fibers of heart muscle may cause myocyte degeneration and cardiac dysfunction. Lipotoxicity of the myocardium by free fatty acids may also cause apoptosis of lipid-laden cardiomyocytes and contribute to cardiomyopathy. Increased C.O., left ventricular hypertrophy (LVH), and LV diastolic dysfunction all predispose to heart failure. Diabetes mellitus (DM), hypertension (HTN), and coronary artery disease (CAD) are other factors that predispose these people to congestive heart failure.

Increased C.O. with normal peripheral resistance causes hypertension. For every 10 kg increase in body weight, there is 3–4 mmHg increase in systolic pressure and 2 mmHg increase in diastolic pressure. This increase is more prominent with abdominal obesity. Peripheral vascular resistance may also increase due to different substances released from adipocytes and sympathetic nervous system stimulation. Obese people with metabolic syndrome specially have higher risk of CAD. Left atrial (LA) dilation increases risk of atrial fibrillation (AF) in these patients. QT prolongation also occurs in 30% of obese patients and risk of arrhythmia and sudden death also is higher.

Despite high C.O., ventricular filling pressures increase, while the pumping function of leg and calf muscles decreases. Both of these factors contribute to higher risk of deep vein thrombosis (DVT) in obesity. Byproducts of adipose tissue may also cause pro-thrombotic or hypercoagulable state.

Respiratory System

Adipose tissue is metabolically active and O_2 consumption and CO_2 production will rise with obesity, as does the work of breathing. Chest wall compliance is decreased in obese people and expiratory reserve volume (ERV) and consequently functional residual capacity (FRC) is significantly reduced. FRC may fall below closing capacity and consequently during normal ventilation small

airways may close. Total lung capacity (TLC) is also reduced. Supine position further decreases FRC and TLC. This often results in ventilation-perfusion mismatch. Decrease in FRC means quicker desaturation during periods of apnea and limited available time between induction of anesthesia and intubation. Postoperative atelectasis is more common in this group of patients due to decreased FRC and TLC. Obesity increases the work of breathing due to decrease in both chest wall compliance and decreased respiratory muscle strength. These may lead to dyspnea.

Obstructive sleep apnea (OSA) is more common in obese people and is characterized by frequent episodes of apnea and airway obstruction at night, snoring, fragmented sleep, and daytime sleepiness. It may be difficult to ventilate and intubate a patient with OSA. Repetitive sympathetic stimulation at night may be responsible for hypertension in these patients. About 70% of people with OSA are obese and 40% of obese people have OSA.

Hypoventilationofobesity (Pickwickian syndrome)is respiratory failure in markedly obese patient characterized by somnolence, daytime hypercapnia ($PaCO_2 > 45$), hypoxemia, polycythemia, pulmonary hypertension, and cardiac enlargement (cor pulmonale). Most of these patients also have OSA.

Gastrointestinal System

Fatty liver (fat accumulation in liver cells >10% of liver weight) is very common in obese patients. Fat accumulation in liver cells may cause inflammation and wide spectrum of liver disease from simple fatty liver to cirrhosis. Abdominal obesity is also associated with **higher risk of gastroesophageal acid reflux** (GERD) and aspiration.

Endocrine and Metabolic System

Obesity is associated with hyperlipidemia, hypertension, insulin resistance, and pro-inflammatory and pro-thrombotic states. Extra

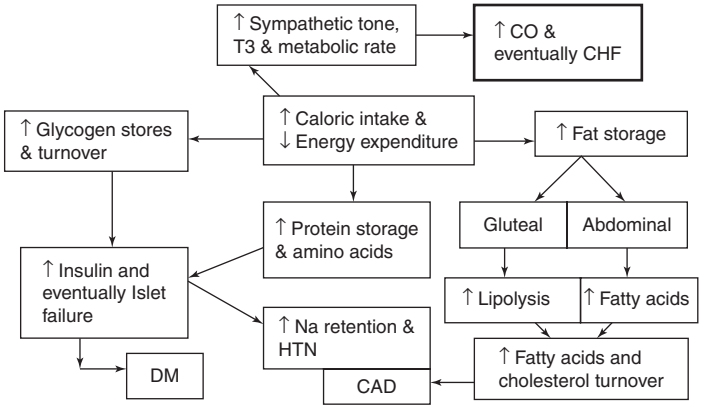


Fig. 21.1 Systemic manifestations of obesity. *CO* cardiac output, *CHF* congestive heart failure, *DM* diabetes mellitus, *CAD* coronary artery disease, *HTN* hypertension

adipose tissue releases several products including nonsteroidal fatty acids (NSFA), cytokines, plasminogen activator inhibitor (PAI)-1, interleukin-6, and adiponectin. These products are responsible for metabolic complications and are associated with higher risk of coronary artery disease. Treatment should be targeted toward weight reduction. Figure 21.1 depicts common systemic manifestations of obesity.

Neurological and Psychological Problems

Body image may be severely distorted in people with obesity, and obese people may be discriminated against in school and workplace. Depression is common and it is important to be sensitive to these issues. Carpal tunnel and other superficial nerve compression are also more common in obese people, and special attention is necessary during positioning these patients in the operating room to prevent nerve injuries. Also, higher risk of stroke has been recorded in this population.

Airway Challenges in Obesity

Excessive soft tissue in the larynx and pharynx, particularly in patients with OSA, should be expected. Increased neck circumference and high Mallampati score may be indicators of a difficult intubation. The incidence of a difficult intubation in obese patients is higher than in general population, although the BMI by itself is not a reliable predictor. These patients may need head and trunk elevation and larger blades for intubation. Even with good positioning, sometimes mask ventilation may be more challenging than intubation. Insertion of an oral airway and two-hand ventilation may improve ventilation.

Surgery for Obesity

Gastric banding and gastric bypass are commonly performed for treatment of severe and morbid obesity (see Fig. 21.2). The goal of surgery is gastric restriction and intentional malabsorption. These procedures are being increasingly performed laparoscopically. Procedures performed through a laparoscopy, compared to laparotomy, may result in earlier recovery, and help minimize

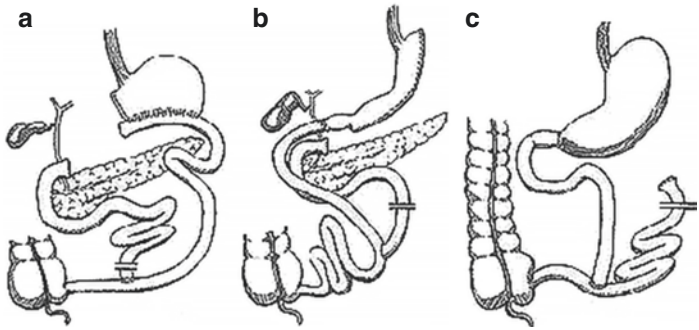


Fig. 21.2 Weight loss procedures (**a**) Laparoscopic adjustable gastric band, (**b**) Roux-en-Y gastric bypass (**c**) Vertical banded gastroplasty. (Image Courtesty J. Ehrenfeld)

postoperative problems associated with pain, reduce postoperative pulmonary complications, decrease postoperative infection, and prevent incisional hernias.

Anesthetic Considerations

Preoperative Evaluation

Airway evaluation should be performed before bringing the patient to the operating room, and a fiberoptic intubation (FOI) cart should be available and ready in the OR if difficult intubation is anticipated. Occasionally, awake FOI may be necessary. Investigation for co-morbidities, including sleep apnea, hypoventilation of obesity, systemic and pulmonary hypertension, coronary artery disease, and diabetes mellitus, is advised. Intravenous access can be a challenge in obese patients, and central access may therefore be necessary.

If the procedure is being performed through a laparotomy, epidural anesthesia may improve postoperative pain control and respiratory status. Evaluation of the lumbar and thoracic spine area and the feasibility of epidural anesthesia should be addressed in preoperative evaluation. Nerve blocks may also be considered for surgery on extremities.

Intraoperative Considerations

Availability of a bariatric operating table and availability of an appropriately sized bariatric hospital bed for the postoperative period should be addressed before bringing the patient to the operating room. It is also important to obtain an appropriately sized noninvasive blood pressure cuff for accurate measurement of blood pressure. If a cuff is too narrow blood pressure will be overestimated.

Obese patients should be preoxygenated with 100% oxygen for at least 3 min before induction with their head and shoulders optimally positioned prior to intubation. It may be advisable to confirm ability to mask ventilate before administering any muscle

relaxant. Discussion about difficult intubation can be found in Chap. 9, Airway Evaluation and Management. A rapid sequence induction (RSI) should be considered in patients with gastrointestinal reflux symptoms.

Positioning difficulties related to patient's body habitus and risk of nerve injury should also be addressed with appropriate padding and positioning. Additional intravenous access, if necessary, should be established soon after induction and before the patient is prepped and draped. As a general rule, medications with weak or moderate lipophilicity can be dosed on the basis of lean body weight (LBW), while highly lipophilic medications with high volume of distribution are usually dosed based on total body weight (TBW). Fluid requirements are usually higher than expected. Sequential compression devices, stockings, and subcutaneous heparin or low-molecular-weight heparin (if not contraindicated by surgery) should be used to prevent deep venous thromboses (DVTs).

Postoperative Considerations

Adequate pain management is important so that the patient can achieve deep breathing (helps prevent lung atelectasis) and early ambulation. Postoperative pain management in abdominal surgery may be achieved with either epidural anesthesia or patient-controlled analgesia (PCA). Long-acting opioids should be used judiciously due to concern for respiratory depression in patients with OSA. Epidural analgesia utilizing local anesthetic and possibly an opioid may be a good alternative to intravenous analgesia. DVT prophylaxis should be continued until the patient is able to ambulate.

CPAP (continuous positive airway pressure) or BIPAP (Bi-level positive airway pressure) should be considered for postoperative care in patients with OSA. Initiation of CPAP therapy in the recovery room and continuation overnight for prevention of post operative atelectasis has been advocated. Sometimes selected patients are left intubated postoperatively, particularly those who had a difficult intubation.

Anesthesia Considerations for General Abdominal Surgery

Preoperative Evaluation

Any emergent surgery warrants full stomach precautions, and intraabdominal emergencies are associated with ileus and higher risk of aspiration – even if the patient had nothing to eat or drink for several hours. Signs and symptoms of ileus include nausea, vomiting, and abdominal distention. Some elective abdominal surgeries carry a higher risk of aspiration due to the nature of the disease, as in anti-gastrointestinal reflux surgery or surgery for achalasia. H2 blockers and sodium citrate are often administered before induction in patients at high risk for aspiration. However, metoclopramide is contraindicated in bowel obstruction.

Fluid loss into the gastrointestinal system or into interstitial tissue, in case of bowel obstruction or peritonitis, can be significant and may lead to severe dehydration. Signs and symptoms of dehydration include thirst, dry mucosa, tachycardia, hypotension, and decreased urine output. Fluid resuscitation should be started before induction of anesthesia to decrease chance of hemodynamic compromise on induction. Blood loss in a patient with gastrointestinal (GI) bleeding may cause significant hypovolemia. Bleeding in the GI tract also increases the risk of aspiration.

Loss of different fluids from the GI system is associated with loss of various electrolytes. For example, loss of stomach secretions either through vomiting or gastric suction is usually associated with decreased H^+ and Cl^- ions leading to hypokalemic, hypochloremic metabolic alkalosis. Elective colon surgery with a bowel prep also can cause electrolyte and fluid imbalance. Consider checking patient's serum electrolytes and hematocrit prior to major abdominal surgeries.

Finally, a patient's underlying disease should also be considered for each procedure. For example, splenectomy for sickle cell disease has different considerations than splenectomy for Idiopathic Thrombocytopenic Purpura (ITP).

Intraoperative Considerations

Laparoscopic Surgery

Laparoscopic surgery is frequently performed for esophageal fundoplication, Heller's myotomy, cholecystectomy, hernia surgery, bariatric surgery, and some bowel surgeries. Prior to insufflations, a nasogastric or orogastric tube is placed to decompress stomach, and a Foley catheter to decompress the bladder.

The respiratory system can be affected in laparoscopic surgery by different mechanisms. Effects of **pneumoperitoneum** (insufflation of the peritoneum by CO_2) include intraabdominal pressure increase, systemic CO_2 absorption, increased end-tidal CO_2, cephalad displacement and impaired movement of the diaphragm, decreased FRC and pulmonary compliance, increased PIPs (peak inspiratory pressures), and ventilatory requirements. Retroperitoneal dissection of CO_2 may cause a pneumothorax. The effects of Trendelenberg or reverse-Trendelenberg positions needed during the procedure should also be considered. Airway pressures including plateau and peak airway pressure may also change.

Effects on cardiovascular system include increases in systemic vascular resistance due to increased sympathetic output from CO_2 absorption, and a neuroendocrine response to pneumoperitoneum. The cardiopulmonary effects of pneumoperitoneum are proportional to the magnitude of intra-abdominal pressure during laparoscopy with significant changes occurring at pressures greater than 12 mmHg. **Decreased venous return** and **bradycardia** (due to profound vasovagal reaction) may occur with pneumoperitoneum. Vascular injection of CO_2 can cause air embolism, hypotension, dysrhythmias, and even cardiovascular collapse. Hemorrhage from vascular injury is another serious complication of laparoscopic surgery.

High intra-abdominal pressure may cause decreased urine output due to decreased blood flow to splanchnic and renal circulation. Hypothermia can occur due to dry gas insufflation, and prevention of hypothermia can be achieved with a fluid warmer, forced air warming devices, and by keeping the OR temperatures

high. *The use of nitrous oxide is contraindicated in bowel obstruction, because it may cause bowel distention*, but otherwise it has been used in other laparoscopic cases.

Laparotomy

Laparotomy (open surgery) is usually performed electively for cancer surgery, solid organ surgeries, and emergency surgeries for trauma and peritonitis. Fluid loss can be significant, even without significant blood loss. Appropriate intravenous access is necessary. Since postoperative pain can interfere with breathing, epidural analgesia may be of benefit in major elective abdominal surgeries. The need for invasive monitoring (arterial, central venous lines) depends on the patient's coexisting disease and anticipated blood loss. Laparoscopic-assisted mini-laparotomies are usually intended to combine laparoscopic techniques with smaller than usual laparatomy incision for solid organ surgery (e.g., kidney or spleen) to minimize postoperative pain and improve cosmetic appearance.

Postoperative Considerations

A high incidence of postoperative nausea and vomiting warrants the use of prophylactic antiemetics in abdominal surgeries. The use of multiple antiemetics with different mechanisms ("multimodal therapy") is useful in high-risk patients (see Chap. 7).

In upper abdominal surgery, the possibility of a pneumothorax or hemothorax in the postoperative period should be considered if there is any respiratory compromise. Hemodynamic changes in the postoperative period may also occur due to intra-abdominal bleeding. Shoulder pain in laparoscopic procedures may occur due to phrenic nerve irritation from pneumoperitoneum. Complete evacuation of pneumoperitoneum at the end of procedure will help to decrease this complication. Intraperitoneal and incisional injection of local anesthetic has been used successfully in laparoscopic cases to improve pain control. At some centers, low-dose ketamine has also been used before incision and during surgery to improve postoperative pain control.

Upper abdominal incisions are painful and are associated with atelectasis. Pain control can be achieved by either epidural anesthesia (for open laparotomy cases) or PCA. A patient's coagulation status is usually checked before epidural catheter placement.

Advantages of epidural analgesia for abdominal procedures include better postoperative pain control, improved deep breathing and decreased risk of atelectasis, sympathetic blockade, faster resolution of ileus after colonic resection, and improved perfusion of intra-abdominal organs. Disadvantages of epidural analgesia include patient discomfort during catheter placement, incomplete block, catheter migration, small but potentially devastating risk of epidural bleeding and abscess formation, risk of dural puncture and postdural puncture headache. It also has non-procedure-related risks such as hypotension, motor blockade, CNS toxicity, urinary retention particularly after anorectal surgery, and pruritis if an opioid is used within epidural infusion.

The level of epidural catheter placement for pain management after abdominal surgery is either low thoracic or lumbar, depending on the incision site. For upper abdominal surgeries, a low thoracic or upper lumbar (T6–L1) catheter is appropriate, and for pelvic and lower abdominal surgeries mid- to low-lumbar (L2–L5) epidural catheter may provide better coverage (Table 21.2).

PCA (patient-controlled analgesia) as an analgesic option with morphine, hydromorphone, or fentanyl is easier to achieve, can provide pain medication upon patient's demand, and does not

Table 21.2 Epidural catheter placement level for postoperative pain control

Type of surgery	Usual incision	Epidural catheter placement
Liver, pancreas, spleen, stomach	Chevron or upper midline	Low thoracic
Kidney and ureter	Oblique flank	Upper lumbar
Colorectal	Low midline	Upper lumbar
Bladder, uterus surgery	Low transverse or low midline	Low lumbar
Hernia	Inguinal	Low lumbar
Hemorrhoid	Anorectal	Caudal

involve a special procedure. However, PCA may prevent the patient from taking deep breaths, may delay ambulation, and can cause respiratory depression and somnolence.

Anesthetic Considerations for Common Abdominal Surgeries

Esophageal Surgery

Surgery for hiatal hernia, achalasia, and GERD is usually performed through a laparoscopic approach. In this group of patients, full stomach precautions and a rapid sequence induction should be utilized. Peripheral IV access and routine ASA monitoring is usually adequate. Patient-specific underlying disease should be considered when deciding on additional hemodynamic monitoring. The possibility of recurrent aspiration pneumonia and diminished pulmonary reserve should be considered in patients with severe gastric reflux.

Stomach Surgery

In ulcer surgery, the anesthesiologist needs to pay attention to the patient's volume status if there is acute bleeding, and consider anemia in chronic bleeding. It is important to have adequate IV access, and blood products for a possible transfusion should be available.

Small and Large Bowel Surgery

Common surgeries involving small and large bowel include volvulus, intussusception, perforation, and tumor resection. Important considerations include full stomach precautions, effects of a bowel prep on electrolytes, and increased fluid requirements.

In cases of peritonitis and interstitial swelling, the risk of **abdominal compartment syndrome** with closing of the incision

at the end of surgery should be considered. Increases in peak inspiratory pressure (PIP) with closing of the abdominal incision and hypotension are signs of abdominal compartment syndrome, and should be discussed with the surgical team. It may be necessary to leave incision open and perform a delayed closure of the incision. Patients with inflammatory bowel disease are usually on chronic steroids and often require stress dose steroids before induction. Malignancies may cause anemia from chronic blood loss and also increase the risk of coagulopathy.

Hemorrhoid Surgery

Hemorrhoidectomy can be performed in lithotomy, prone, or jackknife positions. General anesthesia and spinal anesthesia are both appropriate. Pressure on the peroneal nerve in the lithotomy position can result in foot drop and attention to appropriate padding is important. Patients in the prone or jackknife position require chest support to optimize ventilation and venous return. Care must be taken to position extremities and genitals, and avoid pressure on eyes and ears.

Liver and Biliary Tract Surgery

Liver surgeries include tumors (primary or metastatic) and bile duct surgeries. Major liver surgeries are usually performed through laparotomy. Liver tumors with vascular involvement may result in major bleeding intraoperatively. Appropriate IV access, monitoring, a rapid volume infusion device, and blood product availability should be considered. If the extent of surgery is not known at the beginning, it may be advisable to establish invasive monitoring (arterial line and CVP) before the start of surgery. Keeping the central venous pressure (CVP) low (between 2 and 5 mmHg) may limit the distention of hepatic veins and sinusoids and reduce blood loss during liver surgery. The liver produces all coagulation factors except factor VIII and coagulopathy may be

seen with hepatic insufficiency. Many patients presenting for liver surgery may not be good candidates for epidural catheter placement due to coagulopathy or thrombocytopenia.

Biliary tract surgeries range from simple laparoscopic cholecystectomy to complicated biliary surgeries in extremely ill patients with bile duct tumors. Anesthesia plans should be individualized based on severity of disease and extent of surgery. Gallbladder surgery is usually performed via laparoscopic approach with standard monitors – often on an elective outpatient basis.

Spleen Surgery

Elective splenectomy is either performed for hematological disease and thrombocytopenia or for staging of malignancy. Emergent splenectomy is reserved for trauma, ruptured spelenic aneurysm, and uncontrollable bleeding. Understanding of the underlying reason for spelenectomy is very important for anesthesia care.

In a patient with sickle cell disease, blood transfusion before surgery may be necessary to prevent sickling of red blood cells. For a patient with ITP, platelet transfusion is usually delayed until the spleen is removed. If splenectomy is performed for staging of Hodgkin's disease, history of medications used for chemotherapy is important, as certain chemotherapeutic drugs can affect kidney, lung, and heart function. Emergency splenectomy usually warrants good intravenous access and availability of blood products.

Pancreatic Surgery

Pancreatic surgery is usually performed for pancreatitis, pancreatic cysts, or tumors. Patients with pancreatitis may have respiratory compromise and sepsis. Severe dehydration and electrolyte imbalance, especially hypocalcaemia, is also common. The need for invasive monitors should be individualized.

Hernia Surgery

Increased intra-abdominal pressure from COPD and chronic cough, bladder outlet obstruction (BPH) or ascites may be some of the predisposing factors for hernias and should be addressed before repair to prevent recurrence. Common hernia types include inguinal, umbilical, and incisional. General, regional or local anesthesia may be used for uncomplicated cases and is usually individualized based on underlying disease, hernia size and location, and patient's and surgeon's preferences.

Case Study

A 38-year-old female is scheduled for laparoscopic Roux-en-Y gastric bypass. She is 5 ft, 6 in. tall and weighs 300 lb. She has tried various diet and exercise plans to lose weight without success. She has hypertension treated with an ACE inhibitor. She wheezes on exertion or in hot weather and uses an albuterol inhaler as needed. She snores loudly while sleeping but has not had a formal sleep study and is not interested in CPAP at home due to a poor experience related by a friend. She does not exercise regularly but she is able to walk on level ground for a few minutes at a time in her work as an office postal worker. She has been told she has "borderline diabetes" but is not currently taking any medication for it. Preoperatively, her examination shows BP 180/95, HR 90, RR 24, scattered end expiratory wheezes, which clear with cough, airway Mallampati class II, thyromental distance 4 fingerbreadths.

How severe is her obesity? Does it matter? Can any other obesity measures help you characterize her health risk further?

Her BMI is 48.4, putting her in the morbidly obese category. Although risk is not linearly related to BMI, risk is higher for more obese individuals. The pattern of obesity, however, may be even more important than the absolute

magnitude of her obesity. You could ask her waist size, and if >35 it would correlate with higher risk. Other obesity-related risk factors for perioperative morbidity include her relative inactivity and glucose intolerance. Interestingly, sleep apnea per se probably is not such a risk factor but it has significant anesthetic implications regarding difficulty with intra- and postoperative airway management.

What concerns do you have about her respiratory status? How will these impact your anesthetic plan?

You should be quite concerned. First, she may desaturate with positioning, even before sedative drugs are given, due to lower FRC relative to closing capacity, leading to ventilation-perfusion mismatching. This may worsen with induction of anesthesia, due to limited apneic reserve of oxygen in the lowered FRC. Second, her questionable history of obstructive sleep apnea (snoring) are concerns for possible difficult mask ventilation. Third, you may be concerned that she could have a possibly difficult intubation despite the reassuring airway exam, due to obesity itself. Fourth, she has a history of wheezing, implying she may have reactive airways and thus prone to intraoperative bronchospasm. Finally, though controversial, some consider morbid obesity to be a risk factor for aspiration of gastric contents during induction. In response, you will position her slightly head-up with blankets under her shoulders or a specialized pillow such as the Troop elevation pillow. You will carefully preoxygenate to ensure the longest possible time for intubation. You will have a selection of adjunctive devices available to assist with possibly difficult mask ventilation as well as alternative intubation devices such as a video laryngoscope, which may shorten the time to intubation in obese individuals. Finally, you should have help immediately available should ventilation or intubation prove to be challenging.

How will you monitor her during the anesthetic? Will your plan differ from a normally proportioned patient having laparoscopic surgery?

All ASA standard monitors should be used and will not differ markedly from those used in a normally proportioned patient. The BP cuff must be of appropriate size or you will overestimate blood pressure. An alternative is to place a cuff on the forearm, or consider an arterial line if noninvasive pressure monitoring proves too technically difficult. Depending on your anesthetic plan, you may choose to use a consciousness monitor such as BIS, particularly if you choose to use TIVA during any part of the case. Temperature monitoring availability is an ASA standard, and morbidly obese patients generally do not lose heat as quickly as thin patients in the OR. However, a large portion of the body will be exposed and the insufflating gas is relatively cool, so she may become hypothermic. Since this is a risk factor for wound infection, you should monitor temperature continuously.

How will you induce and maintain anesthesia?

Although any combination of general anesthetics are possible, you may consider short acting, nonlipophilic drugs to avoid excessive somnolence and respiratory problems at the end of the case. You may choose to avoid nitrous oxide to maximize oxygen delivery, but, conversely, it is rapidly eliminated and thus may facilitate a rapid wakeup. You will have to weigh its use against other adverse effects such as bowel distention in laparoscopic surgery. Some anesthesiologists have advocated TIVA at least at the end of the procedure to allow you to fully wash out inhalation anesthetics. Dexmedetomidine and remifentanil can provide excellent analgesia and sedation with minimal postoperative respiratory depression and is one attractive option. You should avoid large doses of long-acting opioids until her respiratory status can be assessed postoperatively. You will fully reverse neuromuscular blockade prior to emergence to avoid hypoventilation due to even subtle weakness.

How will you manage postoperative pain? Would your plan differ if the procedure were an open Roux-en-Y?

It is important to have good pain control but not oversedate the patient. Pain control is important to avoid splinting and hypoventilation that can cause atelectasis and hypoxemia. Patient-controlled analgesia has been successfully used following bariatric surgery. Some advocate increased vigilance for hypoventilation such as continuous pulse oximetry or frequent respiratory rate monitoring. The surgeon can also infiltrate the laparoscopy incisions with long-acting local anesthetic such as bupivacaine with epinephrine to augment the analgesia. If the procedure were an open laparotomy, placement of a thoracic epidural for postoperative pain control should be strongly considered. This technique allows minimization of systemic opioids and may improve pulmonary outcomes.

Suggested Further Reading

1. Bray GA (1992) Pathophysiology of obesity. Am J Clin Nutr 55:488S–494S
2. Brodsky JB (2008) Perioperative management of the obese patient. Conferencias Magistrales 31(1):S85–S89
3. Grundy SM et al (2004) Definition of metabolic syndrome: report of the National Heart, Lung, and Blood Institute/American Heart Association conference on scientific issues related to definition. Circulation 109:433–438
4. Jaffe RA, Samuels SI (2004) Anesthesiologist's manual of surgical procedures, 3rd edn. Lippincott, Williams & Wilkins, Philadelphia
5. Joshi GP (2002) Anesthesia for laparoscopic surgery. Can J Anaesth 49:R11
6. Mantzoros CS (2006) Obesity and diabetes. Springer, Berlin
7. Ogunnaike BO et al (2002) Anesthetic considerations for bariatric surgery. Anesth Analg 95:1793–1805
8. Ortiz VE et al (2009) Perioperative anesthetic care of the obese patient, 1st edn. CRC Press, Boca Raton
9. Paulain M et al (2006) The effect of obesity on chronic respiratory diseases: pathophysiology and therapeutic strategies. CMAJ 174(9):1293–1299. https://doi.org/10.1503/cmaj.051299

10. Poirier P et al (2006) Obesity and cardiovascular disease, pathophysiology, evaluation, and effect of weight loss. Circulation 113:898–918
11. Redai I et al (2004) Anesthetic considerations during liver surgery. Surg Clin North Am 84:401–411
12. Sprung J et al (1992) The impact of morbid obesity, pneumoperitoneum, and posture on respiratory system mechanics and oxygenation during laparoscopy. Anesth Analg 94:1345–1350
13. Strollo PJ, Rogers RM (1996) Obstructive sleep apnea. N Engl J Med 334:99–104
14. Wheatley RG et al (2001) Safety and efficacy of postoperative epidural analgesia. Br J Anaesth 87(1):47–61

Anesthesia for Urological Surgery

22

Jesse M. Ehrenfeld

Key Learning Objectives

- Learn the pertinent urinary system anatomy and physiology
- Understand anesthetic management of common urologic procedures
- Discuss common complications associated with urologic surgery

Anesthesia for urological surgery poses a special challenge for anesthesiologists since patients are often elderly and may have multiple co-morbidities, including renal dysfunction. The scope of the field is broad and ranges from outpatient cystoscopies to major oncological surgeries, so the type of anesthesia needed is variable.

For maximum impact, it is recommended that the case study and questions found on page xxviii are reviewed before reading this chapter.

J. M. Ehrenfeld (✉)
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: jehrenfeld@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_22

Anatomy

It is critical for the anesthesiologist to be familiar with the anatomy of the genitourinary system in order to understand the technical aspects of the procedure. The kidneys are located retroperitoneally, between T12 and L4, surrounded by perirenal fat and contained within Gerota's fascia. On gross examination, there is an outer cortex and an inner medulla, which contains calices that drain into the renal pelvis, and eventually taper into the ureter. The ureters run along the psoas muscles and cross the common iliac prior to entering the bladder. Innervation of the upper ureters is carried by sympathetic fibers that enter the cord at T10-L2 and innervation of the lower ureters is by parasympathetics at S2–S4. This innervation is important when one is administering anesthesia for stone extractions. The bladder holds 400–500 cc of fluid and receives its innervation from the hypogastric plexus (T11–12, S2–4) (Table 22.1).

The blood supply to the kidneys is via a single renal artery, which originates inferior to the superior mesenteric artery (SMA). There are, however, many normal anatomical variants in which multiple renal arteries are possible.

Table 22.1 Spinal pain segments for the genitourinary system

Organ	Sympathetics	Pain pathways
Kidney	T8-L1	T10-L1
Ureter	T10-L2	T10-L2
Bladder	T11-L2	T11-L2 (bladder dome) S2–4 (bladder neck)
Prostate	T11-L2	T11-L2S2–4
Penis	L1 and L2	S2–4
Scrotum		S2–4
Testes	T10-L2	T10-L1

Patient Positioning

There are multiple patient positions utilized in urological surgery and the anesthesiologist must be aware that there are physiological changes that accompany these positions.

The **lithotomy position** (Fig. 22.1) is most commonly used for cystoscopies, transuretheral resection of prostate or bladder tumor (TURP or TURBT), or ureteroscopies. Placement in this position for greater than 2 h may be a risk factor for development of sensory neuropathies or rhabdomyolysis secondary to compartment syndrome. This position increases upward displacement of intra-abdominal contents, decreasing pulmonary compliance, forced residual capacity and vital capacity, and increasing atelectasis. Elevating the legs also increases venous return, cardiac output, and arterial blood pressure, but these changes may not have clinically significant manifestations.

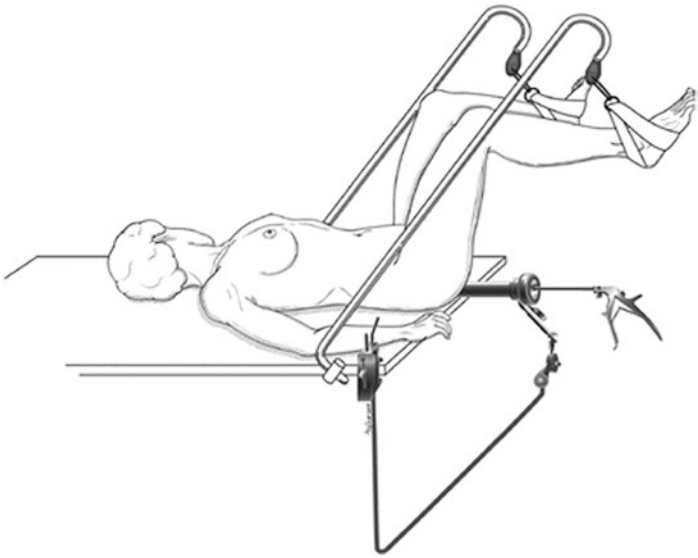


Fig. 22.1 Patient positioned supine in the lithotomy position. (Used with permission. From Cataldo and Buess [1])

Placing the patient in the kidney rest position (also called the lateral flexed position) is preferred for better access during renal surgery. Often an axillary roll (usually a rolled towel) is placed between the table and upper chest to ensure that the brachial plexus is free from compression or injury. The lateral decubitus position has profound effects on creating ventilation–perfusion mismatch and may cause dependent atelectasis. Hemodynamically, there is often a decrease in systemic arterial pressure, cardiac output, and renal perfusion pressures.

Preoperative Assessment

A thorough preoperative assessment is critical in patients undergoing urological surgery and includes all standard preoperative questions including screen for smoking history, medications, cardiac history, and renal function. Lab abnormalities reflective of renal failure include presence of hematuria or proteinuria on urinalysis, elevation in blood urea nitrogen (BUN) and creatinine values, and impaired creatinine clearance. If the patient is found to be in renal failure, the anesthesiologist must discern whether the renal failure is acute or chronic, and determine the etiology: prerenal, intrinsic renal, or postrenal/obstructive.

During surgery, it is critical for the anesthesiologist to avoid nephrotoxic drugs, correct hypovolemia, dose drugs based on renal function, and monitor for causes of urinary outflow tract obstruction. The adult kidney demonstrates autoregulation, maintaining relatively constant rates of renal blood flow (RBF) and glomerular filtration rate (GFR) over a wide variety of mean arterial blood pressures. Anesthesia can result in decreases in RBF and GFR despite normal blood pressure, and decreases in blood pressure as a result of depression of myocardial activity and sympathetic tone.

Anesthetic Management

Cystoscopy/Ureteroscopy/TURBT

These procedures consist of inserting an endoscope to visualize and intervene upon the lower urinary tract. Indications are varied, and include evaluation of hematuria, need for biopsies, extraction of stones, treatment of strictures, excision of bladder tumors (TURBT), and placement of ureteral stents to relieve obstruction. The patient is usually placed in the lithotomy position and irrigating solution is necessary to optimize visualization and remove surgical debris from the field. Procedures tend to be brief, usually under 1 h, and there is minimal need for postoperative analgesia so short-acting opioids are adequate for pain control.

Anesthesia for these procedures can be highly variable and can range from local anesthesia with monitored anesthesia care/sedation to general anesthesia with an LMA. With the advent of the flexible endoscope, general anesthesia is no longer required for patient comfort for these surgeries except in the case of dilatation of the ureter, which is more stimulating. Occasionally, the surgeon will request muscle relaxation for surgery when working in close proximity to the obturator nerve. In these cases, an endotracheal tube is necessary to secure the airway. If a spinal or an epidural is used, surgery on the lower genitourinary tract mandates a T10 level or higher. These procedures are often outpatient surgical procedures, with discharge home a few hours following surgery. For this reason, general anesthesia is usually preferred to regional. However, a short-acting spinal anesthetic may be appropriate. Disadvantages of regional techniques include awaiting return of urination postoperatively and more dilation of venous sinuses causing a slightly increased risk of TURP syndrome (see section “Complications of Urologic Surgery” below).

TURP

Transuretheral resection of the prostate (TURP) is commonly done for benign prostatic hypertrophy, which can cause compression of the lower urethra and result in obstructive urinary symptoms. A cystoscope is inserted into the urethra and a resectoscope, which can coagulate and cut tissue, is inserted through the cystoscope to resect all tissue protruding from the prostatic urethra. This procedure requires continuous irrigation fluid as well, placing the patient at risk for TURP syndrome (see section "Complications of Urologic Surgery").

The patient is positioned in lithotomy and regional or general anesthesia can be used. If general anesthesia is used, muscle relaxation may be indicated or a deep level of anesthesia may be preferred. This will prevent coughing or movement, which may lead to prostatic capsule rupture. Advantages of general anesthesia include positive pressure ventilation, which can decrease the absorption of irrigant solution by increasing venous pressures. Regional anesthesia mandates a T10 level and offers the advantage of an atonic bladder along with the presence of awake patients, in whom TURP syndrome may be detected earlier.

Laser Surgery in Urology

Laser surgery in urology allows for treatment of condyloma acuminatum, interstitial cystitis, BPH, ureteral or bladder stricture, contracture or calculi, and superficial carcinoma of the urinary tract or external genitalia. Laser surgery allows for minimal blood loss and postoperative pain. The types of lasers include carbon dioxide, argon, and pulsed-dye lasers. Concern for **ocular injury by lasers** is paramount for the anesthesiologist during these procedures and **eye protection must be worn** by all OR personnel and the patient. Thermal injury by lasers may also be possible and can be avoided by limiting use to one operator and placing the device in standby to allow for cooling between uses. Inhalation of viral particles and smoke can also pose a safety threat; special

laser masks that prevent small particles should be worn and the OR should be equipped with a smoke evacuation system.

Radical Prostatectomy: Open, Laparoscopic, Robotic

Open radical prostatectomy involves the complete resection of the entire prostate gland, the seminal vesicles, the ejaculatory ducts, and a portion of the bladder neck and is usually performed for prostate cancer. A pelvic lymph node dissection may also be done to aid in cancer staging. The patient is placed in a hyperextended supine position and a midline lower abdominal incision is used. Either general endotracheal anesthesia or regional anesthesia with a T6–8 level may be used for this surgery.

Once the prostatic urethra has been removed and the urethra is reconstructed, diagnostic dyes (methylene blue or indigo carmine) may be requested by the surgeon. A **methylene blue bolus** may lead to hypotension or cause disruption of the pulse oximeter readings; **Indigo carmine** may cause hypertension via α-agonist effects. Complications of this surgery can include large amounts of blood loss, fluid shifts leading to coagulopathy or anemia, and air embolism from Trendelenburg positioning. Large bore IV access is needed and an arterial line or central venous catheter may also be used since urine output will not reliably reflect intravascular fluid status.

Laparoscopic surgery or **robotic assisted surgery** is also becoming increasingly popular because of decreased invasiveness. However, retroperitoneal insufflation has been reported in some studies to be associated with increased systemic absorption of carbon dioxide and decreases in urine output, leading to iatrogenic excessive fluid repletion.

Radical Cystectomy

Radical cystectomy is indicated in patients with muscle invasive bladder cancer. Other less common indications include neurogenic

bladder, chronic urinary obstruction, or pelvic malignancy. In men, the bladder, prostate, seminal vesicles, and urethra is removed. In women, the bladder, urethra, anterior vaginal wall, uterus, and bilateral ovaries and fallopian tubes are removed. A urinary diversion, either to the colon or ileum, is created at the end of the procedure.

Anesthetic considerations and patient positioning are similar to a radical prostatectomy. Bowel surgery introduces additional complications, including longer operative time and increased risk of bacteremia. In addition, in cancer patients, the anesthesiologist must consider effects of previously administered chemotherapeutic agents: doxorubicin has cardiotoxic effects, methotrexate has hepatic toxicity, cisplatin and methotrexate have neurotoxicity and renal toxicity.

Nephrectomy: Open or Laparoscopic

Removal of the kidney, fascia, adrenal gland and upper ureter, or a radical nephrectomy, is usually performed for malignancy/neoplasm, transplantation, cystic disease, or severe calculous disease. In about 5% of patients, the tumor extends into the vena cava, which can result in several complications. If the IVC is fully or partially occluded, there may be a decrease in venous return. The IVC may have to be temporarily clamped during resection, potentially requiring vasopressor support. Rarely, cardiopulmonary bypass may be indicated if there is extensive IVC infiltration.

The patient is typically positioned in the kidney rest position for the retroperitoneal approach. This position can cause caval compression and the patient must be adequately hydrated preoperatively to prevent hypotension. The supine position can also be used if a transabdominal approach is needed. A combined epidural-general anesthetic is often used, and the anesthesiologist must be prepared for large fluid shifts and the potential for large volume blood loss. Laparoscopic nephrectomy is generally done for organ harvest or small tumors (partial nephrectomy) and consists of retroperitoneal insufflation.

Renal Transplantation

Recipients of donor organs tend to be patients with end-stage renal disease and a variety of comorbidities including diabetes mellitus, hypertension, coronary artery disease, or autoimmune disease. Such patients have many physiological perturbations such as anemia, coagulopathy, uremia, and electrolyte disturbances. IV access can be difficult and limited, secondary to presence of fistulas or shunts used for hemodialysis. Anesthetic medications must be dosed based upon renal clearance. General anesthesia is usually preferred because of preexisting coagulopathy, although certain nephrotoxic medications and medications such as succinylcholine may need to be avoided. Maintaining a normal blood pressure is important to preserve renal perfusion, and vasoactive agents, such as dopamine, may be indicated to enhance renal blood flow. The recipient is usually positioned supine for the surgery and the native organs are often left in place. Postoperative pain can be significant, but intravenous opioids used in small doses are preferred to regional techniques.

Orchiectomy, Orchidopexy, Penile Surgery

Radical orchiectomy is usually performed for testicular cancer. Most of these patients tend to be young and healthy but may have received preoperative chemotherapy, placing them at risk for chemotherapy-induced systemic toxicity. Bleomycin is a commonly used chemotherapeutic agent for testicular cancer and is associated with pulmonary toxicity. In patients who have received bleomycin, colloid fluid replacement may be associated with less pulmonary complications than crystalloid and lower inspired oxygen concentrations may be beneficial. The patient is positioned supine and either general anesthesia or regional anesthesia is an acceptable option for this procedure. A retroperitoneal lymph node dissection may also be performed and during left-sided dissection, the intercostal arteries may be compromised, leading to

loss of blood flow through the artery of Adamkiewicz and resultant spinal cord ischemia.

Other surgery involving the testis and external genitalia can be performed with a variety of techniques, ranging from monitored anesthesia care to general anesthesia with an LMA, depending on the extent of the surgery.

Extracorporeal Shock Wave Lithotripsy

Extracorporeal shock wave lithotripsy (ESWL) is a minimally invasive technique used for the treatment of renal calculi and ureteral stones. It consists of a lithotripter, which transmits acoustic waves that are reflected and generate internal echoes that create stress to fracture kidney stones. Dysrythmias from incorrect timing of the shock wave (during cardiac repolarization) can be minimized by triggering the lithotripter to send a shock wave 20 ms after the R wave, when the heart is refractory.

The patient is positioned either supine or prone, depending on the location of the stone. For anesthesia, sedation with an ultrashort acting opioid (e.g., remifentanil) is usually adequate for patients since postoperative pain is minimal. IV hydration is recommended and diuretics may be useful in flushing the stone from the collecting system. Postoperatively, nausea, and bradycardia may be seen from excess vagal tone, hematuria may be present, and a subcapsular renal hematoma may occur in patients with hypertension. Patients who are pregnant, at risk for bleeding or have an active infection should not undergo ESWL.

Complications of Urologic Surgery

There are many complications unique to urological surgery. **Bladder perforation** during cystoscopy can occur by inadvertent stimulation of the obturator nerve leading to violent thigh muscle contraction or high irrigation pressures. The awake patient would complain of lower abdominal pain and nausea, whereas one might see hemodynamic instability under general

anesthesia. The pain can localize to the suprapubic, inguinal, peri-umbilical, or upper abdominal regions, or refer from the diaphragm to the shoulder.

Another rare but serious complication of cystoscopy is **autonomic hyperreflexia**, which usually presents as a hypertensive emergency in spinal cord injury patients with an existing level of injury at T6 or higher. Other signs, such as headache, chest tightness, flushing, and sweating, can also be seen. Treatment is limited to short acting β-blockers or other intravenous agents that can achieve rapid blood pressure control.

The bladder needs to be distended by irrigation fluid to optimize visualization during cystoscopies and TURP procedure. There are a number of choices of irrigating solutions currently used in practice, each with advantages and disadvantages (Table 22.2). Ideally, one would prefer an isotonic fluid that does not cause hemolysis when intravascularly absorbed, is transparent, nonelectrolytic, inexpensive and nontoxic. Since this is not possible, a number of other solutions have been employed and it is critical that the anesthesiologist be aware of the type of solution being used and its associated potential perioperative complications.

Table 22.2 Commonly used irrigating solutions

Irrigating solution	Relative osmolality	Advantages	Disadvantages
Distilled water	Very hypoosmolar	↑ Visibility	Hemolysis, hemoglobinemia, hemoglobinuria, hyponatremia
Glycine	Hypoosmolar	↓ TUPR syndrome incidence	Transient postoperative visual syndrome
Sorbitol	Hypoosmolar	↓ TUPR syndrome incidence	Hyperglycemia, osmotic diuresis
Mannitol	Isosmolar	Not metabolized	Osmotic dieresis, may cause intravascular volume expansion

TURP syndrome is a phenomenon that can be caused by intravascular absorption of irrigation fluid into the venous sinuses of the distended bladder when the pressure of the irrigating fluid exceeds venous pressure. The TURP syndrome is defined as a constellation of signs and symptoms that reflect rapid absorption of irrigating solution, leading to respiratory distress from volume overload, dilution of serum electrolytes and proteins, and resultant cardiopulmonary changes (Table 22.3). Central nervous system manifestations in the awake patient include nausea, agitation, confusion, visual changes, seizures, and even coma. These effects are most likely secondary to hyponatremia leading to cerebral edema and hyperglycemia causing hyperammonemia (ammonia is a metabolite of glycine). In the anesthetized patient, the anesthesiologist may observe hypertension, bradycardia, dysrythmias, desaturation secondary to pulmonary edema, and delayed emergence. Coagulopathy can also develop from dilutional thrombocytopenia or disseminated intravascular coagulation.

To treat TURP syndrome, one must begin with the ABCs (Airway, Breathing, Circulation). Once oxygenation and circulatory support have been established, serum electrolytes, arterial blood gases, and electrocardiogram must be checked and fluid restriction with diuresis (usually with furosemide, a potent loop diuretic) must be initiated. If the serum sodium concentration is <120 mmol/L, hypertonic saline can be used but the sodium deficit must be corrected slowly, in order to prevent the development of central nervous system demyelinating conditions. If there is a

Table 22.3 Symptoms of TURP syndrome

Cardiovascular	Neurologic	Other
Hypertension	Confusion/disorientation	Hemolysis
Arrhythmias	Seizures	Hyponatremia
Congestive heart failure	Unresponsive	Hyperglycinemia
Pulmonary edema	Visual problems or blindness	Hyperammonemia
Hypoxemia myocardial ischemia		

coagulopathy present, the treatment is supportive and consists of plasma and platelet transfusions to replace factor deficiencies.

Bacteremia may also be seen following TURP, given the high-pressure irrigation and because many of these patients have an indwelling foley catheter. Prophylactic antibiotics are usually given prior to the start of the procedure and continued for 2–3 days after the catheter is removed. **Hypothermia** can also be seen in elderly patients who have received large volumes of cool irrigating fluid and have impaired thermoregulatory mechanisms.

Case Study

A 68-year-old manhassymptoms of benign prostatic hypertrophy and is to undergo transurethral resection of the prostate (TURP). He has hypertension and hyperlipidemia and takes an ACE inhibitor and atorvastatin (Lipitor). He is physically active and has no symptoms of angina or heart failure.

What else will you investigate in the preoperative assessment?

In addition to the usual systems review for any anesthesiology preoperative assessment, you should make certain there are no contraindications to regional anesthesia (anticoagulation, spine abnormalities) and whether there are signs of renal dysfunction. The former may influence the choice of anesthetic technique, and the latter may influence the choice of drugs employed.

Will you recommend regional or general anesthesia? What are the relative merits of each?

Both anesthetics are commonly used and patient preference should be at least one important factor. Spinal anesthesia allows CNS monitoring for signs of the TURP syndrome, may relax the bladder efficiently, and may be associated with less blood loss. Conversely, general anesthesia with positive pressure ventilation increases venous pressure and reduces absorption of irrigation fluid, potentially decreasing

the risk of TURP syndrome. In practice, no important differences in outcomes have been demonstrated between the two techniques.

After discussion with the patient, you decide on general anesthesia. How will you induce and maintain anesthesia?

Any reasonable combination of drugs is reasonable for general anesthesia. Most patients stay overnight and thus rapid emergence as required for outpatient surgery is not required. However, shorter acting drugs may allow for easier monitoring in the PACU for signs of fluid absorption and TURP syndrome. Therefore, induction with either thiopental or propofol is reasonable. Maintenance could be with a volatile anesthetic, with or without nitrous oxide, and a modest dose of a short-acting opioid such as fenanyl. Muscle relaxation often used to prevent movement when the resectoscope is in place.

The procedure takes longer than expected due to a very large amount of prostatic tissue requiring resection. At the end of the operation, you extubate the patient and take him to the PACU. He is hypertensive, confused, and agitated. How will you assess him?

Although much attention is paid to it, do not assume it is TURP syndrome! First, check for the common causes of agitation in the PACU, including hypoxia, hypercapnia, pain, and emergence delirium. If you have excluded these causes, you can obtain laboratory studies to help you make the diagnosis. In particular, you can check a serum sodium and possibly an ammonia level (because glycine in the irrigating fluid is metabolized to ammonia).

If you believe he has TURP syndrome, how will you treat him?

The treatment of the syndrome is largely supportive. Begin, as always, with the ABCs: administer supplemental oxygen, ensure a patent airway and adequate ventilation, examine the patient for signs of volume overload and treat hemodynamic derangements with appropriate drugs to

lower blood pressure. You will monitor the electrocardiogram for dysrhythmias, and treat them with appropriate drugs if they occur. When you have confirmation that there is hyponatremia, you will then fluid restrict the patient and consider diuresis with a loop diuretic such as furosemide. Rarely you will need to use hypertonic saline to raise the sodium level (generally if severely low, <120, or in the presence of CNS or cardiovascular symptoms). This is done slowly, to avoid myelinolysis. You will also check for the presence of dilutional coagulopathy or anemia and treat if present with factor replacement (fresh frozen plasma) and blood components as needed.

Suggested Further Reading

1. Cataldo PA, Buess GF (2009) Transanal endoscopic microsurgery: principles and techniques. Springer, New York
2. Colombo JR Jr, Haber GP, Jelovsek JE, Nguyen M, Fergany A, Desai MM, Kaouk JH, Gill IS (2007) Complications of laparoscopic surgery for urological cancer: a single institution analysis. J Urol 178(3 Pt 1):786–791, Epub 2007 Jul 13
3. Conacher ID, Soomro NA, Rix D (2004) Anaesthesia for laparoscopic urological surgery. Br J Anaesth 93(6):859–864, Epub 2004 Sep 17
4. Hanson RA, Zornow MH, Conlin MJ, Brambrink AM (2007) Laser resection of the prostate: implications for anesthesia. Anesth Analg 105(2):475–479
5. Hedican SP (2004) Complications of hand-assisted laparoscopic urologic surgery. J Endourol 18(4):387–396
6. Lynch M, Anson K (2006) Time to rebrand transurethral resection of the prostate? Curr Opin Urol 16(1):20–24
7. Nabi G, Downey P, Keeley F, Watson G, McClinton S (2007) Extracorporeal shock wave lithotripsy (ESWL) versus ureteroscopic management for ureteric calculi. Cochrane Database Syst Rev 24(1):CD006029

Anesthesia for Pediatric Surgical Procedures

23

Herodotos Ellinas

Key Learning Objectives

- Understand important anatomic and physiologic differences between pediatric and adult patients
- Describe and discuss perioperative evaluation in pediatric patients
- Describe common anesthetic techniques in children
- List common anesthetic medications used in children

Preoperative Evaluation

Psychological Assessment

Many factors influence how children and families remember their perioperative experience. The preanesthetic interview should be used to gather pertinent information and identify specific causes of anxiety. Potential anesthetic risks and complications should be described using **simple and clear language.** Postoperative pain

H. Ellinas (✉)
Department of Pediatric Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: hellinas@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_23

management should be well outlined with **reasonable** expectations explained to reassure patients and parents of a smooth postoperative course.

The perioperative period can be traumatic and anxiety provoking for many children. Providers need to utilize any available measures to ensure a comfortable and pleasant first perioperative experience to prevent future patient distress. Comfort objects such as blankets or stuffed animals may be brought with the child into the procedure room to ease induction. Preoperative anxiolytics or sedative medications (Table 23.1) with or without parental presence ("parental presence for induction-PPI) may help facilitate the acceptance of the induction mask [1, 2].

Physiological Assessment

The otherwise healthy child who presents for a brief, outpatient procedure rarely requires more than a focused history, pertinent review of systems and a targeted physical exam to assess acute heart or lung dysfunction. **Blood tests (CBC, chemistries) and imaging (ultrasound, CXR, CT/MRI) studies are often unnecessary** and add to perioperative anxiety and cost of care while providing little benefit. However, the child with a complex past medical history may require a more thorough evaluation that includes such studies. Table 23.2 provides a template for preoperative patient evaluation, and Tables 23.3 and 23.4 show normal age-based vital signs and age-based weight (kg) [1].

Table 23.1 Preoperative anxiolytics/sedative medications

Drug	Route	Dose
Midazolam	Oral	0.3–0.5 mg/kg
	IV	0.05–0.1 mg/kg
	Intranasal	0.2 mg/kg
Dexmedetomidine	Intranasal	2–3 mcg/kg
	IV	0.5–1 mcg/kg
Ketamine	IV	1–2 mg/kg
	IM	3–4 mg/kg
Fentanyl	IV	0.5–1 mcg/kg

Table 23.2 Preoperative pediatric history, physical exam and review of systems

History	Important questions and pertinent findings
Prenatal care / delivery	Gestational age; Apgar scores at birth; duration of intubation and ventilatory support; associated congenital conditions (BPD, cyanotic heart disease); home monitoring after hospital discharge (presence of apnea/bradycardia); frequency of hospitalizations; review of growth curves (failure to thrive)
Airway	Dysmorphic features (e.g., Pierre-Robin is associated with a difficult airway); micrognathia, loose teeth
Respiratory	Symptoms c/w acute or recent URI; asthma; sick contacts; second-hand smoke exposure; presence of wheezing, stridor, nasal flaring, cyanosis; sleep apnea
Cardiac	Murmurs associated with PFO, PDA, or congenital heart disease; frequency/duration of cyanotic spells; tachypnea; poor feeding/activity tolerance
Neurologic	Patterns of seizure activity; developmental delay; hypotonia; evidence of elevated ICP (vomiting, visual changes, headaches)
Hematologic	Bruising; pallor; family history of sickle cell disease or thalassemia
Gastrointestinal	Repetitive vomiting; delayed meconium passage; abdominal distention

BPD bronchopulmonary dysplasia, *PFO* patent foramen ovale, *PDA* patent ductus arteriosus, *URI* upper respiratory infection, *ICP* intracranial pressure

Table 23.3 Aged-based pediatric vital signs: normal ranges

Age	RR (bpm)	HR (bpm)	SBP (mmHg)	DBP (mmHg)
Preterm	55–60	120–180	45–60	20–45
Neonate	40–55	100–160	55–75	20–60
Infant (<6 months)	30–50	80–140	85–105	55–65
1 year	30–35	80–120	90–105	55–65
6 years	20–30	75–110	95–105	50–70
10 years	20–30	80–100	95–110	55–70
16 years	15–20	60–80	110–125	65–80

RR respiratory rate; *HR* heart rate; *SBP* systolic blood pressure; *DBP* diastolic blood pressure

Table 23.4 Age-based weight

Age	Weight (kg)
Full term infant	3–3.5
6 months	2× BWt
12 months	3× BWt (about 10 kg)
3 yo	15
5 yo	20
7 yo	25
9 yo	30
11 yo	35

BWt birth weight; after 1 yo children gain about 5 kg every other year until adolescence

Anatomy and Physiology

Airway

The upper airway in children is markedly different from that of their adult counterparts. Children have a larger tongue relative to the size of their mouth, and the mandible is shorter. The epiglottis is longer, narrower, and omega-shaped, making elevation with a laryngoscope blade difficult. Figure 23.1 outlines pediatric upper airway anatomy.

In the past, image evaluation of the pediatric airway suggested that the narrowest portion of the infant airway was at the cricoid cartilage. Newer data though suggest that the narrowest point for both adults and children is the same and at the glottic opening. Despite this controversy, in children, endotracheal tubes (ETTs) passed through the vocal cords may meet resistance below the glottic opening thus requiring a smaller diameter tube to avoid trauma and possible subglottic stenosis.

Pediatric anesthesiologists routinely use cuffed endotracheal tubes to allow for the administration of higher airway pressures with positive pressure ventilation when warranted. To avoid laryngeal edema and postprocedure stridor (a hoarse, "barky" cough indicating the presence of upper airway obstruction) an air leak of

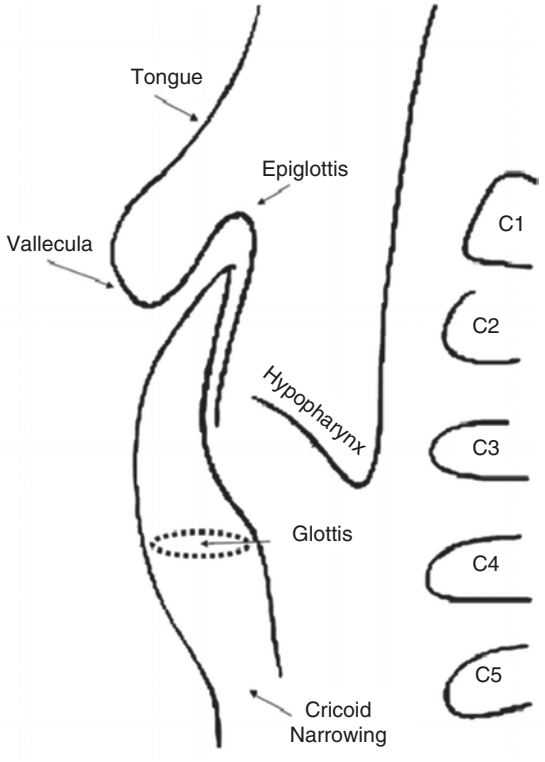


Fig. 23.1 Pediatric upper airway anatomy. (Image adapted from Cote et al. [3])

≤25 cm H_2O is recommended. If an air leak is not present, the ETT should be replaced for one with a smaller diameter [4].

The trachea is only 5 cm long in the infant. During intubation, it is possible that the endotracheal tube may be advanced too far, most often into the right mainstem bronchus. Auscultation for bilateral breath sounds and direct observation of equal chest expansion should always be performed immediately after intubation, and any adjustment of the tube position should be made if necessary.

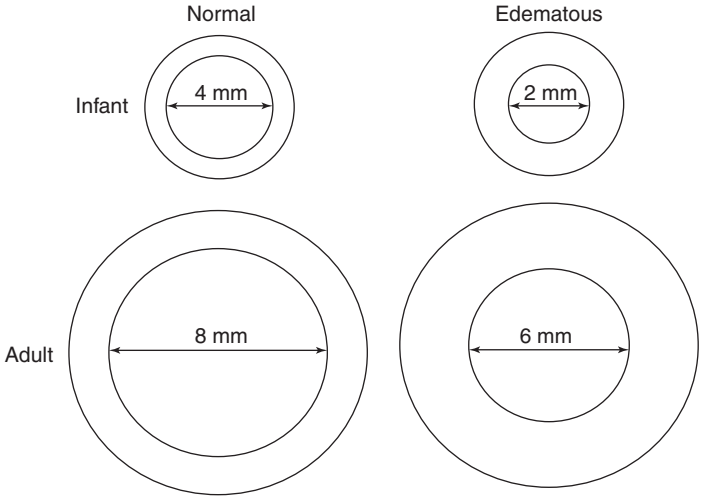


Fig. 23.2 Tracheal diameters: Infant (*top*) and Adult (*bottom*) in both normal (*left*) and edematous by 1 mm (*right*) states (decrease of cross sectional area by 75% in children and by 45% in adults). (Adapted from Cote et al. [3])

The trachea is only 4–5 mm in diameter in an infant, and edema caused by rough placement of an endotracheal tube, multiple intubation attempts or a large diameter ETT can significantly increase airway resistance and decrease laminar (nonturbulent) airflow (Fig. 23.2).

Transition from Fetal to Neonatal Circulation

Oxygenated blood is delivered to the fetus by the umbilical vein. Intracardiac (i.e., foramen ovale) and extracardiac (i.e., ductus arteriosus and venosus) shunts form a parallel circulatory system that bypasses high resistance pulmonary vessels until birth. Figure 23.3 shows a schematic representation of neonatal circulation.

This transition to the normal neonatal circulation occurs after the umbilical cord is clamped and spontaneous breathing begins.

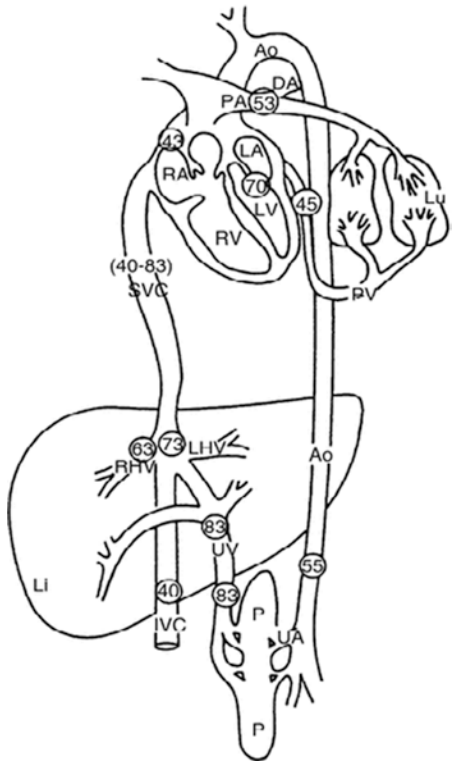


Fig. 23.3 Neonatal circulation. Normal fetal circulation with major blood flow patterns and oxygen saturation values (*circled numbers* indicate percent saturation). *IVC* inferior vena cava, *P* placenta, *Li* liver, *RHV* and *LHV* right and left hepatic veins, *SVC* superior vena cava, *RA* and *LA* right and left atria, *RV* and *LV* right and left ventricles, *DA* ductus arteriosus, *PA* pulmonary artery, *Ao* aorta, *Lu* lung, *DV* ductus venosus, *PV* pulmonary vein, *UV* umbilical vein, *UA* umbilical artery. (Reproduced with permission from Datta [5])

As the pulmonary vascular resistance decreases, systemic blood flow is altered. Changes in pressure, plasma oxygen concentration, and diminishing placental prostaglandins help to close the shunts. However, conditions such as sepsis, meconium aspiration and severe acidosis may cause these shunts to remain open, resulting in persistent fetal circulation.

Respiratory

The architecture of the major conducting airways is established by the 16th week of gestation. Alveoli mature after birth and

increase in number until 8 years of age. The chest wall of infants is composed predominantly of cartilage and deforms easily. Accessory muscles are poorly developed and tire quickly. The diaphragm has only a fraction of the typical adult fatigue-resistant type I muscle fibers. These attributes result in paradoxical chest wall movement when increased inspiratory effort is attempted. The increased caloric work is unsustainable, and respiratory fatigue and failure may follow.

Oxygen consumption in neonates is 5–7 ml/kg/min compared with adults of 2–3 ml/kg/min. This leads to faster induction and awakening from anesthesia but also may lead to hypoxia quicker [6].

Cardiac

The neonatal/infant heart (up to about 6–12 months of age) consists of less contractile tissue compared with the adult heart. The chambers are less compliant and unable to significantly increase stroke volume (SV) to compensate for elevated metabolic needs [7].

Cardiac output (CO = HR × SV) is therefore **dependent upon heart rate** (HR), and bradycardia in young children is poorly tolerated and may lead to cardiovascular collapse if not treated promptly. Factors that contribute to low heart rates include hypoxia, hypercarbia, hypothermia, and surgical manipulation.

Neurologic

Developmental milestones represent the average rate of neurobehavioral maturation. The healthcare team should be familiar with the basic domains of these milestones (gross and fine motor, language and personal—social skills) to properly manage a pediatric patient during the perioperative period. Deviations from the norm may still be within the range of normal but should be reviewed prior to the administration of anesthesia to avoid unnecessary distress and evaluation postoperatively. Some diseases (malnutrition,

intracranial trauma) and congenital disorders (chromosomal anomalies) may adversely affect future development.

Hematologic

The estimated blood volume (EBV) is 80–90 ml/kg at term and gradually declines with age to reach adult levels of 60–70 ml/kg. The hemoglobin species HbF is most prevalent after birth and has a greater binding capacity for oxygen than HbA (predominant in adults). As HbF is replaced over the first 2–3 months of life, and along with a rapid increase in blood volume and a decrease of intrauterine direct oxygen supply, transient physiologic anemia develops (the so-called "physiologic anemia of infancy"). Normal hemoglobin for a full-term neonate at birth is about 16 g/dl and falls to about 10–12 g/dl by 8–12 weeks of age ("physiologic nadir").

Hepatic

In neonates, lower hepatic flow, immature hepatic function, and lower albumin levels compared to adults alter anesthetic drug bioavailability and metabolism.

Infants, especially those that are preterm or small-for-gestational age, have **limited glycogen stores** to maintain their metabolic requirements. Although stress and infection tend to increase blood sugar levels, the lack of adequate glycogen stores requires vigilant monitoring for hypoglycemia in the perioperative period. Thus, most clinicians maintain neonates on dextrose infusion during the administration of anesthesia.

Renal

The kidneys are very active in utero and fetal urine output contributes to the volume of amniotic fluid. The glomerular filtration rate (GFR) is lower at birth but continues to mature to adult levels by about 2 years of age. A low GFR may interfere with infants' and

young children's ability to remove large amounts of fluids or drug metabolites from their bodies. To prevent acute kidney injury, most clinicians avoid the administration of potentially nephrotoxic medications (i.e. ketorolac) during the first 6 months of life.

Gastrointestinal

Meconium is a mixture of water, pancreatic secretions, and intestinal cells that is usually passed within hours after birth. Premature evacuation, or meconium staining of amniotic fluid, is evidence of a "stressed" fetus and may pose a hazard if this material is aspirated into the immature lungs. The lower esophageal sphincter may take several weeks to reach the tone normally found in adults. Projectile vomiting after feedings, usually around 6–8 weeks of age, is considered a classic sign of **pyloric stenosis**.

Skin

Infants and small children have a **large surface area-to-weight ratio**, causing them to lose body heat quickly, via all possible heat loss mechanisms (radiation, convection, evaporation and conduction). They also have limited subcutaneous insulating fat and adipose reserves for generating heat. Infants rely upon a special brown adipose tissue for nonshivering heat generation. This is a catecholamine response which is exhausted rapidly and may cause a decrease in peripheral perfusion, increased oxygen consumption, hypoxia and acidemia.

Intraoperative Care

Pharmacology

Changes in the volume of fat, muscle, and organ mass are age-dependent and affect pharmacodynamics and kinetics of anesthetic drugs. Since infants and young children have a **higher body**

water content, the volume of distribution is increased. Enzyme complexes are immature, and drugs may have delayed metabolism. Age-related differences in drug responses may be due in part to variations in receptor sensitivities. Most drugs used for pediatric anesthesia have not been formally approved for use in children by the FDA. A weight-based dosing methodology presumes similar clinical responses, but this may be inaccurate. Nevertheless, this paradigm continues to be observed based upon best clinical practice guidelines.

OR Equipment and Setup

Radiant heat loss is the most frequent cause of hypothermia in children. To maintain normothermia intraoperatively, pediatric anesthesiologists use a variety of techniques: a heated circuit, heated fluids especially for large-bore IV infusions, ambient warming lamps, and heating blankets, adjust the room thermostat, and cover exposed body parts.

A selection of age-appropriate face masks, laryngoscope blades, oral and nasal airways should be readily available to meet the typical needs of children with a diverse range of weight and body habitus. Table 23.5 shows the choice of endotracheal tube diameter and depth of placement (length) based on patient's age and weight. Table 23.6 shows the choice of laryngoscopic blade and LMA size based on patient's age. Table 23.7 shows the most common pediatric emergency drug dosages.

Table 23.5 Endotracheal tube sizes and approximate insertion depths

Age/weight	Internal diameter (mm)	Length (oral) in cm	Length (nasal) in cm
<1.5 kg	2.5 uncuffed	9–10	12–13
1.5–3.5 kg	3.0 uncuffed	9–11	13–14
Term-6 months	3.0 cuffed	10–12	13–14
6–12 months	3.5 cuffed	11–12	14–15
12–24 months	4.0 cuffed	12–13	14–16

Table 23.6 Laryngoscopic blade and LMA sizes

Age	Blade	Weight	Supraglottic Device
Premature	Miller 00/Miller 0	<5 kg	–
Neonate	Miller 0	5–10 kg	1
1–4 years	Miller 1/1.5	10–20 kg	1.5/2
4–10 years	Miller 2, Mac 2	20–30 kg	2.5
Adolescent	Miller 2, Mac 3	>30 kg	3.5

Table 23.7 Common pediatric emergency drugs

Drug	IV	IM/(SQ)
Atropine	0.01–0.02 mg/kg	0.02 mg/kg
Succinylcholine	1–2 mg/kg	3–4 mg/kg
Ephedrine	0.1–0.2 mg/kg	–
Epinephrine	10 mcg/kg	(10 mcg/kg)
Phenylephrine	1–5 mcg/kg	–

A frequently used app by the Society for Pediatric Anesthesia (SPA), Pedi Crisis 2.0 [8], provides medication calculations

Venous Access

Young children will resist any attempts at intravenous catheter placement while they are awake. Access is attempted with initiation of inhalation induction and only after adequate depth of anesthesia has been achieved. In occasions where IV induction is indicated (i.e. full stomach, difficult airway) sedation is provided with an intramuscular injection or intranasal administration of sedative drugs. Common sites to access include the dorsum of the hand, the antecubital fossa, and saphenous veins adjacent to the medial malleoli. Intraosseous routes (a noncollapsible needle is placed within the cavity of the tibia) may be needed in the presence of severe trauma or burn injury.

Intravenous access can also be obtained with the use of ultrasound, a modality frequently used today.

Arterial Access

Critical operations with anticipated significant blood loss and fluid shifts may require the use of an arterial line for perioperative monitoring and frequent blood draws. Access is usually obtained at the radial or posterior tibial arteries with the aid of ultrasound especially in small children.

Intravenous Fluids

Since many young children may still have partially patent shunts, all air bubbles should be evacuated from intravenous tubing prior to administration to prevent paradoxical air embolism and catastrophic cardiovascular collapse.

Intravenous fluid management is based upon calculating the sum of the NPO deficit, ongoing maintenance, blood loss (if any), and the potential for surgically induced fluid shifts (see also Chaps. 14 and 15; Electrolytes and Acid–Base and Fluids and Transfusion Therapy) [9]. The formula most often applied is commonly known as the "**4-2-1 rule**" (Table 23.8). Based on their electrolyte composition, osmolarity and pH (Table 23.9), crystalloid solutions such as Lactated Ringer's or Plasmalyte fulfill the majority of basic infusions. Glucose infusions are used for the newborn or premature infant because of their limited glycogen stores.

Table 23.8 Pediatric maintenance fluid (per hour)

Weight	Rate
<10 kg	4 ml/kg/h
10–20 kg	40 ml/h + 2 ml/kg/h for each kg >10 kg
>20 kg	60 ml/h + 1 ml/kg/h for each kg >20 kg

Baxter (Parkland) formula

Table 23.9 Composition of commonly used crystalloid solutions

	Normal saline	Lactated Ringers	Plasma-Lyte A	Healthy human plasma
pH	5.5	6.6	7.4	7.4
Osmolarity (mOsm/L)	308	273	294	285
Sodium (mEq/L)	154	130	140	140
Chloride (mEq/L)	154	109	98	104
Calcium (mEq/L)	0	3	0	2.3
Potassium(mEq/L)	0	4	5	4
Magnesium(mEq/L)	0	0	3	1.5
Lactate (mEq/L)	0	28	0	Negligible
Gluconate (mEq/L)	0	0	23	Negligible
Acetate (mEq/L)	0	0	27	Negligible

Pediatric Drug Preparation

Drugs should be drawn up in an appropriate syringe size that will deliver the desired dose of agent in a minimal volume. Succinylcholine and atropine should be available with appropriate syringes and 22-gauge needles for IM injection in case vascular access is unavailable and laryngospasm or bradycardia develop.

Techniques

Induction

A smooth anesthetic induction can be achieved in a variety of ways. All methods have their advantages and disadvantages (Table 23.10) [1].

Maintenance

Effective anesthetic depth may be maintained with a number of drug and technique combinations. The selection should be based upon individual needs and guided by the presence of comorbidities, anticipated procedure duration and other case-specific features.

Table 23.10 Pediatric induction methods

Technique	Advantages	Disadvantages
Mask induction (Sevoflurane/ N_2O[a])	Quick onset (2–3 min) Maintenance of spontaneous respirations Facilitation of IV start via vasodilatation	Breath-holding/ laryngospasm Unprotected airway Pungent odor Malignant hyperthermia triggering agent
Intravenous (Propofol)	Rapid onset (<30 s) Minimal duration of unprotected airway	Pain upon injection Anxiety about "shots" (prevented with po/iv midazolam)
Intramuscular (Ketamine)	Quick onset (2–4 min) Can inject at multiple sites Does not require cooperation	Pain upon injection Unprotected airway Increased secretions Psychomimetic effects

[a]N_2O nitrous oxide provides amnesia and second-gas effect

Many clinicians use the "**4-2-1 rule**" as a guide to fluid replacement (Table 23.8; see also Chaps. 14 and 15; Electrolytes and Acid–Base and Fluids and Transfusion Therapy) [9]. Neonates and infants require additional care to avoid fluid overload and provide appropriate glucose supplementation (D5 ¼ NS, D5 ½ NS are appropriate). Estimated blood volume (EBV) (see Table 23.11) should always be calculated to guide fluid therapies for surgeries involving significant blood loss. Although young children tend to tolerate a lower hematocrit, it is important to remember that they also have higher metabolic rates and oxygen needs.

Postoperative nausea and vomiting (PONV) may escalate level of care (admission for observation instead of discharge to home) in the pediatric patient due to the risk of acute dehydration. Risks include age ≥ 3 years, strabismus surgery, surgical procedure ≥30 mins, and history (or family history) of PONV. To prevent PONV, clinicians use anti-emetics such as 5-HT3 antagonists (i.e. ondansetron) and dexamethasone [10].

Emergence

Extubation criteria should include normothermia (body temp >36 °C), hemodynamic stability, resolution of neuromuscular blockade and evidence of appropriate analgesia. Although infants and young children will generally not follow verbal commands, they may reach up and try to extubate themselves. Appropriate equipment should be immediately available to secure the airway if extubation fails.

Monitored transport with oximetry is recommended but may not be practical in the emerging, active child. Pulse oximetry is very sensitive to motion artifact, so the recovering child should be closely observed for evidence of airway obstruction. Phonation and crying are reassuring signs under these circumstances, because they confirm the presence of a patent airway. Supplemental oxygen may be required during transport to maintain SpO2 ≥ 92% but that does not preclude close monitoring for airway obstruction.

Parents are often invited to stay with their child in the recovery area once the physician and nurses are satisfied with the patient's clinical status. The parents will provide a reassuring presence and help limit any mild disorientation that may occur. The patient is ready for discharge if they are reasonably comfortable, hemodynamically stable, and with minimal nausea. Children may not resume normal oral intake or void prior to discharge, but this does not need to unnecessarily prolong their stay as long as fluid replacement has been adequate. Some common specific operations in children and the associated anesthetic considerations are given in Table 23.11.

Table 23.11 Estimated hematocrit (HCT) and estimated blood volume (EBV)

Age	HCT (%)	EBV (ml/kg)
Premature	45–60	90–100
Neonate	45–60	80–90
3–6 months	30–33	70–80
6 months–1 year	32–35	70–80
1–12 years	35–40	70–75
Adult	38–45	60–70

Pain Management

Perioperative pain control is achieved with non-opioids (i.e. acetaminophen, non-steroidal anti-inflammatories-ketorolac), opioids (i.e. fentanyl, morphine, hydromorphone) and adjuvant medications (i.e. muscle relaxants-diazepam) [11].

Certain procedures (e.g., bilateral herniorrhaphy) permit the use of supplemental regional anesthesia. Single-shot caudal epidurals (0.25% Bupivacaine, 0.8–1.0 ml/kg) are frequently used and relatively easy to perform and provide 8–12 h of analgesia while reducing the potential side-effects of opioids.

Pediatric Surgical Conditions

A list of the most common pediatric surgical conditions and their anesthetic implications are shown in Table 23.12.

Table 23.12 Common pediatric surgical conditions

Pyloric stenosis
Associated findings: Nonbilious, projectile vomiting, hypochloremic metabolic alkalosis, hypokalemia, hyponatremia, dehydration, hypovolemic shock
Anesthetic considerations: Medical NOT surgical emergency, rehydrate and correct metabolic abnormalities prior to surgery, usually decompress stomach with orogastric tube prior to a rapid sequence intubation
Diaphragmatic hernia
Associated findings: Respiratory distress, bowel sounds heard over the chest, decreased breath sounds, scaphoid abdomen
Anesthetic considerations: Bowel decompression with a nasogastric tube, avoid mask ventilation because it may cause bowel distension and worsen respiratory status, avoid hypoxia, watch for tension pneumothorax.
Omphalocele and gastroschisis
Associated findings: Abdominal contents covered by membrane (omphalocele only), fluid loss, infection, associated anatomic anomalies esp. cardiac (omphalocele only).
Anesthetic considerations: Volume resuscitation, need for muscle relaxation to allow inserting abdominal contents back into the abdomen, potential for postoperative ventilatory support.

(continued)

Table 23.12 (continued)

Tracheoesophageal fistula
Associated findings: Blind esophageal pouch with a distal fistula near carina (most common type), anatomic anomalies, coughing and choking, dehydration
Anesthetic considerations: Increased risk of aspiration, gastric decompression, maintain spontaneous ventilation to avoid further gastric distention

Case Study

A previously healthy 5-year-old boy has abdominal pain, decreased appetite and intermittent vomiting for 2 days. His po intake has been limited. Upon arrival to the emergency department abdominal ultrasound reveals an enlarged thickened appendix consistent with acute appendicitis. He is scheduled for laparoscopic appendectomy. He has no known drug allergies.

Vital signs are temp 37.9 C, RR 24, HR 120, BP 95/50, weight 20 kg.

How will you assess his volume status prior to surgery? What metabolic derangement would you suspect him to have?

The child is likely volume depleted, as assessed by history of limited PO intake and vomiting for 2 days. The elevated heart rate and low normal blood pressure for his age imply moderate, but not severe volume depletion. You can estimate the volume loss by the 4-2-1 rule for maintenance fluid requirements and assume that he is depleted up to 2 days' worth. However, this likely overestimates his volume depletion because people do not consume fluids overnight, and because his vital signs do not reflect a severe deficit. You can also assess other signs such as skin turgor, urine production and concentration. He likely has hypochloremic, hypokalemic, metabolic alkalosis since he has been vomiting and thus losing hydrochloric acid while the

kidney wastes potassium in preference to absorbing sodium. However, if the hypovolemia is severe, he may also have volume-associated acidosis.

The child is anxious and teary. How can you help during the preparation for and induction of anesthesia?

The goal here is to establish a secure airway as safely as possible. If you have an IV in place, you can administer a small dose of a short acting anti-anxiety medication such as midazolam. If not, you can consider sedation via the intramuscular, nasal, or oral routes. The oral route is less desirable in this child in the setting of vomiting. Intranasal midazolam or dexmedetomidine, and intramuscular ketamine have all been used for pediatric sedation to obtain intravenous access. Many children in this age group have a favorite toy, stuffed animal, or other "transition object" which comforts them, and you can bring such an object to the OR with you. Although parental presence for induction can be useful for elective procedures, in urgent/emergent situations where airway must be obtained rapidly, this technique can be frightening for most parents and should be avoided.

Would you perform an inhalation or intravenous induction?

Many children are anesthetized for routine cases with mask inhalation of a volatile agent, prior to starting an IV. In this case, there is evidence of abdominal pathology and even though the patient has not eaten for 2 days, you must treat him as at risk for aspiration of gastric contents. Therefore, you should induce with intravenous drugs and secure the airway before beginning positive pressure ventilation.

If you decide on an intravenous induction, how can you facilitate placement of the IV in this frightened child?

Many of the sedative options and other comfort measures noted above are available to you. Nitrous oxide may

provide adequate sedation to obtain intravenous access but should be used with caution because it may exacerbate vomiting. Topical anesthesia may also be used to facilitate access (i.e. EMLA cream, subcutaneous needless injection of lidocaine).

How will you induce and maintain anesthesia? What size endotracheal tube will you use?

Once you have placed an IV, consider replacing the volume deficit at least partly before induction (10–20 ml/kg crystalloid/colloid administration). Proceed with intravenous induction with propofol, or ketamine and rapid sequence intubation. Muscle relaxation should be used to facilitate intubation and can be accomplished with either succinylcholine or a non-depolarizing muscle relaxant (i.e. rocuronium).

A cuffed endotracheal tube is used to secure the airway. The usual formula is (16 + Age)/4 in mm internal diameter for uncuffed endotracheal tubes; a half size lower is employed when a cuff is used. In this case, a 4.5 mm cuffed ETT should be the appropriate size.

How will you know when you are able to extubate the patient at the end of the procedure?

All patients emerging from anesthesia should be breathing spontaneously, fully reversed from neuromuscular blockade, normothermic, hemodynamically stable, and be able to protect their airways. Adults should follow verbal commands such as “squeeze my hand” or “open your eyes” but children of this age are likely to be unable to do so. If you detect signs of purposeful movement (such as reaching for the endotracheal tube) or spontaneous eye opening, you can extubate the patient. You should observe for signs of a patent airway such as a strong cry. You should monitor the patient carefully on the way to the PACU, using a portable pulse oximeter. Supplemental oxygen should be used if needed.

References

1. Ghazal EA et al (2019) Preoperative evaluation, premedication, and induction of anesthesia. In: A practice of anesthesia for infants and children, vol 4, 6th edn. Elsevier, Philadelphia, pp 35–68.e11
2. Niezgoda J, Beers SR (2017) Behavioral development. In: Smith's anesthesia for infants and children, vol 2, 9th edn. Elsevier, Philadelphia, pp 10–22.e1
3. Fiadjoe JE et al (2019) The pediatric airway. In: A practice of anesthesia for infants and children, vol 14, 6th edn. Elsevier, Philadelphia, pp 297–339.e21
4. Holzman R (2017) Airway management. In: Smith's anesthesia for infants and children, vol 18, 9th edn. Elsevier, Philadelphia, pp 349–369.e2
5. Datta S (2004) Anesthetic and obstetric management of high-risk pregnancy, 3rd edn. Springer, New York
6. Motoyama EK, Finder JD (2017) Respiratory physiology. In: Smith's anesthesia for infants and children, vol 3, 9th edn. Elsevier, Philadelphia, pp 23–72.e15
7. Baum VC, Yuki K, de Souza DG (2017) Cardiovascular physiology. In: Smith's anesthesia for infants and children, vol 4, 9th edn. Elsevier, Philadelphia, pp 73–107.e6
8. https://pedsanesthesia.org/pedi-crisis-app/. Accessed 5 July 2022
9. McClain CD, McManus ML (2019) Fluid management. In: A practice of anesthesia for infants and children, vol 9, 6th edn. Elsevier, Philadelphia, pp 199–216.e4
10. Gan TJ et al (2020) Fourth consensus guidelines for the management of postoperative nausea and vomiting. Anesth Analg 131(2):411–448
11. Walker BJ, Polaner DM, Berde CB (2019) Acute pain. In: A practice of anesthesia for infants and children, vol 44, 6th edn. Elsevier, Philadelphia, pp 1023–1062.e15

Physiology and Anesthesia for Older Adults

24

Rozalin Thapa

For maximum impact, it is recommended that the case study and questions found on page xxix are reviewed before reading this chapter.

Key Learning Objectives

- Understand the physiologic changes associated with aging
- Learn the specific considerations for peri-operative management of the older adult
- Understand common postoperative anesthetic complications

Care of the older adults requires knowledge of the normal age-associated physiologic changes and age-related illnesses. The pre-operative management should be focused on identifying and optimizing any comorbid conditions prior to surgery. Assessing the patient's frailty, a multisystem loss of physiological reserve, is

R. Thapa (✉)
Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: rothapa@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_24

also important given it is a prognostic factor for poor outcomes. During the intraoperative phase, one should take into consideration the physiological changes that occur in older adult. This often requires the use of shorter acting agents and additional invasive monitoring to maintain hemodynamic stability. Postoperative care should be focused on early identification and treatment of postoperative complications such as postoperative delirium, hypoxia, and hypotension.

For anesthesiologists, it is important to assess preoperatively the baseline physical and mental status of the patient as well as determine the physiological reserves. Functional reserve is the difference between maximal and basal function. Chronological age is not an accurate indicator of general fitness but aging inevitably reduces functional reserve even in those individuals who are physiologically "young." The relationship between maximal and basal physiologic function is shown in Fig. 24.1.

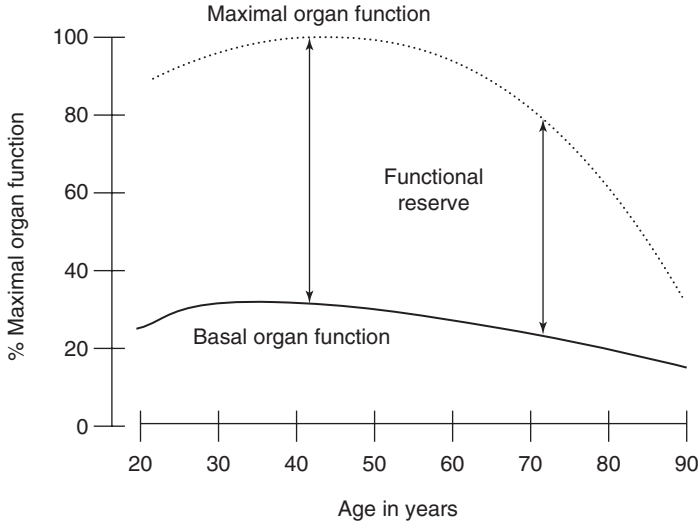


Fig. 24.1 Relationship between age and organ function

Physiological Changes with Aging

Cardiovascular System Changes

The cardiovascular system undergoes considerable changes with age and is responsible for most of the perioperative morbidity seen in the older adult. A decrease in arterial compliance leads to an increase in afterload. In response, the left ventricle hypertrophies over time and its compliance decreases. The inability of the left ventricle to relax during diastole is termed "diastolic dysfunction," which can be quantified by echocardiography. Left ventricular filling then becomes increasingly dependent on preload and atrial contraction. Hence, **maintaining sinus rhythm** is important to ensure adequate left ventricular filling and cardiac output. The venous vasculature also loses some of its compliance and its ability to act as buffer against volume overload. This predisposes older adults to pulmonary edema with excessive fluid administration.

Conduction system abnormalities are often seen in the older adults because of conduction system fibrosis. There is an increased incidence of atrial fibrillation, cardiac conduction abnormalities and SA node dysfunction. The responsiveness of β-adrenergic receptors is also diminished, rendering the older adults unable to initiate compensatory increases in heart rate in response to hypovolemia. Therefore, older patients are likely to develop orthostatic hypotension. Although cardiac output may remain unchanged, systolic blood pressure increases with age, whereas diastolic blood pressure increases until age 60–65 years and then plateaus or decreases (see Fig. 24.2). Valvular abnormalities are more common due to sclerosis and calcification, and more than 70% percent of older patients have an audible heart murmur.

Pulmonary System Changes

The major changes that occur with aging can be broadly attributed to the following factors:

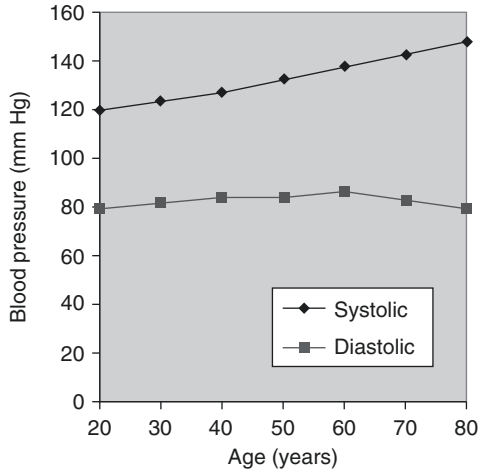


Fig. 24.2 Changes in blood pressure with age

- Blunting of the central nervous system reflexes to hypoxia and hypercapnia
- Decrease in the compliance of the thoracic wall
- Impaired gas exchange
- Increased closing capacity that approximates functional residual capacity

The larger proximal airways tend to dilate with age, causing an increase in dead space. The distal airways tend to collapse, causing an increase in closing capacity and an increase in ventilation perfusion mismatch. When functional residual capacity is below closing capacity, shunt will occur causing the observed decrease in resting arterial oxygen tension with older age. The compliance of the chest wall decreases due to muscle mass loss and changes to the rib cage. It also hinders the ability to cough and adequately clear secretions.

The central nervous system reflexes in response to hypoxemia and hypercapnia are also diminished. Clinically, all these changes combined with the older adult's exaggerated response to the respi-

ratory depressant effects of anesthetic drugs predispose the patients to hypoxemia in the perioperative setting. Finally, **hypoxic pulmonary vasoconstriction**, which is responsible for shunting blood away from poorly ventilated parts of the lung is diminished, leading to greater ventilation–perfusion mismatching and difficult one-lung ventilation.

Renal System Changes

A decline in renal function is seen in older patients due to nephrosclerosis and total renal blood flow (RBF). The serum creatinine may not reflect the extent of renal impairment as muscle mass declines with age. Creatinine clearance can provide a much more accurate reflection of renal function in the elderly. Older patients are also **predisposed to dehydration** because of diminished compensatory mechanisms, including perception of thirst and the renal response to antidiuretic hormone (ADH) (Table 24.1).

Nervous System Changes

With age, there is a decrease in volume of both gray and white matter. This loss is more pronounced in the gray matter due to neuronal shrinkage whereas there is neuronal loss of white matter. Additionally, diminished levels of neurotransmitters (dopamine,

Table 24.1 Renal changes in the elderly

Decrease in renal blood flow
Decline in glomerular filtration rate
Decline in ADH response
Decrease in total body water
Decreased ability to conserve sodium
Diminished urine concentrating ability
Decline in renin-aldosterone levels
Decreased thirst perception

serotonin, norepinephrine and acetylcholine) predispose older patients to cognitive deficits which can be accentuated in the postoperative period. Sensory perception such as vision, hearing and taste also diminishes with age.

Postoperative Cognitive Dysfunction and Delirium

Postoperative delirium is one of the most common postoperative complications in older patients and is associated with adverse patient-centered outcomes. **Postoperative delirium** is an acute alteration in mental status involving change in cognition, attention and levels of consciousness which tends to fluctuate. It commonly presents acutely in older patients during hospitalization, and frequently in the postoperative setting. There are **extrinsic** as well as **intrinsic causes** of **postoperative delirium**. There are many intrinsic factors that contribute which include preexisting cognitive dysfunction, alcohol abuse, multiple comorbidities and low functional reserve or frailty. Extrinsic factors include the stress of illness and surgery, an unfamiliar environment, medications (e.g., benzodiazepines, narcotics, anticholinergics), underlying infection, kidney dysfunction and pain. Some of the most important and treatable causes of postoperative delirium are hypotension, hypoxemia, and hypercarbia. Table 24.2 outlines the common causes of postoperative delirium.

Table 24.2 Causes of delirium

General: Increasing age, multiple comorbidities, severity of illness, alcohol or drugs of abuse, low functional reserve or frailty, disability, living in an institution
Intraoperative: Surgical complexity, duration and approach, cardiopulmonary bypass, transfusion, blood pressure, glycemic control, depth of sedation/burst suppression **Medication exposure**: Benzodiazepines, diphenhydramine, scopolamine, ketamine, meperidine, morphine, zolpidem, histamine-receptor antagonists
Postoperative: Hypoxemia, hypercarbia, infection, pain, anemia, renal insufficiency, atrial fibrillation, sleep disturbances, mechanical ventilation

Postoperative cognitive dysfunction differs from delirium in that the presentation is greater than 1 week after surgery. In most patients, there is clinically apparent or subclinical cognitive dysfunction at baseline, which can be elicited during the preoperative examination by performing a simple mini-mental status examination. The incidence of postoperative cognitive dysfunction after non-cardiac surgery has been stated to be approximately 26% in the immediate postoperative period and 10% after 3 months. Postoperative cognitive dysfunction may be related to medications, surgery and issues with the patient. Patients with postoperative cognitive dysfunction at discharge have been shown to have higher mortality rates during the first year after surgery. An overarching new term to describe a number of postoperative cognitive conditions has been recently introduced: "postoperative neurocognitive disorders" or PND. PND includes postoperative delirium, short-term postoperative cognitive dysfunction and longer-term cognitive impairment seen in some patients.

Pharmacokinetic and Pharmacodynamic Changes

With age, there is a progressive change in the constitution of the various body compartments. Total body water diminishes, fat stores increase, and serum albumin decreases. As a result, the **volume of distribution** of the administered drugs **decreases**, leading to an increase in initial plasma drug concentration. As the lipid stores are increased, lipid-soluble drugs (e.g. morphine) may have a prolonged duration of action. A decline in liver and renal function may also slow down drug metabolism and excretion. Because of these changes, the dosages of most medications should be decreased in older adults, and the dosing interval should be increased (Table 24.3).

Table 24.3 Pharmacology of anesthetics in older patients

	Potency	Clearance
Fentanyl	Increased	Unchanged
Propofol	Increased	Decreased
Remifentanil	Increased	Decreased
Midazolam	Increased	Decreased
Rocuronium	No change	Decreased

Anesthetic Management

Preoperative Examination

The purpose of the preoperative examination is to (1) determine the baseline physical and mental status of the patient, and (2) identify and optimize any medical comorbidities prior to undergoing a surgical procedure. The older patient has on average **three or more comorbid conditions** at any given time. The preoperative examination is challenging as these patients may not be able to provide accurate histories due to underlying cognitive dysfunction and memory deficits. "Polypharmacy" is common and a detailed list of medications should be obtained. A baseline ECG may be helpful given that ECG abnormalities are more likely to be present in older patients, but there is no recommended age at which this is necessary for the preoperative evaluation and should be guided by existing medical conditions and risk of surgery.

Further cardiovascular testing is dictated by a patient's underlying history and an assessment of the risk of surgery (see Chap. 8, The Preoperative Patient Evaluation). For example, a patient with cardiac impairment might be able to proceed for a cataract extraction (a low risk procedure) without extensive preoperative cardiac testing, but the same patient might require further testing (e.g. a stress test) if undergoing a thoracic procedure.

Preoperative **screening for frailty and cognitive impairment** should be performed given these are risk factors for poor outcomes and postoperative delirium and cognitive dysfunction. Finally, a preoperative assessment should allow some determination of the feasibility of ambulatory care versus postoperative hospital admission. This advance planning should be guided by the patient's baseline level of functioning and the availability of support at home.

Premedication

As has been discussed above, older patients are more sensitive to benzodiazepines and most of medications have a prolonged duration of action. Premedication should be used judiciously, with decreased doses and titrated to effect. Anticholinergic agents,

such as scopolamine and atropine, should be used with caution as they may be contributory to postoperative delirium.

Monitoring

The elderly are predisposed to hemodynamic fluctuations in the intraoperative period. They are more prone to develop cardiovascular complications such as hypotension, arrhythmias, myocardial infarctions, or heart failure. Therefore, close monitoring of vital signs and hemodynamic status with invasive monitoring is critical, especially in cases of intermediate and high-surgical risk. Monitoring of anesthetic depth may be beneficial to avoid burst suppression and/or overexposure to anesthetic.

Intraoperative Management

With age, the minimum alveolar concentration (MAC) decreases (see Chap. 5, Pharmacology of Inhalational Anesthetics). The total dose of medications should be decreased, and shorter-acting agents should be used, if possible. **Induction agents** should be titrated to effect. Propofol decreases peripheral vascular resistance and can cause significant hypotension. If hemodynamic stability is a major concern, consider using ketamine or etomidate for induction or a reduced dose of propofol.

Because **thermoregulation** is altered in older patient, they are at risk for hypothermia and its associated complications (e.g. coagulopathies, myocardial ischemia, poor wound healing). Temperature monitoring is therefore important and active rewarming may be required.

There are no data to support the use of one inhalational agent over the other. There is limited evidence that total intravenous anesthesia (TIVA) with propofol reduces post-operative cognitive dysfunction.

Shorter-acting opioid medications like fentanyl tend to cause less cumulative effects when compared with longer-acting agents like morphine. Meperidine has been associated with postoperative delirium and should be avoided in elderly patients.

The duration of nondepolarizing muscle relaxants is mildly prolonged in the elderly because of decline in metabolic function, although this is not typically clinically significant. The pharmacokinetics of depolarizing agents (e.g. succinylcholine) are not affected. Muscle relaxants should be adequately reversed and patients should be extubated only after return of muscle strength and airway reflexes. Any residual paralysis can potentiate respiratory depression, hypoxia and hypercarbia.

General Anesthesia Versus Regional Anesthesia

Studies comparing general to regional anesthesia in the elderly have not shown a significant difference in outcomes. Because the epidural and spinal spaces decrease in volume with age, a similar dose of epidural local anesthetic in an elderly patient may result in a higher sensory motor loss as compared to a younger patient. While the incidence of postdural puncture headaches (PDPH) is decreased in the elderly, the placement of a neuraxial block may sometimes be difficult due to restrictions in positioning.

The Postoperative Period

The elderly are vulnerable to prolonged effects of medications and should be closely monitored for respiratory depression, hypoxia, and hypercarbia. Pain in the elderly may atypically present as **agitation** and **delirium**. Postoperative delirium is commonly seen in the elderly and can be a manifestation of a variety of conditions – acute hypoxia and hypotension should always be ruled out. The incidence of postoperative delirium peaks between postoperative days 1–4. With ambulatory procedures, it is very important to assess the physical and cognitive status of the patient prior to discharge. It is also important to know about the support structure at home.

Case Study

An 82-year-old female suffered a fall, fractured her right hip, and is to undergo open reduction and hemiarthroplasty. She has no other injuries and did not lose consciousness. She is a smoker with a 60-pack-year history, but currently smokes just 2–3 cigarettes per day. She has chronic hypertension and an electrocardiogram from last year showed a right bundle branch block and a left anterior hemiblock with a sinus rhythm and rate of 55. She is a retired professor of pathology, a medical school dean, and still serves on your hospital's faculty council on promotions. She is in mild-moderate pain, which is much worse with movement of the right leg. She has expressed some concern regarding the effects of anesthetics on postoperative cognitive function.

What preoperative assessment will you perform before deciding on an anesthetic plan? How would it differ from the preop you would perform if the patient were having an elective cataract surgery?

In large measure, you will perform the usual preoperative assessment you do for any patient, including review of her airway, pulmonary status, NPO status, physiology, or disease of any other systems. You can ask about her exercise tolerance before the injury to get an idea of her cardiovascular reserve. You will also assess her volume status, because "bones bleed." A significant fracture, even without external injuries, can lead to a significant volume and red cell loss. This case can be done with a variety of anesthetic techniques, so you will also examine her for suitability for regional anesthesia, including examination of her back and lumbar spine and an assessment of whether she can be positioned without too much discomfort for the placement of a neuraxial block. You may want some laboratory studies, including a complete blood count and a new ECG. In a case

such as a cataract done under monitored anesthesia care, there is evidence that routine laboratory studies do not change the anesthetic plan or outcomes, so they can be safely foregone.

How will you address her concern about postoperative cognitive dysfunction?

She is medically sophisticated, so you will be clear and discuss the evidence as best as you can from a scientific point of view. In animal models, you can tell her, isoflurane and some other anesthetics that act as gamma aminobutyric acid (GABA) agonists and N-methyl-d-aspartate (NMDA) antagonists can trigger apoptosis or programmed cell death. In older animals, isoflurane can increase beta amyloid formation, which is part of the pathophysiology of Alzheimer's disease. To date, however, no direct human evidence has definitively linked exposure to anesthetics to long term cognitive decline. Nonetheless, there is indeed a theoretical concern. You can offer her an anesthetic excluding isoflurane, though it is certainly possible that other inhalation anesthetics may share this property. You can also offer her TIVA and regional anesthesia. Drugs used for TIVA are also GABA agonists and/or NMDA antagonists, so you cannot absolutely assure her that there are not adverse neurological effects, and indeed they have been shown to have some adverse effects in animal models of developing (neonatal) brain. Regional anesthesia does offer the possibility of avoiding all suspect drugs.

Will you favor regional or general anesthesia?

Given the possibility of pulmonary issues in this chronic smoker and the possibility of avoiding neurotoxic drugs, you should consider regional anesthesia. There are other potential advantages, including less blood loss and risk of venous thromboembolism. Conversely, given the fact that she has suffered some blood loss already, might experience negative hemodynamic effects from spinal or epidural anesthesia, and has disease of her cardiac conduction system,

some would consider general anesthesia. Positioning may be difficult given the hip fracture. Ultimately both are reasonable choices and you should discuss them with the patient.

Will you premedicate the patient prior to anesthesia?

You will ask the patient what she wants, rather than giving drugs reflexively. You will proceed gently, focusing on pain control rather than sedative effects. This may reduce the likelihood of respiratory side effects, as well as reduce postoperative delirium or short-term cognitive dysfunction.

If you and the patient agree on regional anesthesia, what type will you perform?

There are several approaches to hip fracture. In simple cases, a screw is placed to stabilize the femoral neck; the procedure is short and can be done under isobaric spinal anesthesia. Hemiarthroplasty involves more surgical manipulation and blood loss because the entire femoral head is replaced. This involves reaming of the femur, fitting and cementing a prosthesis. Because of the longer surgical duration, you may consider an epidural block or combined spinal-epidural (CSE). The presence of the epidural allows you to extend the block's duration should the procedure take longer than the spinal alone lasts. In addition, the epidural may be used postoperatively, which may be helpful in reducing opioid exposure, respiratory depression, and reduce the chance of cognitive dysfunction.

Suggested Further Reading

1. Apfelbaum JL, Connis RT et al (2012) Practice advisory for preanesthesia evaluation: an updated report by the American Society of Anesthesiologists Task Force on Preanesthesia Evaluation. Anesthesiology 116(3):522–538
2. Cook D, Rooke A (2003) Priorities in perioperative geriatrics. Anesth Analg 96:1823–1833

3. Vacas S, Cole DJ, Cannesson M (2021) Cognitive decline associated with anesthesia and surgery in older patients. JAMA 2: https://doi.org/10.1001/jama.2021.4773
4. Fowler RW (1985) Ageing and lung function. Age Ageing 14(4):209
5. Franklin SS, Gustin WT, Wong ND et al (1997) Hemodynamic patterns of age-related changes in blood pressure: the Framingham Heart Study. Circulation 96:308–315
6. Hughes CG, Boncyk CS, Culley DJ et al (2020) American Society for Enhanced Recovery and Perioperative Quality Initiative Joint Consensus Statement on Postoperative Delirium Prevention. Anesth Analg 130(6):1572–1590
7. Irwin MG, Ip KY, Hui YM (2019) Anaesthetic considerations in nonagenarians and centenarians. Curr Opin Anaesthesiol 32(6):776–782
8. Kam PCA, Calcroft RM (1997) Peri-operative stroke in general surgical patients. Anaesthesia 52:879–883
9. Khuri SF, Daley J, Henderson W et al (1995) The National Veterans Administration Surgical Risk Study: risk adjustment for the comparative assessment of the quality of surgical care. J Am Coll Surg 180:519–531
10. Kronenberg RS, Drage CW (1973) Attenuation of the ventilatory and heart rate responses to hypoxia and hypercapnia with aging in normal men. J Clin Invest 52:1812–1819
11. Lin HS, Watts JN, Peel NM et al (2016) Frailty and post-operative outcomes in older surgical patients: a systematic review. BMC Geriatr 16(1):157
12. Moller JT, Cluitmans P et al (1998) Long-term postoperative cognitive dysfunction in the elderly: ISPOCD 1 study. Lancet 351:857–861
13. Monk T et al (2008) Predictors of cognitive dysfunction after major non cardiac surgery. Anesthesiology 108(1):18–30
14. Peter A (2002) Structural changes that occur during normal aging of primate cerebral hemispheres. Neurosci Biobehav Rev 26(7):733–741
15. Redfield MM et al (2005) Age and gender related ventricular vascular stiffening. Circulation 112(15):2254–2262
16. Seymour DG, Vaz FG (1989) A prospective study of elderly general surgical patients: II. Post-operative complications. Age Ageing 18:316–326

Ambulatory Anesthesia

25

Joshua H. Atkins

For maximum impact, it is recommended that the case study and questions found on page xxix are reviewed before reading this chapter.

Key Learning Objectives

- Learn about patient selection, intraoperative management and postoperative care of ambulatory patients
- Understand specific practices of ambulatory anesthesia such as patient-centered care, fast-tracking and multimodal management of pain and PONV

Introduction

Ambulatory surgery (a.k.a. day surgery) describes procedures performed in a wide variety of clinical settings such as hospital, ambulatory surgery centers, and clinics or offices. The patient is

J. H. Atkins (✉)
Department of Anesthesiology and Critical Care, University of Perelman School of Medicine at the University of Pennsylvania, University of Pennsylvania Health System, Philadelphia, PA, USA
e-mail: joshua.atkins@pennmedicine.upenn.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_25

expected to return home within hours of the procedure in a condition that closely approximates baseline functional status. The variety and complexity of procedures that meet this definition are tremendouss and as such ambulatory patients are not necessarily healthy or straightforward. Similarly some procedures are being done in the overnight observation category which is neither strictly ambulatory surgery nor considered to inpatient admission. Ambulatory surgery represents an ever changing landscape and the anesthesiologist must stay abreast of current advances, technologies, and regulatory changes.

The percentage of surgical procedures done in ambulatory and office settings continues to grow for a variety of reasons including cost, patient convenience, and system capacity and this is especially true after COVID-19 in contrast to hospitals, which can and do perform outpatient procedures, ambulatory surgical centers and office-based surgery practices are subject to strict regulations that vary by locality. These regulations stipulate types of surgery, rules of patient selection, protocols, and necessary emergency resources that are appropriate for each location. The Society for Ambulatory Anesthesia (SAMBA, www.sambahq.org) has extensive additional resources on this that the reader may find useful.

Ambulatory Surgery

Ambulatory surgery generally places a great emphasis on the aesthetics of the patient experience from arrival to discharge and on maximization of efficiency and facility throughput. It is the true opportunity for patient-centered care. The goals of ambulatory anesthesia include rapid emergence from anesthesia, expedited discharge by “fast-tracking” patients to the most robust functional recovery possible. This includes prevention and treatment of postoperative nausea and vomiting (PONV), adequate pain control, increased operating room efficiency, and attentiveness to patient expectations.

Preoperative Considerations

The range of facilities in which ambulatory procedures occur is diverse and represents an important consideration for patient selection and planning. Unforeseen difficulty can be managed rather routinely when ambulatory surgery is performed in the setting of the full support services of an inpatient hospital. In contrast, even basic problems, such as the need for postoperative bladder catheterization, may not be easily handled in the office-based practice.

Specific preoperative issues to consider for ambulatory surgery patients include:

1. Is the nature of the surgical procedure compatible with same-day discharge?
2. Do patient characteristics or co-morbid conditions (see Table 25.1) predispose the patient to complications that might require hospital admission?

Indeed, even the simplest procedure done on a physiologically complex patient may require hospital admission and overnight observation. Table 25.1 provides representative considerations used to decide whether the patient might be an appropriate candidate for ambulatory surgery. Table 25.2 presents surgery- and procedure-related factors one might consider in deciding whether the proposed procedure is appropriate for the ambulatory setting. Table 25.3 lists common ambulatory procedures. However, *no* procedure is *always*

Table 25.1 Patient selection factors for ambulatory surgery

Caregiver available for transport home and postoperative evaluation
Patient willingness to go home the day of surgery
Co-morbidities: morbid obesity, obstructive sleep apnea, poorly compensated cardiopulmonary disease, implantable cardiac device, chronic pain, renal failure, urinary retention, significant neurologic disease (myasthenia, Parkinson's, dementia), bleeding diathesis, severe anemia
Prior anesthetic problems: difficult airway, PONV, postoperative cognitive dysfunction, malignant hyperthermia, poor pain-control, difficult intravenous access

Table 25.2 Procedure-related considerations for ambulatory surgery

Duration of surgery (no absolute cutoff) Risk of post-operative opioid induced respiratory compromise (elevated in OSA, obesity, chronic opioid use)
Intraoperative fluid shifts, bleeding and need for transfusion Need for post procedure implantable cardiac device interrogation
Risk of serious postoperative complications (bleeding, infection, airway or pulmonary compromise)
Extent of postoperative pain and analgesic needs
Need for intravenous medications or inability to tolerate oral intake

Table 25.3 Common ambulatory procedures

Local lesion removal (cyst, melanoma, breast biopsy/part, mastectomy)
Most orthopedic procedures not involving major fractures
Basic ENT procedures (sinus, tonsillectomy, cochlear surgery, thyroidectomy, hyoglossal nerve stim)
Limited plastics procedures (blepharoplasty, scar revision, liposuction, breast implant/reduction)
Limited urologic procedures (cystoscopy, biopsy, vasectomy, circumcision)
Ophthalmologic procedures (excluding vitrectomy and enucleation)
Limited GYN procedures (hysteroscopy, D&C/D&E, cone biopsy, tubal ligation) Limited spine surgery (single level microdisectomy) Limited oncologic procedures (breast biopsy, lumpectomy, melanoma resection)

done in an outpatient basis. Even a low risk procedure (e.g. cataract removal) done on a physiologically complex patient may require hospital admission and overnight observation.

Preoperative testing and evaluation requires the use of patient triage protocols and following existing clinical guidelines. Patients are best screened and evaluated well in advance of the planned procedure. Advance assessment allows problem identification and implementation of optimization strategies that may facilitate handling of medically complex patients in the outpatient setting or appropriate shunting to a more clinically appropriate setting.

Generally, patients planned for same-day discharge should not have active issues that require substantial medical consultation or interdisciplinary planning. If such medical co-morbidities are present, regardless of anesthetic or surgical approach, the risk of perioperative exacerbation of underlying medical conditions is real and the expertise and resources to assess and manage these conditions may not always be available, especially in a free-standing ambulatory facility. The challenges and dangers intrinsic to the management of sick patients in a stand-alone ambulatory surgery center or office-based practice, in many cases, outweigh the potential benefits of rapid discharge, patient convenience, and decreased cost. However, a carefully selected patient with medically optimized conditions generally does quite well in the ambulatory center.

Preoperative testing focused on specific patient factors is appropriate. Medically informed common sense should guide this decision-making. For example, patients with hypertension or other known cardiovascular disease should have a preoperative ECG; patients on medications that affect electrolyte balance (e.g. furosemide, spironolactone, and potassium) should have a recent preoperative chemistry panel; patients with chronic anemia or recent active bleeding (e.g. menorrhagia, epistaxis, and GI bleed) should have a hemoglobin value measured since the last bleeding episode. Transfusion is not routine in the ambulatory setting and not usually an option in a stand alone surgical center due to the lack of a blood bank. A healthy patient generally needs no preoperative testing and "routine" tests such as complete blood count, chemistry panel and chest X-ray should never be ordered without a clear idea of why the test results will be useful in the anesthetic planning and perioperative management of the patient. Nil-per-os (NPO) guidelines have substantially evolved and this has always been a source of strain for patients. Clear liquids are now allowed and in many cases encouraged until 2 h before the procedure.

Certain procedures simply cannot be performed on an outpatient basis; this is primarily due to the need for continuous postoperative monitoring (e.g. measurement of gastric drainage, placement of drains for bleeding, and need for frequent electrolyte studies), ongoing interventions (intravenous medications for pain, fluid resuscitation, and complex dressing changes), or inability to eat, drink, or urinate. Examples are listed in Table 25.4.

Table 25.4 Procedure exclusions for outpatient management

Requires drain or nasogastric drainage tube to be placed Hysterectomy, bowel resection, multi-level, neck dissection
Oral medications inadequate for postoperative pain control Radical Mastectomy, major abdominal surgery
May require postoperative bladder catheterization Ventral hernia repair, bladder tumor resection, ureteral stent
Frequently requires intraoperative or postoperative transfusion Hysterectomy, ORIF femur
Expectation of postoperative electrolyte fluctuations Pituitary resection
Elevated risk for airway complications & inability to tolerate oral intake Transoral ronotic surgery, Zencker's diverticulum, uvulopalatopharyngoplasty
Requires hourly patient assessment Free-flap, craniotomy, patients with severe sleep apnea

Intraoperative Management

Anesthetic management in ambulatory surgery is based on the SAMBA S.A.F.E. principles. S.A.F.E. is an acronym that stands for *s*hort-*ac*ting, *f*ast-*e*mergence anesthetic. General, regional, combined regional/general, and monitored anesthesia care are all compatible with rapid patient discharge. An important consideration is that the anesthetic plan be compatible with patient expectations, surgical needs, and patient-specific factors. Many patients have a preconceived notion that general anesthesia implies delayed emergence and long recovery. These same patients may not appreciate, for example, the delay in discharge that can be associated with time needed for return of motor or bladder function after neuraxial (spinal, epidural) blockade or the residual "hangover" of benzodiazapines and fentanyl relative to propofol. Patients should participate in the anesthetic planning where appropriate, with their concerns specifically addressed in the preoperative discussion. Default pre-medication with anxiolytics is common practice but not always necessary.

Generally speaking, short-acting anesthetic agents are better suited to rapid recovery. Midazolam is preferable to diazepam, propofol to thiopental, and bupivacaine or lidocaine to tetracaine. Likewise medications which may seem ideally suited to sedation such as dexmedetomidine often produce persistent effects in the recovery room (e.g. bradycardia or hypotension) that result in substantially enhanced PACU stays. There is no clear difference in outcomes or experience between a propofol based intravenous anesthetic and inhaled agents. The inhaled potent agents are all similar in their clinical profiles provided that depth is titrated appropriately, although desflurane, due to its low blood solubility, likely has some clinical advantage in subgroups of patients such as the morbidly obese. In this regard, a processed EEG, such as BIS or SEDLine monitors, may have some utility as a guide to titration of anesthetic depth in order to avoid overdose of agents, which may prolong emergence or recovery. Succinylcholine can produce very substantial myalgias and there is no reliable preventive or treatment strategy. This can be highly debilitating and dissatisfying to patients who expected to be ambulatory and functioning in the days after surgery.

Adequate postoperative analgesia is of paramount importance. In the absence of effective regional anesthesia, hydromorphone, morphine, and fentanyl are all acceptable opioid options in the intraoperative period. Using several analgesics that work by different mechanisms, known as **pre-emptive and multimodal analgesia** may help to reduce opioid requirements and related side-effects. Approaches may be protocolized and in some cases involve patient taking oral medications in the hours or days leading up to surgery. There is conflicting data regarding the efficacy of these approaches and careful attention should be given to patient selection. Part of the efficacy of this approach may be related to the anti-inflammatory effects of some medications. Analgesia options in selected patients include low-dose dexamethasone, low-dose ketamine, NSAIDs such as intravenous ketorolac or meloxicam, acetaminophen (oral or IV), intravenous lidocaine infusion, oral gabapentin or pregabalin, wound infiltration by long acting depot local anesthetic, or via single-shot nerve block or continuous catheter. Ketamine may enhance delirium in

older patients. Gabapentin may produce somnolence, dizzieness, or confusion that could contribute to falls. Intravenous lidocaine can produce enhanced side-effects in patients with low albumin. Use of regional blocks requires staff with specialized training in the techniques, ultrasound equipment and needles, and intralipid for rescue of local anesthetic toxicity. Patients who have elevated pain and anxiety levels or chronic opioid use at baseline may not be optimal candidates for a fast-track approach. If they are, every effort should be made to encourage either adherence to the baseline regimen through the morning of surgery or otherwise attempt to taper pain medications under expert guidance.

Postoperative nausea and vomiting (PONV) is one of the major reasons for delayed discharge or unplanned admission after elective surgery. Anesthetic medications and opioids are both substantial contributors to PONV. In light of the availability of safe, efficacious, and inexpensive agents for PONV prophylaxis (see Chap. 7) there generally appears to be no downside to a single dose of a 5HT-3 antagonist for most patients. Multimodal PONV prophylaxis should be considered in patients at higher risk. High risk patients include those with prior history of PONV, motion sickness, female nonsmokers, and patients undergoing ear, eye, gynecologic, or abdominal surgery. Inner ear and eye surgery patients are also are especially difficult. A common prophylactic combination is low-dose dexamethasone (4–8 mg) with 5HT-3 antagonist. Although associated with dry mouth, transdermal scopolamine is another excellent option with the advantage that the patch can be left on for up to 72 h if the patient is concerned about PONV during transit home or having significant opioid related symptoms. Caution should be used in patients with a history of delirium, dementia, Parkinson's disease or other neurologic impairment as the medication crosses the blood-brain barrier and could worsen symptoms. Medications such as metoclopramide are likely to have fewer sedating effects than droperidol, prochlorperazine, promethazine, or diphenhydramine but these medications should be considered when necessary for rescue or patients who have failed prior multimodal prophtylactic regimens. A propofol-based anesthetic and fluid-loading may be advantageous in higher risk patients. In patients who have a history of PONV

despite aggressive prophylaxis, administration of the oral NK-1 receptor inhibitor aprepitant can be considered. Amilsupride, a D2/D3 dopamine receptor antagonist has recently been added to the armamentarium of medications for PONV.

Postoperative Management

Ambulatory surgery patients and their families desire rapid discharge from the PACU to home. Facilities differ in their discharge criteria, but almost all have well-defined protocols. PACU is often divided into Phase I (immediate recovery with active, ongoing issues such as blood pressure control, pain, and hypoxia) and Phase II (imminently ready for discharge except for voiding, ambulation, or demonstration of oral intake). Some facilities will use established scoring systems like those of Aldrete to objectively manage patient flow and discharge. These scoring systems emphasize pain control and return to baseline neurologic, hemodynamic, and pulmonary function. Most facilities require patients to have vital signs within 20% of baseline, to consume a light snack and beverage and reach reasonable pain control on oral medication prior to discharge. Some still require postoperative voiding while in many centers voiding is not a criterion, provided the patient is not at high risk of urinary retention, has access to support persons at home and can be transported to the ER in the event of a problem.

"**Fast-Tracking**" after ambulatory surgery is a widely accepted practice which involves transferring patients from the operating room to the later stage recovery area (Phase II), by bypassing the early stage (Phase I). The success of fast-tracking depends upon appropriate modification of the anesthetic technique, to allow rapid emergence from anesthesia and the prevention of pain and PONV. Implementation of a fast-track program involves the use of clinical pathways that reduce hospital stay and ensure patient safety.

Inadequate pain control and continued **nausea or vomiting** with inability to tolerate oral intake are the two most common reasons for discharge delay. These clinical problems should be treated aggressively. PONV in the PACU should be treated with

an agent of a different class than used for prophylaxis. Pain should be treated with rapidly acting IV analgesics, and the patient should then be transitioned to oral medications.

Case Study

A 49-year-old woman who takes oral Vicodin daily for lower back pain is scheduled for axillary lymphadenectomy. She is a caregiver to two children at home. She is strongly motivated to have the procedure performed as an outpatient and requested a first start to get home as early as possible. She has limited availability for additional childcare support as her partner works at night. She is generally healthy, though she notes that she has seasonal allergies and occasional wheezing for which she takes an antihistamine and uses a metered dose inhaler (albuterol) as needed. Her BMI is 29 and she snores but denies obstructive sleep apnea. She does not smoke, drinks alcohol on the weekends (3–4 drinks once per week), and does not use recreational drugs. She has a history of motion sickness.

Is it appropriate to do this case in an outpatient surgery center? What other information do you need to decide?

Of the various criteria commonly used, she meets most: she is motivated, generally healthy, and has only moderate coexisting disease. The procedure is limited, is not associated with high blood loss, fluid shifts, or the need for drains postoperatively. Her snoring is concerning, but otherwise she has no major risk factors for sleep apnea. She is on chronic opioid therapy and optimal management will be for her to take her baseline pain medications on the regular schedule. She will need no special post-op monitoring. She needs a caregiver for 24 h, and you will need to make sure her asthma symptoms are not currently active. She is at risk for PONV and needs to be counseled regarding the inability to guarantee that she will not experience nausea and vomit-

ing at home. As with any patient presenting for surgery in any venue, you will need to perform a complete history and certainly must assess her airway. Some centers have cutoff values for maximum BMI.

Is she at high risk of postoperative nausea and vomiting (PONV)?

Yes. According to the criteria proposed by Apfel she meets three of four: she does not smoke, and has a history of motion sickness (or PONV). The fourth factor, use of postoperative opioids, is something we can hope to plan to avoid. With three risk factors, her approximate risk of PONV is 60%.

How will you induce and maintain anesthesia?

You will follow the S.A.F.E. principles suggested by the Society for Ambulatory Anesthesia and give short acting, fast emergence drugs. Propofol for induction is a rational and popular choice. You can consider using no muscle relaxants and no intubation, maintaining the airway with an LMA and maintaining spontaneous respiration. Sevoflurane or desflurane are logical choices, given their low solubility and rapid elimination. You will also avoid large doses of intraoperative opioids and use short-acting drugs such as fentanyl, sufentanil, or remifentanil. Total intravenous anesthesia is a potential alternative which can minimize the risk of PONV, but it will also generally require controlled ventilation, and often endotracheal intubation.

How will you manage postoperative pain?

Your goal is to have a comfortable patient but to minimize opioids. She will take her Vicodin pre-operatively according to the regular schedule and will be prescribed 975 mg of oral acetaminophen in the pre-op holding area. You will discuss local anesthetic infiltration with the surgeon and discuss the use of NSAIDs, such as single-dose ketorolac, to augment the effect of small doses of short-acting opioids such as fentanyl. A single shot regional block such as a pectoral block (PECS II) may also be considered.

How will you reduce the risk of PONV?

Given her relatively high risk for PONV, you will probably administer two- or three-drug prophylaxis. Dexamethasone and ondansetron is a popular combination. You can also consider a scopolamine patch, which has particular efficacy against motion sickness. Often patients do well in the PACU only to experience PONV on the ride home, so this is a good choice for this patient. Importantly, you should also set reasonable expectations with patient, and let her know that is acceptable to experience some nausea and vomiting, even after discharge, as long as she can take oral fluids.

Anesthesia and emergence are uneventful and you take the patient to the PACU. When can she go home?

She should meet the ordinary PACU discharge criteria for any patient: alert and oriented, hemodynamically stable, with reasonable control of pain and nausea. This does not imply that she must be 100% pain or nausea free, but she must be comfortable. There are also special considerations for discharge home. She needs a ride home with a responsible adult. She should be able to ambulate and take limited oral intake, which may be defined as fluids only, or fluids and light solids such as crackers. The latter varies by institution and is not an evidence-based standard. Formerly, many outpatients were required to void prior to discharge. However, many surgical patients may have reduced urine production due to the surgical stress response, drug effects, or mild hypovolemia. Many centers have therefore dropped this requirement and discharge patients with a "due to void" instruction and an understanding of what to do if she does not urinate within a few hours after discharge. Finally, she must understand her post-discharge instructions and be comfortable leaving the medical facility. You and her other physicians should have a way to reach her by telephone should any immediate follow-up be required, and she should know how to contact you and your colleagues should problems arise at home.

Suggested Further Reading

1. Afonso AM, Tokita HK, McCormick PJ, Twersky RS (2019) Enhanced recovery programs in outpatient surgery. Anesthesiol Clin 37(2):225–238
2. Aldrete JA (1995) The post-anesthesia recovery score revisited. J Clin Anesth 7:89–91
3. Apfel CC, Korttila K, Abdalla M, Kerger H et al (2004) A factorial trial of six interventions for the prevention of postoperative nausea and vomiting. N Engl J Med 350(24):2441–2451
4. Liu SS, Strodtbeck WM, Richman JM, Wu CL (2005) A comparison of regional versus general anesthesia for ambulatory anesthesia: a meta-analysis of randomized controlled trials. Anesth Analg 101(6):1634–1642
5. Raeder J, Urman RD (2015) Practical Ambulatory Anesthesia. 1st Ed, Cambridge University Press, New York
6. Twersky R, Philip B (2008) Handbook of ambulatory anesthesia, 2nd Ed. Springer, New York

Non-operating Room Anesthesia

26

Joshua A. Spiro, Thomas J. Hatzidais, Diana Ayubcha, and Mark S. Weiss

Introduction

The number of NORA (Non-Operating Room Anesthesia) procedures have been steadily rising over the past decade. In 2010, NORA cases constituted 28.3% of cases in the United States. By 2014, the percentage of cases being performed outside of the operating room had risen to 35.9% [1]. Anecdotally, today over half of all cases are considered NORA cases. It is the responsibility of the anesthesia team to provide safe and efficient anesthetic care in the often-remote settings of endoscopy, electrophysiology, radiology, interventional pulmonology, radiation oncology or electroconvulsive therapy suites. The opportunity to provide anesthesia in these NORA settings comes with a unique set of procedures, challenges, anesthetic implications, and risks for which creative problem solving is necessary.

J. A. Spiro · T. J. Hatzidais · D. Ayubcha · M. S. Weiss (✉)
Department of Anesthesiology and Critical Care, University of Pennsylvania, Philadelphia, PA, USA
e-mail: Joshua.Spiro@pennmedicine.upenn.edu; Thomas.Hatzidais@pennmedicine.upenn.edu; Diana.Ayubcha@pennmedicine.upenn.edu; Mark.Weiss@pennmedicine.upenn.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_26

General Considerations of NORA

Three major factors are contributing to the rapid growth of NORA cases. The first contributing factor is an aging, higher acuity patient population with an ever-increasing expectation for the level of care. Concomitantly, increasingly innovative yet complex, minimally invasive procedures (e.g. percutaneous cardiac valve replacements or ventricular tachycardia ablations) are being performed. Finally, economic factors such as insurance bundling, cost control, bed occupancy, and long-term rehabilitation are incentives to create and implement these new, innovative therapies.

In the NORA suite, which may have been originally constructed prior to the advent of procedures requiring anesthetic involvement, one may find there is inadequate space for the anesthesia team as well as their necessary equipment. In addition, the proceduralists, whose specialty training represents a wide array of backgrounds from medical subspecialties, may not share the same vernacular, culture, and protocols that anesthesiologists are accustomed to in an operating room setting. Given the minimally invasive nature of many of these procedures, many patients, staff, and proceduralists may not completely understand the complexity of our care as well as the implications of an anesthetic. These aforementioned issues are often compounded by distance, whether from the patient (and their airway) such as during an MRI case or more generally from other supporting anesthesiologists. Thus, it is paramount to establish clear communication in this setting, and to properly relay plans and concerns to those involved with patient care.

An excellent tool to facilitate efficient and safe, yet high complexity care is the gathering of the patient team (anesthesia, procedural team, nursing staff) for a meeting before procedures start termed the “morning huddle.” During this huddle, the entire team has the opportunity to review each case, allowing each team member to share their concerns and in turn prepare for potential complications such as difficult airway issues, acquisition of necessary

equipment, complex transport, etc. This develops the habit of exchanging, rather than "siloing" information among the care team. The patients in the NORA suite can be quite ill, suffering from many co-morbidities; therefore, this huddle helps to establish protocols and guidelines to ensure that each patient receives care tailored to their specific needs. For example, items to review during this huddle could include the patient's preparation (NPO status), follow up on consultations, additional testing or coordination with another team i.e. the LVAD (left ventricular assist device) team. Having a morning huddle allows the care team to plan and, hopefully, use available resources more efficiently.

In theory, the team should review each patient twice during the day. The first review is in the aforementioned morning huddle (see Table 26.1), when all patients are assessed for special needs, equipment, airway concerns, etc. The second review is more patient centric and should take place at the "time out" immediately prior to the procedure start where issues of site, equipment, NPO status, appropriate lab results, and special needs are addressed. Position and rescue equipment availability are also reviewed each day. It is important to stress communication, coordination, and collaboration with every member of the NORA team. Reviewing patients prior to the procedural day is overall time and cost efficient as the preceding discussion of potential complications/complexities will allow for a better prepared team, and a more efficiently run day.

Due to their minimally invasive nature, many of the cases in NORA may be performed safely under monitored anesthesia care (MAC). However, when emergencies occur, NORA patients can be extremely difficult to manage without the same knowledgeable staff and resources typically found in the operating room setting. Earlier studies have identified an increased risk in patients receiving anesthesia in NORA locations as opposed to the operating room. However, more recent data from the National Anesthesia Clinical Outcomes Registry (NACOR) have demonstrated a lower rate of complications, morbidity, and mortality in NORA locations overall [2]. Cardiology and radiology subgroups did demon-

Table 26.1 An example of a standardized patient list to efficiently communicate anesthetic and procedural concerns

Daily GI log (aspiration risk and airway selection)					
Date:	AM Case review (time-out) Y N		Videoscope in room Y N		
Patient MRN	Procedure		Yes	Special considerations	
	EGD	Aspiration risk discussion			
		Head of bed elevated			
	POEM ERCP	hCG/coag status OK?			
MAC GA					
	EGD	Aspiration risk discussion			
		Head of bed elevated			
	POEM ERCP	hCG/coag status OK?			
MAC GA					
	EGC	Aspiration risk discussion			
		Head of bed elevated			
	POEM ERCP	hCG/coag status OK?			
MAC GA					
	EGD	Aspiration risk discussion			
		Head of bed elevated			
	POEM ERCP	hCG/coag status OK?			
MAC GA					
	EGD	Aspiration risk discussion			
		Head of bed elevated			
	POEM ERCP	hCG/coag status OK?			
MAC GA					

MRN, medical record number; *EGD*, esophagogastroduodenoscopy; *MAC*, monitored anesthesia care; *GA*, general anesthesia; *POEM*, peroral endoscopic myotomy; *ERCP*, endoscopic retrograde cholangiopancreatography

strate a higher level of mortality than both the operating room and other NORA delivery sites. Evidence from the anesthesia closed claims database has demonstrated that while there generally appears to be a lower overall number of malpractice claims in NORA compared with OR settings, there is a higher proportion of claims for death in NORA when compared to the operating room [3]. The single most prevalent factor for a poor outcome in the NORA suite was found to be inadequate monitoring. Independent of location, the anesthesia team must always perform standard ASA monitoring as well as have additional equipment/medications available in the event of an emergency.

Gastroenterology (GI) Endoscopy

GI endoscopy involves the placement of an endoscope either through the oropharynx (esophagogastroduodenoscopy or EGD, endoscopic retrograde cholangiopancreatography or ERCP) or through the anus (colonoscopy or sigmoidoscopy) to evaluate for gastrointestinal tract bleeding, cancer, biliary pathology, or inflammatory bowel disease. Endoscopic procedures are either diagnostic or therapeutic. These cases are typically brief (5–45 min), resulting in a quick turnover rate, allowing for a high number of cases to be performed per room each day. These procedures will often have a dynamic range of stimulation intensity requiring careful planning, monitoring, and vigilance to minimize patient awareness and reaction to stimulation. Adequate anesthetic depth is necessary to blunt coughing, gagging, and laryngospasm reflexes during certain portions of the case.

Many purely diagnostic procedures may be performed with minimal to no sedation; however, deep sedation or general anesthesia with a secured airway may be required for others. There are several ways to maintain the patient's airway in the GI suite ranging from spontaneous ventilation, to specialized laryngeal mask airways (LMA) with central openings to allow for simultaneous use of the gastroscope, to endotracheal tube intubation (ETT). Some indications to proceed with general anesthesia with ETT would include complex procedures, patients at higher risk for

aspiration, emergencies, ASA class III/IV, and altered mental status, among other factors [4]. When the GI endoscope is placed trans-orally, the anesthesiologist will be unable to mask ventilate the patient to provide positive pressure ventilation or to intubate until the endoscope is entirely removed. Therefore, in cases of pathology with an increased risk of aspiration such as bowel obstruction, or in a patient that requires positive airway pressure ventilation, an endotracheal tube must be placed and secured prior to performing the procedure. If the risk for aspiration is high, a rapid sequence induction (RSI) should be considered when the endotracheal tube is placed to minimize the risk of gastrointestinal contents entering the lungs. (See Chap. 9 for description of RSI).

The depth of anesthesia and type of airway management are important decisions the anesthesia team will make. The highest proportion of NORA malpractice claims occurred in the GI suite with 89% of the claims occurring during MAC [3]. If a secured airway is not a necessity, then maintenance of spontaneous ventilation should be maintained using a higher FiO2 and ETCO2 monitoring (a standard of care based on the ASA monitoring standards) [5]. As anesthetic management may result in intermittent apnea or hypoventilation. Once the depth of anesthetic and type of airway has been determined, the anesthesiologist should then tailor their anesthetic with several goals in mind: amnesia, prompt emergence, and blunting of reflexes in response to stimulation.

It is important that the patient is properly positioned to prevent injury. These procedures are usually performed on an operating room table, but on occasion may be performed on a patient stretcher. Patients presenting for endoscopic procedures are typically positioned in left lateral decubitus for upper endoscopy and colonoscopy procedures, or prone for ERCP. Ensuring proper padding minimizes the risk of peripheral nerve damage. The patient's eyes are particularly vulnerable during an anesthetic which obliterates the corneal reflex; therefore, the eyes must also be protected, taped, and kept free from external pressure to minimize the risk of eye injuries such as corneal abrasions and ischemic optic neuropathy.

Prior to an upper endoscopy, a "bite block" is often placed in the patient's mouth by the nursing sta. This plastic ring is inserted into the mouth and over the teeth to protect both the patient's dentition as well as the endoscope. It is imperative to ensure that the patient's lips are free from pressure to avoid trauma. It is also prudent to wait until the patient is completely awake to remove the bite block to avoid any potential damage to the patient's teeth.

Topical local anesthetics may be applied to the pharynx for insertion of the endoscope. Intravenous propofol is often used during endoscopies due to easy titration, smooth emergence, and decreased postoperative nausea and vomiting. Other common intravenous medications include benzodiazepines either alone or with an opioid such as fentanyl. Ketamine has also been used during endoscopies for its analgesic properties and minimal respiratory depression; however, this drug is associated with increased secretions that may interfere with the proceduralist's view during the procedure. When general anesthesia with an endotracheal tube is required, a volatile anesthetic or total intravenous anesthetic (TIVA) are appropriate choices for a maintenance agent. Other important anesthetic considerations during GI procedures include the potential for relative hypovolemia and electrolyte abnormalities due to bowel preparations, and, in extreme circumstances, the potential for bowel perforation from indelicate use of the gastroscope.

The management of the shared airway is a challenge in the GI suite; therefore, many institutions develop protocols for the management of the airway (see Table 26.2). Factors such as Body Mass Index (BMI), time of day, hemodynamics, airway comorbidities, positioning, and NPO status may be included in the decision process when determining whether or not one should secure the patient's airway with an endotracheal tube. Also, as noted throughout this chapter, it is often helpful to discuss with the GI team directly, as they may offer insight if they already have a rapport with the patient. This additional information, such as a prior aspiration, or delayed gastric emptying, would potentially influence your management of the patient.

Table 26.2 An example of intubation guidelines for ERCP. If total score from all categories is over 4, or if the patient is known to have a FULL STOMACH or a Gastric Outlet Obstruction should warrant strong consideration for endotracheal intubation. If uncertain of GI status, consult with GI attending. There is no substitution, however, for the thoughtful evaluation and judgement of the anesthesia team

ERCP intubation guidelines			
	0 Points	1 Points	2 Points
BMI	<25	25–35	>35
Time	Elective	Urgent/After 5:30 PM/ Weekends	
GI status	NPO/No GERD	GERD/H/o aspiration/NG/ GI Bleed	
Hemodynamic status	Stable	Unstable	
Airway	Mallampati = 2	Mallampati ≥ 3	
Total score = ___			

Electrophysiology Lab (EP)

Electrophysiologists perform a wide variety of procedures including pacemaker placement, external cardioversion, internal defibrillator placement, and arrhythmia ablation. By definition, patients in the EP Lab have underlying cardiac disease which may include severe heart failure, coronary artery disease, and hemodynamically unstable arrhythmias. Bulky equipment, such as imaging devices (C-arm), large magnets, and monitors, often interfere with access to the patient's airway and intravenous catheterization sites (see Fig. 26.1) Because many of the interventions during the procedure that the interventional cardiologist performs may have profound hemodynamic effects with anesthetic implications, an arterial catheter is often an important and necessary tool in the EP lab to measure beat-to-beat blood pressure variation as well as enable access to draw blood for frequent lab measurements. The cardiologist will often require specific hemodynamic and anesthetic parameters during an EP procedure. Therefore, clear, real-

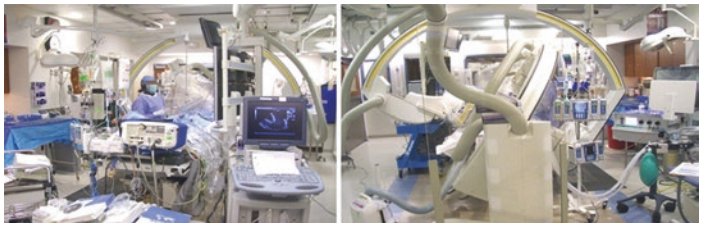


Fig. 26.1 View of electrophysiology suite from the control room (left) and from the anesthesiologist's work area (right). Note access to the airway is markedly restricted by the C-Arm at the head of bed

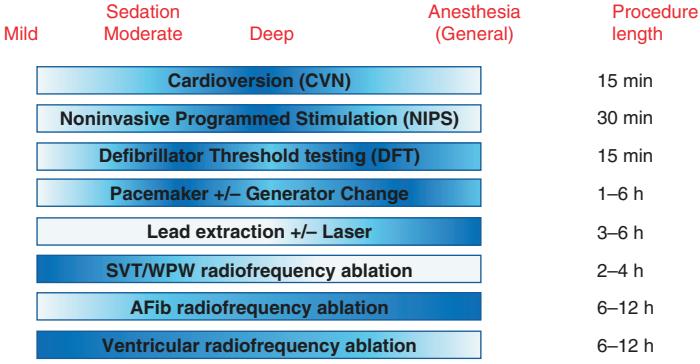


Fig. 26.2 Electrophysiology procedures, depth of anesthetic required, and length of procedure

time communication between the cardiologists, the anesthesia team, and the nursing staff is of the utmost importance as some anesthetic medications may interfere with the ability to generate aberrant cardiac foci. Due to the distance between providers, headphones with microphones can be used to facilitate communication.

Electrophysiologic procedures have a wide range of duration (See Fig. 26.2) from several minutes to several hours. For example, an external cardioversion will usually last less than 15 min; radiofrequency ablations for atrial fibrillation can last up to 12 h (or longer) as the chambers are carefully mapped and arrhythmo-

genic foci are ablated with the aid of fluoroscopy. As with many NORA sites, a wide range of anesthetics is compatible with anesthesia for EP procedures, but the type of procedure may also dictate the type or level of anesthetic required. Some of the longer procedures may be performed under MAC or general anesthesia. Conversion to general anesthesia may need to be performed emergently; therefore, one must carefully prepare for any emergencies prior to the case start given the suboptimal patient positioning in the procedural suite. As part of preparation for such emergencies, access to a video laryngoscope is highly recommended in the EP lab. This allows one the ability to access and manipulate the patient's airway as well as decrease trauma that may occur during intubation, which may be exaggerated in a patient who is anticoagulated for the procedure.

When general anesthesia is required, a variety of different induction medications may be utilized on patients with preserved ejection fraction. For patients with a normal ejection fraction, propofol may often be used safely, whereas for those patients with a low ejection fraction, etomidate may be more appropriate. For cases such as electrical cardioversion, these induction medications may be all that is required for the few minutes of brief general anesthesia. For maintenance of general anesthesia, volatile anesthetics or TIVA may be used for longer cases. For patients who require atrial fibrillation ablation/pulmonary vein isolation for atrial fibrillation, high frequency jet ventilation (HFJV) may be utilized. High frequency jet ventilation is a type of mechanical ventilation which utilizes a high respiratory rate (often around 100) and very small tidal volumes to minimize movement of the heart and lungs allowing for more accurate ablation during atrial fibrillation procedures. With HFJV, the ability to accurately monitor end tidal capnography and volatile anesthetic levels become unreliable. It is then necessary to use TIVA with endotracheal intubation for anesthetic maintenance. The use of non-depolarizing muscle relaxants is typically avoided in an effort to assess for phrenic nerve injury. To monitor ETCO2, an alternative means of carbon dioxide sampling (arterial catheter or transcutaneous capnography) is utilized. A Bispectal Index (BIS) may be used as an additional means of determining proper anesthetic depth.

Electrophysiology procedures require the utmost vigilance to anticipate and respond to rapid hemodynamic variation during these cases. Electrophysiologists' interventions such as induction of arrhythmias or use of chronotropic agents (I.e. isoproterenol) necessitate an arterial line to monitor acute blood pressure fluctuations and draw arterial blood gases. The use of ablation catheters may also induce injuries such as cardiac tamponade or esophageal perforation requiring emergent cardiothoracic surgery involvement. Esophageal perforation from atrial ablation may be avoided by careful monitoring with an esophageal temperature probe [6].

Diagnostic Radiology

During diagnostic radiology, the anesthesia team may be required to care for patients who need magnetic resonance imaging (MRI) or computed tomography scans (CT). In the adult setting, anesthesiologists may on occasion be required to care for patients with claustrophobia or altered mental status who are unable to lay motionless during imaging. However, in the pediatric population, anesthesiologists are required much more frequently. A recent study by Uffman demonstrated that anesthesiologists were required for 28% of pediatric MRIs in 2014 [7]. Issues the anesthesiology team may encounter when working in this location include the use of specialized equipment, exposure to radiation, and physical barriers between the anesthesia care team and the patient.

MRI utilizes a strong static magnetic field and second pulsed radiofrequency field to create an image. If metallic equipment is brought near an MRI with the magnet on, it can quickly become a ballistic projectile resulting in patient, staff, or equipment harm. Equipment such as the pulse oximeter or looped EKG cables may cause radio frequency burns due to excessive heat deposition. Therefore, special MRI safe versions of anesthetic equipment are required such as anesthesia machines, extra-long IV extension tubing or even wireless monitoring. The anesthetic requirements for a patient must be discussed with the radiology team well in

advance of the procedure to ensure access to necessary equipment. Planning for emergencies prior to the procedure is critical as the anesthesia team are often required to stay outside of the MRI suite. For patients undergoing MAC during the MRI scan, one should have a clear airway rescue plan. Other emergencies, such as cardiac arrest, require the immediate removal of the patient from the MRI scanner, in order to perform advanced cardiovascular life support (ACLS). Preparation of emergency rescue equipment and resuscitative drugs is absolutely necessary in such locations. To avoid respiratory depression, an anesthesiologist should also be aware of alternative methods of anxiolysis in their armamentarium such as swaddling and feeding in pediatric patients [8].

X-Rays and computed tomography scans (CT) utilize ionizing radiation to image the body. X-ray or fluoroscopy may be used in many other NORA locations including endoscopy (during ERCP), electrophysiology, or interventional pulmonology. Ionizing radiation presents an occupational hazard to anesthesiologists as accumulated radiation exposure may result in damage to the human body particularly the corneas, thyroid, and gonads. Therefore, lead aprons and glasses should be used to block the harmful effects of radiation, and radiation exposure badges must be worn. Just as with MRI, the anesthesia team usually stays in the control room while a CT scan is taking place, but there are instances where the anesthesia team is needed to provide direct care for a patient during imaging.

Neuro-interventional (NIR) and Interventional Radiology (IR)

Both diagnostic and therapeutic procedures are performed in neuro-interventional radiology (NIR). Cerebral angiography and angioplasty, aneurysm coiling, preoperative embolization of vessels feeding intracranial lesions, and kyphoplasty for pain related to spinal compression fractures are among the procedures done in the NIR suite. Many of these procedures are in delicate areas of the brain or in cerebral arteries, and therefore patients must remain

still and cooperative for the procedure. For diagnostic procedures such as cerebral angiography, patient participation is often required; therefore, a titratable MAC is favored with either a low dose propofol infusion or some combination of midazolam and fentanyl. When possible, tailor the anesthetic plan to the needs of both patient and proceduralist. For instance, a patient with severe sciatica who may not be able to lay motionless and supine for an extended period of time without experiencing severe pain. In this scenario, a general anesthetic should be chosen over a MAC. These procedures generally are most stimulating at the onset when vascular access is obtained through either the femoral or radial arteries. When this stimulation occurs, the patient may be treated with a combination of local anesthetic infiltration and deepening of anesthetic. As with anesthetics performed in the MRI and CT scanner, the anesthesia team must be prepared for conversion to general anesthesia in case of emergency (e.g. aneurysm rupture).

For procedures involving intervention on cerebral vessels such embolectomy for ischemic stroke or coiling of aneurysms, general endotracheal anesthesia is often preferred to ensure that the patient remains motionless, and hemodynamics are tightly controlled. Choice of induction strategy should be catered to the specific patient and pathophysiology under management. Usually, an amnestic dose of volatile anesthetic with maintenance of muscle relaxation is appropriate. An arterial line is often placed to enable the careful monitoring necessary to ensure control of hemodynamic variability within a prespecified range, depending on the patient's pre-procedure blood pressure and the pathology at hand. Vasopressors and vasodilators such as phenylephrine and nicardipine, respectively, should be readily available. The decision to extubate the patient at the end of the procedure depends on their pre-procedure neurologic exam as well as successful intervention of the patient's pathology.

A variety of other procedures may be performed in musculoskeletal/body interventional radiology, such as embolization of arterial vessels for gastrointestinal bleeding/postpartum hemorrhage or vertebral augmentation. Many of these cases can be performed either with local anesthetic at the site of access or with MAC. Regardless of the procedure, planning ahead for emergen-

cies that may arise becomes even more important as these facilities may be both isolated as well as unfamiliar with anesthetic issues as they arise.

Many cases in the radiology suite may be performed in non-traditional positions. Prone or lateral positioning may require more than just additional attention to the airway, but also proper padding of the limbs, genitalia, and eyes in order to minimize risk of nerve injury. Tape, foam cushioning, blankets, and protective eyewear are some of the tools necessary to ensure safe positioning of such patients. The patient should be reevaluated as necessary with each movement into and out of the scanner as frequent movement may lead to repositioning, resulting in trauma of the limbs, digits, or other parts of the body.

Interventional Pulmonology

Interventional pulmonologists perform procedures utilizing both flexible and rigid bronchoscopy. The most common procedures include bronchoalveolar lavage, airway stenting, and endobronchial ultrasound (EBUS) for biopsy to diagnose conditions such as cancer, infection, or pulmonary fibrosis. Such patient pathology may affect not only the ability of the patient to maintain oxygenation, but also the patient's lung compliance requiring increased airway pressure to ventilate the lung. Airway mass lesions may cause central airway obstruction (CAO) of the trachea or bronchi resulting in difficulty with ventilation. In certain cases, keeping patients breathing spontaneously is necessary to avoid collapsing the airway with introduction of positive airway pressure. When the rigid bronchoscopy is used, the large diameter of the instrument facilitates suctioning of blood/clot, removal of foreign bodies, or coring out tumors.

For cases utilizing flexible bronchoscopy, general anesthesia is often required with placement of an endotracheal tube or supraglottic airway. These procedures necessitate a shared airway in which the pulmonologist places a fiberoptic scope through the airway device. Blunting of airway reflexes becomes very impor-

Table 26.3 Therapies for resolving laryngospasm and bronchospasm

Therapy for laryngospasm	Therapy for bronchospasm
Larson Maneuver	Bronchodilator (i.e., albuterol)
Positive pressure mask ventilation	Increased positive pressure
Deepening anesthetic (Propofol bolus)	Deepening anesthetic
Small dose of muscle relaxant	Epinephrine

tant as instrumentation may lead to bronchospasm or laryngospasm which can be overcome by several maneuvers (See Table 26.3) The Interventional Pulmonologist may also use a topical local anesthetic to block the upper airway reflexes and utilize the fiberoptic bronchoscope to stent open the vocal cords if they are in partial spasm. The shared airway may cause air and volatile anesthetic to leak around the devices or be suctioned out which makes TIVA the ideal choice for maintenance of anesthesia. Pulmonology procedures often do not have the process of closing various layers of tissue seen in operative cases; therefore, there may be little warning to titrate down anesthetics prior to the end of a procedure. As at any site within the NORA bloc, the importance of clear, real-time communication between the anesthesia team, the proceduralist, and the support staff cannot be overstated. Propofol and remifentanil are ideal choices for maintenance of anesthesia as this combination allows for both akinesia and a quick emergence. When rigid bronchoscopy is performed, extreme immobility/paralysis is necessary to avoid movement; therefore, neuromuscular blockade is indicated.

Electroconvulsive Therapy (ECT)

Electroconvulsive therapy is performed by attaching electrodes to the scalp to pass a current through the brain. This is typically performed for cases of refractory depression, mania, catatonia, and affective disorder. It may also be indicated in cases of neuroleptic malignant syndrome, status epilepticus, and Parkinson's disease. Contraindications to ECT include increased intracranial pressure,

pheochromocytoma, coronary artery disease, arrhythmia, cerebrovascular accident, space occupying lesion or severe pulmonary disease. The current passed will cause a brief seizure which, in an unsedated, unparalyzed patient, will cause significant pain and convulsions and potentially result in fractures. Therefore, an anesthesia team is required to ensure both safety and tolerability of the procedure.

To prepare for ECT, the first step is to preoxygenate the patient, followed by the placement of soft bite block. Induction of the patient is usually accomplished with medication such as propofol, methohexital, or etomidate and succinylcholine (to preclude violent convulsions and assist mask ventilation). Once activated, the current from electroconvulsive therapy will often initially produce a parasympathetic response causing bradycardia and salivation, followed by a sympathetic response with tachycardia and hypertension. Patients are often pretreated with glycopyrrolate as prophylaxis for the initial bradycardia. The subsequent tachycardia may be treated with esmolol, and hypertension may be treated with short-acting antihypertensives such as labetalol or hydralazine. Patients require mask ventilation throughout the procedure until they regain consciousness, and hyperventilation is more conducive to achieving adequate therapy. Those at risk for aspiration such as pregnant patients may require endotracheal tube placement. Though patients may be anxious prior to the procedure, benzodiazepines are contraindicated for the procedure due to their anticonvulsant properties [9]. Many other anesthetic medications can have different effects on seizure activity; therefore, it is important to be familiar which medications have proconvulsant vs anticonvulsant properties (see Table 26.4).

Table 26.4 Common anesthetic medications and effect on seizures

Proconvulsant medications	Anticonvulsant medications
Etomidate	Propofol (at high doses)
Ketamine (at low doses)	Ketamine (at high doses)
Opioids	Benzodiazepines
Methohexital	

Case Study

A 65-year-old female with past medical history significant for severe lower back pain radiating into her legs bilaterally presents for magnetic resonance imaging (MRI) of the lumbar spine. The patient has a history of chronic, long-term lower back pain requiring oxycodone 15 mg four times per day. Patient co-morbidities include congestive heart failure (CHF) with a reduced ejection fraction (45%) secondary to ischemic cardiomyopathy, atrial fibrillation status post permanent pacemaker placement, and a history of COPD. An MRI was attempted a week prior; however, due to the patient's severe claustrophobia she was unable to tolerate the procedure despite midazolam administration. You are asked to provide anesthesia for the imaging so that the patient may tolerate the procedure.

What pre-procedure preparation will you perform to ensure a safe anesthetic for the patient?

The American Society of Anesthesiologists (ASA) has mandated that the standards of care in the NORA suite are the same as any other anesthetizing site [6]. You should prepare for the case just as you would for a case in the operating room including but not limited to: an equipment check, ensuring access to extra help, a working anesthesia machine, suction, airway equipment, intravenous supplies, and emergency drugs. When speaking with the patient, perform a full history and physical exam. You should communicate with the radiology team to identify the length of the imaging and logistics of performing anesthesia in the MRI suite. By speaking with the patient's cardiologist, you can identify how to place the patient's pacemaker in an MRI safe setting. Finally, you should ensure that your anesthesia colleagues know that you will be in MRI should you need an extra set of hands in an emergency.

What are the advantages of doing the case under general anesthesia versus monitored anesthesia care (MAC) for this patient in the MRI suite?

Under general anesthesia the patient would have a protected airway; therefore, the risk of having to move the patient out of the MRI to emergently intubate would be avoided. Additionally, under general anesthesia the patient would be able to stay motionless ensuring the best quality imaging. The use of monitored anesthesia care may avoid the hemodynamic instability of induction of anesthesia in a patient with ischemic cardiomyopathy. When performing an anesthetic that requires repeated medication boluses, one must be careful to account for the length of dead space in the long intravenous tubing required to get from the patient inside the MRI to outside of the MRI suite where it is injected. In this patient with heart failure, repeated boluses of medication would also result in a high volume of crystalloid being infused into the patient.

The patient adamantly opposes having general anesthesia for the MRI and wants to do the case under MAC. You decide to use a propofol infusion with a non-rebreather. What monitors will you use for this patient?

The ASA standard monitors should be utilized for any patient undergoing anesthesia. Therefore, this patient will require pulse oximetry, blood pressure, electrocardiogram, and capnography. However, these may need to be modified for the task at hand. MRI safe pulse oximeters and electrocardiogram cables should be used, and careful attention should be made to ensuring that the EKG cables are not forming loops which could cause burns if in contact with the skin.

The patient tolerates the MRI for 30 min, but then starts thrashing around in the machine saying she cannot stand it any longer. You reassure the patient and bolus some propofol to help her tolerate the procedure; however, she goes apneic and does not resume spontaneous ventilation. What steps do you take to rescue the patient?

When an emergency occurs in a remote location, the first step should be to call for help as soon as possible. The more

remote, the more difficult it will be for others to find you and help rescue the patient. The next step is to remove the patient from the MRI scanner so that you can access her airway and resuscitate her as needed. As with any MAC case it is important to have arranged for emergency induction and intubation prior to the beginning of any procedure.

As the technicians remove the patient from the scanner, it is apparent that she is now hypoxemic and getting progressively more bradycardic. Cardiovascular compromise seems imminent. How do you proceed with resuscitation?

Immediately assign someone to start chest compressions and ask another staff member to bring a gurney to transfer the patient outside of the MRI suite. Once the gurney is ready, the patient should be transferred out of the MRI suite as quickly as possible so that advanced cardiac life support may be initiated with the emergency response team.

References

1. Nagrebetsky A, Gabriel RA, Dutton RP, Urman RD (2017) Growth of nonoperating room anesthesia care in the United States: a contemporary trends analysis. Anesth Analg 124(4):1261–1267
2. Chang B, Kaye AD, Diaz JH, Westlake B, Dutton RP, Urman RD (2018) Interventional procedures outside of the operating room: results from the National Anesthesia Clinical Outcomes Registry. J Patient Saf 14(1):9–16
3. Woodward ZG, Urman RD, Domino KB (2017) Safety of non-operating room anesthesia: a closed claims update. Anesthesiol Clin 35(4):569–581
4. Sekar B (2016) Non-operating room anesthesia in the endoscopy unit. Gastrointest Endosc Clin N Am 26(3):471–483
5. American Society of Anesthesiologists. Standards for basic anesthetic monitoring. https://www.asahq.org/~/media/Sites/ASAHQ/Files/Public/Resources/standards-guidelines/standards-for-basic-anesthetic-monitoring.pdf. Accessed on 23 June 2020.
6. Liu E, Shehata M, Liu T, Amorn A, Cingolani E, Kannarkat V et al (2012) Prevention of esophageal thermal injury during radiofrequency ablation for atrial fibrillation. J Interv Card Electrophysiol 35(1):35–44

7. Uffman JC, Tumin D, Raman V, Thung A, Adler B, Tobias JD (2017) MRI utilization and the associated use of sedation and anesthesia in a pediatric ACO. J Am Coll Radiol 14(7):924–930
8. Antonov NK, Ruzal-Shapiro CB, Morel KD, Millar WS, Kashyap S, Lauren CT et al (2017) Feed and wrap MRI technique in infants. Clin Pediatr (Phila) 56(12):1095–1103
9. Stripp TK, Jorgensen MB, Olsen NV (2018) Anaesthesia for electroconvulsive therapy – new tricks for old drugs: a systematic review. Acta Neuropsychiatr 30(2):61–69

Orthopedic Surgery

27

Eric R. Sloan and Jesse M. Ehrenfeld

Introduction

Orthopedic procedures challenge the anesthesiologist. The Center for Disease Control and Prevention report that orthopedic surgeries currently account for a significant portion of the 48 million inpatient surgeries performed annually in the United States. This chapter focuses on the types of orthopedic procedures and the perioperative concerns which confront the anesthesiologist. Patients of all ages can present with a multitude of comorbidities and anesthetic concerns. How should we safely anesthetize these patients? Is general anesthesia indicated? Can we safely perform a spinal anesthetic? Are there contraindications to spinal anesthesia? The use of bone cement, methyl methacrylate can cause a syndrome that includes hypoxemia, hypotension and arrhythmias. Patients are at increased risk of thromboembolism following pel-

E. R. Sloan (✉)
Department of Anesthesiology, Rush Medical College, Chicago, IL, USA
e-mail: Eric_Sloan@rush.edu

J. M. Ehrenfeld
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: jehrenfeld@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_27

vic, hip, and leg surgeries. Tourniquets creating a bloodless field can cause an accumulation of acid metabolites which may lead to hemodynamic changes, pain, and thromboembolism. Fat embolism syndrome presents within 72 hours following long bone or pelvic fractures with dyspnea, confusion, and petechiae. Orthopedic procedures are fraught with potential problems and concerns. The anesthesiologist must be aware and react to these issues in a proactive manner.

Choice of Anesthetic

Approximately 1.6 million hip fractures are encountered worldwide with increasing numbers due to the aging population. There is a high morbidity/mortality with fixation of these fractures. Approximately 5% die during hospitalization and 10% die within 30 days because of pulmonary and cardiovascular complications. Interestingly, few interventions exist to reduce mortality after surgical correction. The safest technique for hip fractures in the elderly remains a controversial issue in the literature [1]. Neuraxial techniques reduce the incidence of deep vein thrombosis, surgical site infection, pulmonary complications and blood loss. Conversely, general anesthesia has lower incidence of hypotension and CVA. Several studies suggest that there is no significant difference in mortality in either technique. Currently, no consensus exists as to which is the best method of anesthesia employed in the fixation of hip fractures. Therefore, the choice of anesthesia is based on patient preference, morbidities and procedure-specific considerations.

Upper Extremity

Orthopedic procedures of the upper extremities i.e., shoulder and arm may be performed under regional, general anesthesia or both. A combination of general and regional anesthesia is often selected

because of limited access to the patient's airway during the procedure. These surgeries are typically performed in the "beach chair "(see Fig. 27.1) position particularly if the shoulder is being operated on. The hips and knees are flexed as well as a 10–20-degree reverse Trendelenburg position to promote venous return. Hypotension may occur assuming this position. Blood pressure should be measured at the head and not at right atrial level. Blood pressure at the head level in patients having surgery in the sitting or beach chair position may become insufficient for adequate cerebral perfusion. There is a 2 mmHg difference in measured pressure for every inch change in height. The patient is shifted laterally to the edge of the operating table. The head must be appropriately supported to avoid stretch injuries to the brachial plexus.

A combination of regional and general anesthesia is typically utilized. As mentioned earlier, general anesthesia is chosen

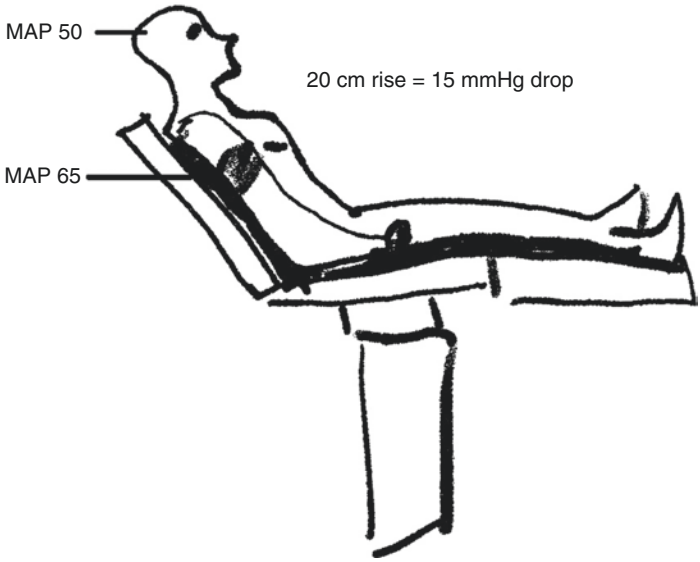


Fig. 27.1 Beach Chair position. (Image Courtesy J. Ehrenfeld)

because of limited access to the patient's airway. Either an endotracheal tube or supraglottic airway may be used. An interscalene block is performed preoperatively using an ultrasound guided technique. Interscalene block refers to the placement of local anesthetic around the roots or trunks of the brachial plexus at the level of the C3 vertebral body between the anterior and middle scalene muscles. The brachial plexus at the interscalene level is seen lateral to the carotid artery and internal jugular vein. This block will provide excellent surgical anesthesia and postoperative analgesia. Ropivacaine and bupivacaine are the two local anesthetics commonly used because of their long duration of action. With the combination of regional and general anesthesia, the amount of inhalational agents and opioids required is reduced because the regional technique provides analgesia in the operative extremity. This may offer a considerable advantage to the patient. Interscalene blocks should be performed with caution in patients with severe pulmonary disease. This is because of ipsilateral diaphragmatic paresis and loss of pulmonary function caused by the block.

Hip Surgery

Total hip replacement and fractures of the hip are very common procedures especially with an aging population. Neuraxial blocks are the techniques of choice. Either combined spinal/epidural, epidural, or spinal with sedation are preferred. There have been many studies indicating that neuraxial blocks are associated with better outcomes, i.e., reduced blood loss, deep vein thrombosis, pulmonary embolism, and mortality. The data seems to indicate that there is decreased blood loss when a regional technique is employed. The other potential benefits are to be determined. Additionally, postoperative cognitive impairment with general anesthesia is a legitimate concern considering the patient population for total joint replacement is older. Regardless of the anesthetic, strict attention must be made to fluid optimization and

blood loss. As mentioned earlier, regional anesthesia reduces blood loss. Maximal allowable blood loss should be calculated and based on the patient's comorbidities a safe hemoglobin should be determined.

Neuraxial anesthesia may be performed in either the lateral or sitting position. Hyperbaric or isobaric local anesthetics are selected based on the duration of the procedure. Isobaric local anesthetics will provide longer block duration. Baricity influences the distribution of local anesthetic solution in CSF. Baricity effects local anesthetic spread and block height since gravity causes hyperbaric solutions to flow downward in the CSF. Gravity has no effect on isobaric solutions. Adequate hydration must be achieved prior to the implementation of the block. Neuraxial anesthesia will cause a sympathetic blockade and subsequent hypotension. Spinal morphine (Duramorph) can be added to the local anesthetic to provide excellent postoperative analgesia. As with all opioids, pruritis, urinary retention, and respiratory depression are potential sequelae.

Hip fractures are another common procedure in orthopedics (see Fig. 27.2). Unfortunately, the geriatric population are commonly impacted by this traumatic injury. Dementia combined with osteoporosis are two main factors that cause hip fractures. Hip fractures are a significant cause of morbidity and mortality in the elderly patients. There is a significant amount of blood loss and large drop in hemoglobin associated with the initial trauma rather than the operation. Even with surgery, the incidence of postoperative complications is high with a 1-year mortality estimated to be 30%. Both general and neuraxial techniques can be used and there are proponents of both techniques. For example, a case report of a 105 year old patient was presented with a femoral neck fracture. Successful spinal anesthesia was performed with 12.5 mg of bupivacaine. In many geriatric patients, respiratory difficulty associated with decrease lung capacity, postoperative atelectasis, and potential aspiration makes general anesthesia risky.

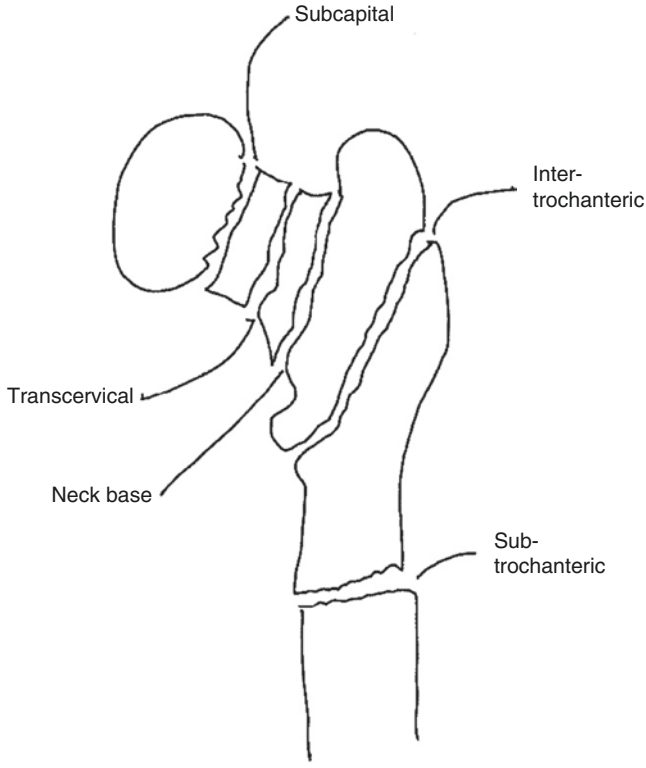


Fig. 27.2 Hip fracture locations. (Image Courtesy J. Ehrenfeld)

Knee Surgery

More than 300,000 total knee replacements are performed annually in the United States. Patients undergoing total knee arthroplasty (TKA) experience significant post-operative pain. Failure to provide adequate analgesia impedes post op physical therapy and rehabilitation. Similar considerations are followed as with total hip replacements. The only real difference is that a thigh tourniquet is used to create a bloodless field. Tourniquet pain may be of concern to the anesthesiologist particularly after

prolonged usage. General anesthesia combined with an adductor canal block is a common technique. However, spinal anesthesia with an adductor canal block is the anesthetic of choice. The adductor canal or more precisely the saphenous nerve block in the adductor canal is a single shot or continuous catheter technique for analgesia of the knee and medial leg (see Fig. 27.2). This block is performed with ultrasound as well. The transducer is positioned transverse on the anteromedial thigh at the junction between the middle and distal third of the thigh below the knee at the level of the tibial tuberosity. Local anesthetic is injected lateral to the femoral artery and deep to the sartorius muscle. The adductor canal block provides less motor blockade which is why it is a very popular block. Some institutions will not perform an adductor canal block but will add Duramorph to the spinal. This provides excellent postoperative analgesia as well.

Ankle and Foot Surgery

Innervation of the foot is provided by the femoral and sciatic nerve. Spinal anesthesia and peripheral nerve blocks at the upper leg, knee or ankle are appropriated regional techniques. Tourniquets are typically used for foot and ankle surgery. As with knee surgery, one must be aware of tourniquet related issues.

Postoperative Analgesia

Pain following orthopedic surgery can be severe and a well-developed perioperative pain plan is critical in the successful management of these patients. Neuraxial anesthesia and peripheral nerve blocks with or without catheters can be successfully used. Opioids are the still the mainstay of postoperative analgesia however with the opioid crisis multimodal analgesia is much more prevalent. Opioids are often supplemented with nonsteroidal anti-inflammatory medicines such as Ibuprofen and Ketorolac,

acetaminophen, steroids, and anticonvulsants (gabapentin). Preemptive analgesia has shown to be of benefit to orthopedic patients.

Orthopedic Trauma

Traumatic orthopedic injuries can present with minor isolated wounds or complex injuries involving multiple organ systems that require emergent surgery and resuscitative efforts. Unstable patients with severe trauma may be treated according to damage control protocols, i.e., application of external fixation. Fractures that result in neurovascular compromise, vascular injury, or compartment syndrome require emergent surgery. Open fractures should be urgent and not considered emergent. It is important to go to surgery as soon as possible so that your open wound can be cleaned out to help prevent infection. Vascular injuries associated with open fractures should be addressed within 3–4 hours prevent ischemia. Typically, general anesthetics are performed due to the severity and length of procedure. However, an epidural or continuous spinal can be used because of the ability to redoes the catheter. Patients are all considered full stomach and rapid sequence inductions with cricoid pressure are done. Hemodynamic optimization with crystalloid, colloid and blood products are critical to the postoperative outcomes.

Special Considerations

Blood Loss

Blood loss estimation after trauma particularly long bone, pelvic and acetabulum fractures and early identification of the potential sources of bleeding are critical in the anesthetic management. Substantial volumes of blood loss that require transfusion therapy are very common. Frequently, arterial line monitoring is performed for persistent blood pressures as well as assessing hemoglobin levels, oxygenation and lactate levels.

Positioning Injuries

Orthopedic procedures frequently place patients in positions that could lead to nerve or musculoskeletal injury. Regardless of the position, it is important to pad all pressure points and ensure there is no undue stretch or compression on joints or neurological plexus (axillary rolls can avoid brachial plexus compression). There are five mechanisms for perioperative peripheral neuropathies, stretch, compression, ischemia, metabolic, and surgical section. Ulnar nerve injury is the most common followed by brachial plexus injury. Interesting, the mechanism for ulnar nerve injury is uncertain while external compression or excessive stretch may be indicated. Brachial plexus injury is usually from excessive abduction (greater than 90 degrees). Radial and median nerve injuries are rare. Lumbosacral nerves are usually injured from improper positioning such as with lithotomy.

Tourniquet Issues

As mentioned previously, tourniquets are used in many orthopedic procedures to decrease surgical blood loss. Two common problems are pain and reperfusion injury. Tourniquet pain commonly begins approximately 45 minutes after inflation and is frequently described as aching and burning and is associated with progressive hypertension. This resolves when the cuff is deflated. Prolonged cuff inflation is also associated with peripheral nerve injury. Reperfusion injury is due to the release of accumulated acid metabolites back to the central circulation following release. Tachycardia, a rise in serum potassium and carbon dioxide tension in blood can be seen.

Methyl Methacrylate Cement

Cement is used to bind prosthetics to bones. During cement mixing and insertion, the substance expands as it hardens, greatly increasing pressure in the affected bony cavity. A rise in intramed-

ullary pressure increases the risk of fat emboli syndrome. Drilling a hole in the distal end of the long bone can minimize this. As a result, solid cement, marrow, and fat globules can be forced into the vasculature resulting in micro emboli causing hypotension, hypoxemia, and tachycardia. In the older patient papulation these effects can be devastating. Fluids and vasopressors can be used to minimize these sequelae.

Fat Embolism

Fat embolism syndrome (FES) is associated with multiple traumatic injuries and surgery involving long bone fractures. Risk factors include male gender, hypovolemic shock, intramedullary instrumentation, rheumatoid arthritis, THA, and bilateral total knee arthroplasty. Mortality rate associated with this condition approaches 10 to 20%. Clinical signs are truncal petechiae, dyspnea/hypoxemia, mental status changes, and coma. Symptoms usually occur 12 to 40 hours after the injury. Disseminated intravascular coagulation can also occur. Treatment of FES requires early recognition, reversal of aggravating factors such as hypotension, early stabilization of fractures, and respiratory support.

Antithrombotic Prophylaxis

Patients undergoing major orthopedic surgeries are susceptible to thromboembolic phenomenon [2]. Thromboprophylaxis is based on identification of risk factors. Enoxaparin (Lovenox) and Warfarin (Coumadin) are commonly administered. The timing of these antithrombolytics are critical, particularly when neuraxial anesthesia is considered (Table 27.1).

In conclusion, as with all anesthetics whether general or regional, successful outcomes are based on a thorough knowledge of the patient ‘s comorbidities and implementing an anesthetic to address these concerns. Regardless of anesthetic choice, our goals and objectives are always the same. The anesthesiologist must perform the safest and most efficacious anesthetic for the patient.

Table 27.1 Anticoagulation Guidelines for Neuraxial Procedures

Anticoagulants	Minimum time last dose and spinal/epidural	Antithrombic agents with catheters
Warfarin (Coumadin)	INR < 1.5	Contraindicated
Heparin	PTT < 40 or 6 hours after last dose	Indwelling catheter OK
Enoxaparin (Lovenox) 1 mg/kg SQ BID	24 hours	Contraindicated
Enoxaparin (Lovenox) 40 mg SQ q D	12 hours	Contraindicated
Dabigatran (Pradaxa)	7 days	Contraindicated
Clopidogrel (Plavix)	7 days	Contraindicated

Case Study

92 year old male fell at the assisted living facilty sustaining a left intertrochanteric fracture. Past medical history is significant for chronic smoking, COPD, severe aortic stenosis, dementia, and thrombocytopenia. Pertinent labs are a hemoglobin of 8 gm/dl.

What are the anesthetic considerations with this traumatic injury and comorbidities?

Patient's age and dementia would be a relative contraindication for general anesthesia. Postoperative cognitive impairment is common in the elderly population. Morever, pulmonary issues may be of concern considering this patients chronic history of tobacco abuse. Spinal anesthesia would be an excellent choice and is not contraindicated because of the aortic stenosis. Maintaining preload, careful monitoring, and avoidance of hypotension are the primary goals of a safe anesthetic. A continuous spinal or epidural may allow for a safer initiation and titration of anesthesia than a single shot spinal. Fluid optimization and vasopressors are critical when dealing with preload concerns and decreased blood pressure from the spinal anesthetic.

How would you manage blood loss starting with a hemoglobin of 8gm/dl?

Because of the inherent risk associated with the surgery (high morbidity/mortality) and anesthesia, starting an arterial line would be indicated. Serial blood gases can guide blood and fluid replacement therapy . One must avoid hypotension in a patient with aortic stenosis. A drop in pressure could result in serious cardiovascular compromise. Because hemoglobin is a factor of arterial oxygen content we must optimize hemglobin to allow adequate oxygen perfusion to the tissues.

References

1. Onal O, Ozdemirkan A, Kutahya EC (2015) Our anesthesia experience with a 105-year-old geriatric patient. J Anesth Crit Care Open Access 2(3):00054
2. Barash P, Cullen B, Stoelting R (2006) Chapter 40: clinical Anesthesia. In: Anesthesia for orthopedic surgery

Trauma Surgery

28

Olga Kaslow

Introduction

Injuries and violence affect everyone, regardless of age, race, or economic status. This makes injury the leading cause of death among persons 1–44. Each year 214,000 people die from injury - 1 person every 3 minutes. Those who survive are faced with life-long mental, physical, and financial problems. The total costs of injuries and violence in the United States was $671 billion in 2013 [1].

Mechanism of Injury

Knowledge of what the trauma mechanism is allows one to predict the pattern and the severity of injury to the patient's skeleton, organs and vascular structures. The most common mechanisms are typically characterized as blunt, penetrating and blast. Motor

O. Kaslow (✉)
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: ozakharo@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_28

vehicle collisions and falls are the most common examples of blunt trauma. Gunshots and stab wounds represent penetrating trauma, and blast injuries frequently occur in the military combat.

In blunt trauma, the most common forces at work are compression and acceleration-deceleration. **Compression of the solid organs** (liver, spleen) against a fixed or moving object (e.g., steering wheel, baseball bat) causes crushing and bleeding. **Compression of the hollow organs** creates a rapid increase in an intraluminal pressure. This results in hollow organ rupture and subsequent peritoneal contamination. **Deceleration** generates shearing of the organ tissues between fixed and mobile structures. This causes liver and spleen lacerations at the site of their fixed ligaments, and damage to the mesentery and large vessels.

In penetrating trauma, the tissue damage depends on velocity of the missile object. **Stabbing has low velocity** which creates direct damage by lacerations. The most frequently injured organs are the liver, diaphragm, and small and large bowel. **Gunshots create high velocity wounds.** They cause damage by a combination of direct laceration by the missile and its fragments, cavitation effect within the organs along the missile track, and crushing from the blast injury. Solid organs like liver, spleen, and kidneys are frequently injured by the cavitation effect. Hollow organs (stomach, bowel, and bladder) are not affected by cavitation if empty, but may suffer considerable damage if they contain fluid.

Initial Patient Evaluation and Management

American College of Surgeons (ACS) created an organized system for treating trauma patients in the United States. It developed the Advanced Trauma Life Support (ATLS) course for physicians involved in trauma care. ATLS provides a script for initial assessment and resuscitation of trauma patient ensuring a smooth team-based approach [2].

ATLS prioritizes care during first 60 minute after trauma. This is known as the “golden hour” as the best outcomes are achieved with rapid diagnosis and intervention.

The primary survey identifies life threatening conditions, mainly hemorrhage and hypoxemia, and life-saving treatment is initiated immediately. It is conducted in a prescribed sequence known as "**A-B-C-D-E":**

A - Airway patency assessed and established. Oxygen applied, intubation performed(when necessary) with in-line C-spine immobilization
B - Breathing verified and optimized
C - Circulation assessment with hemorrhage control. Check for signs of shock: pallor, diaphoresis, altered mental status, hypotension, tachycardia, peripheral vasoconstriction. Placement a large bore IV and initiation of blood transfusion
D - Disability: evaluation of neurological status (Glasgow Coma Scale (GCS), significant visible injuries, musculoskeletal deformities
E - Exposure, with environmental control. Removal of patient's clothes, physical exam conducted

Initial resuscitation occurs concurrently with the primary survey. This includes placement of monitors (electrocardiogram (ECG) leads, pulse oximetry, blood pressure (BP) cuff), insertion of intravenous catheters (IVs), gastric and urethral catheters, drawing laboratory samples (labs). Diagnostic studies, radiographs and FAST exam (focused assessment with sonography for trauma) are performed. If the patient is unstable or in extremis, he or she should proceed to surgery.

If the patient is stable, **the secondary survey** should be performed. It includes:

- Meticulous head-to-toe examination. **All injuries, not immediately posing threat to life, are identified**
- Patient's **AMPLE** history is taken: **A**llergies, **M**edication, **P**ast illnesses/**P**regnancy, **L**ast meal, **E**vents related to injury
- Necessary diagnostic studies are performed

Hemorrhaging Shock

Shock is a life-threatening circulatory failure, causing inadequate oxygen delivery to meet cellular metabolic needs and requirements of oxygen consumption, thus producing cellular and tissue hypoxia. The effects of shock are initially reversible, but rapidly become irreversible, leading to multiorgan failure (MOF) and death.

Although shock may be caused by a variety of precipitating insults, in the setting of acute trauma it should be presumed to be hemorrhagic until proven otherwise [3, 4].

Pathophysiology of Hemorrhaging Shock

Acute blood loss initiates a systemic response: central sympathetic outflow is increased, and parasympathetic flow is decreased, resulting in increased in heart rate and contractility. Adrenal stimulation produces in the "fight or flight" response, with increased levels of circulating epinephrine.

Bleeding decreases filling pressures in the heart and lowers cardiac output. Low blood pressure, pain, and cortical perception of injury trigger vasoconstriction which, in turn, redirect blood flow from ischemia-tolerant tissues and organs (e.g., skin, muscle, gut) to organs dependent on a continuous oxygen supply, (e.g., the heart and the brain).

Hypovolemia and hypoperfusion eventually lead to cellular death and organ failure. Reperfusion of these tissues following reestablished blood flow, releases toxic metabolites and inflammatory mediators into the circulation.

Death from hemorrhagic shock occurs from one of the two causes:

1. Acute exsanguination soon after injury due to uncontrollable bleeding
2. Subacute death occurs when bleeding control is achieved, patient survived the surgery and resuscitation, but the cumulative burden of ischemia proves lethal: patient succumbs to multiple organ system failure days, weeks, or even months later

- Acute lung injury and pulmonary failure may be followed by acute renal failure, gut dysfunction, and immune system compromise, leading to sepsis

Life threatening bleeding can occur in one of five compartments:

- **Outside the body** - from open wounds. It is easy to diagnose and to manage by direct pressure and surgical ligation
- **Thighs** – bleeding from femur fractures is brisk at the time of injury, and normally resolves spontaneously through vasoconstriction and tamponade
- **Abdomen** – hemorrhage is diagnosed with FAST or computer tomography (CT), and unstable patient is taken to OR
- **Chest** – hemodynamically significant bleeding is detected by X-ray and managed with a chest tube or with emergent thoracotomy for those with high output
- **Retroperitoneum** – bleeding may be suspected in a case of unstable pelvis on physical exam and confirmed by pelvic film. Treatment requires a combination of external compression (by binder or fixator), angiographic embolization, external fixation, or even internal packing

Recognition of shock is crucial for timely resuscitation. Unfortunately, it might be difficult if shock is compensated and its signs are subtle until the patient reaches the limits of compensation and develops hypotension and vascular collapse. One should be vigilant watching for the clinical signs of shock:

- Impaired consciousness
- Pallor
- Diaphoresis
- Decreased capillary refill
- Tachycardia
- Tachypnea
- Hypotension
- Decreased urinary output (UO)
- Difficulty obtaining a pulse oximetry signal

Table 28.1 Classification of Hemorrhagic Shock

	Class I	Class II	Class III	Class IV
Blood volume lost	<15%	15–30%	30–40%	>40%
Heart rate (beats per minute)	<100	100–120	120–140	>140
Blood Pressure	Normal	Normal	Decreased	Decreased
Need for blood transfusion	No	Possible	Yes	Massive transfusion

Laboratory values may be helpful in diagnosis and assessment of shock severity: pH, base excess (BE), lactate and coagulation parameters should be taken into consideration.

ATLS classifies hemorrhagic shock into four categories based on degree of hemorrhage (Table 28.1).

ATLS guidelines utilize patient's response to a bolus of 1 L of ctystalloid solution to estimate the severity of blood loss and to determine the likelihood of surgical intervention.

The type of response can be:

- Rapid response: vitals return to normal and remain normal. Estimated blood loss (EBL)
- < 20%. Low need for blood or crystalloid
- Transient response – temporary improvement, recurrence of hypotension and tachycardia EBL – 20 – 40%. Continuously requires fluid or blood. Will likely go to OR
- No response – persistent signs of hemorrhagic shock – EBL > 40%. Need for immediate transfusion and surgery

Airway Management in Trauma Patient

Indications for endotracheal intubations in trauma, according to ATLS guidelines, are the following:

- Need for oxygenation and ventilation in a patient with inadequate respiratory effort, apnea, massive blood loss, severe head injury

- Need for airway protection due to the risk of aspiration, airway obstruction, unconsciousness and severe maxillofacial fractures

The patient with trauma presents unique challenges for airway management:

- The patient might be uncooperative, with severe pain and hemodynamic instability. Time pressure often does not allow a thorough airway exam and pre-oxygenation.
- The patients present with a "full stomach": fasting time is not relevant; the stress of trauma leads to delayed gastric emptying and a **high risk of aspiration**. Therefore, **rapid sequence induction (RSI)** with **a cricoid pressure** should be employed for all injured patients.
- **Cervical spine injury** should be assumed in blunt trauma patients. ATLS recommends the use **of manual in-line stabilization (MILS)** in patients with possible c-spine injuries. To do it, one provider should place one hand on each side of the patient's head at the level of the ears and maintain normal alignment of the head and neck while keeping the occiput and shoulders against the backboard.
- **Associated injuries**, including face, neck and head could alter airway anatomy and make intubation difficult. **A surgical airway** maybe the best choice in certain conditions (e.g., oromaxillofacial trauma).

The American Society of Anesthesiologists (ASA) difficult airway algorithm has been modified for trauma patients. This modified algorithm offers an excellent guideline for difficult airway management in unique setting of trauma [5].

General anesthesia in trauma patient:
Providing anesthesia for expediting surgery is challenging. The surgery cannot wait for completion of laboratory or radiological studies, crossmatching blood, or placing invasive monitors [6, 7].

Operating room (OR) should be properly set up for the trauma patient:
Beside the standard set up including a functioning and calibrated anesthesia machine, standard ASA monitors and working suction, the following equipment should readily available:

- Warmed OR to avoid hypothermia
- Various types of prepared airway equipment
- IV lines connected to the warmer and flushed, kits for large bore IV and arterial and central venous lines
- A primed rapid transfusion device
- Warm air blankets and pads connected to a power source

Induction:
Premedication with small doses of midazolam prior to induction may be done if there is adequate blood pressure. **Induction agents and opioids** may precipitate severe hypotension in a patient with hemorrhagic shock for the following reasons:

- The anesthetic is diluted in a smaller total blood volume resulting in higher serum levels
- The drugs produce direct myocardial depression and vasodilation, they also inhibit endogenous catecholamines

Etomidate (0.1–0.2 mg/kg) and ketamine (0.25–1 mg/kg) are the preferred drugs for the patient in severe shock. Propofol and thiopental may also be used, but in reduced and fractionated doses. **Neuromuscular relaxant** Succinylcholine (1.0–1.5 mg/kg) is a drug of choice due to its fastest onset for RSI (30–60 seconds).

Intubation:
If patient's airway exam is favorable, thorough preoxygenation is performed followed by **RSI with cricoid pressure and MILS**. Ideally, no ventilation should be attempted before intubation. In a case of poor preoxygenation (uncooperative patient) and difficult laryngoscopy resulting in desaturation, gentle mask ventilation should be performed to avoid hypoxia.

Resuscitation Strategies of Hemorrhagic Shock

Current treatment concepts focus on rapid anatomic control of hemorrhage, facilitation of hemostasis, and maintenance of blood composition. Anesthesiologist's resuscitation must be coordinated with surgical efforts to achieve hemorrhage control.

Surgical hemostasis may be achieved by several means:

- Application of a tourniquet or pelvic binder
- Surgical ligation of a bleeding vessels in OR
- Embolization of a bleeding source in radiology suite

Anesthesiologist's goals during resuscitation from hemorrhagic shock include:

- Restoring circulating volume and microcirculation
- Maintaining adequate perfusion pressure to the brain and other vital organs
- Avoiding irreversible shock

Prevention and aggressive treatment of **hypothermia, acidosis and coagulopathy - the "triad of death"** which has been recognized as a significant cause of death in patients with traumatic injuries.

Damage Control Resuscitation

Severely injured patients often do not have the physiologic reserve to tolerate a lengthy surgery. The principles of **"damage control"** surgery and resuscitation dictate the management of these patients: life-threatening conditions are addressed first, while definitive repair of these and non-life-threatening injuries are delayed until after appropriate resuscitation [6–8].

Essentials of damage control surgery:

- Hemostasis: ligation of bleeding vessels, packing for diffuse bleeding

- Rapid excision of badly injured organs
- Control of contamination: bowel injuries stapled, without anastomosis
- Definitive closure deferred
- Long-bone or pelvic fractures are externally stabilized
- Patient transferred to the intensive care unit for completion of resuscitation
- Reoperation, definitive repair when patient is stable

Damage control is intended to minimize surgical time, excessive fluid administration and to preserve normothermia. It therefore reduced the secondary surgical and inflammatory insult from extensive surgical reconstruction.

Early resuscitation occurs from the moment of injury until the time when definitive anatomic control of active hemorrhage is achieved (through surgery or angiographic embolization). During active hemorrhage, vigorous fluid administration in the effort to normalize arterial pressure should be avoided - it increases blood loss, dislodges intravascular clots and dilutes clotting factors. Instead, approach known as **hemostatic resuscitation** [8] is recommended. Its most important components include permissive hypotension and early support of coagulation.

Permissive hypotension:

- Mild hypotension to systolic blood pressure (SBP) 80–90 mmHg is beneficial, provided the patient does not have traumatic brain injury or known ischemic heart disease
- HR of less than 120 beats per minute
- Detectable pulse oximeter and urinary output indicate the presence of basic tissue perfusion
- pH in the range of 7.10 to 7.25
- Hematocrit >25%

In hemorrhaging patients, blood composition must be maintained, crystalloid fluid should be limited, and colloids should be avoided. Asanguineous fluids dilute red blood cells (RBCs), clotting factors and platelets. Vasopressors should be reserved as a last resort in patients who don't respond to fluid resuscitation.

Packed Red Blood Cells (PRBC) (most often uncrossmatched Type O) provide adequate oxygen delivery to avoid tissue ischemia if hematocrit is maintained at 25%–30%.

Support for Coagulation

Coagulopathy in the trauma patient is multifactorial: hemodilution from administration of fluid lacking clotting factors, hypothermia, and acidemia from profound shock. Upregulation of activated protein C, platelet dysfunction, increased fibrinolysis also contributes to trauma induced coagulopathy.

Thus, aggressive administration of plasma and platelets is recommended to maintain normal clotting studies and platelet count over 50,000.

Blood component therapy in early resuscitation is paramount: blood products are transfused in a ratio that approximates whole blood.

- Studies recommend ratio of PRBC to fresh frozen plasma (FFP) to Platelets of 1:1:1 as an optimal one for massive transfusion. **Massive transfusion** is defined as the administration of four or more units within one hour with ongoing bleeding or one blood volume (ten units of blood) given in 24 hours.
- During massive transfusion, coagulation parameters such as prothrombin time (PT), partial thromboplastin time (PTT), platelet count, fibrinogen and D-dimer should be used to monitor the patient's coagulation status. Viscoelastic tests can also assess some aspects of platelet function, fibrinogen level, and fibrinolysis.
- Early support of coagulation includes administration of an antifibrinolytic, typically tranexamic acid, to preserve clot stability during resuscitation.
- Hypocalcemia is a complication of excessive amounts of citrate administered with blood products. Ionized calcium is monitored and administered in the form of calcium chloride or gluconate concurrently with transfused blood products.
- Hypothermia must be aggressively treated: core temperature greater than 35 °C should be maintained.

Late resuscitation starts once surgical control of bleeding is achieved. Its goal is to restore circulating blood volume with additional fluid administration and to titrate anesthetic agent or narcotics which, in turn, enhances vasodilation and tissue perfusion. It promotes stabilization of vital signs, laboratory values, and blood composition.

Goals for late resuscitation:
- **S**BP > 100 mm Hg
- Heart rate <100 bpm
- Normal urinary output
- Restoration of adequate microvascular perfusion, as indicated by normal pH, BE and lactate
- Hematocrit >20%
- Normal coagulation function, platelet count of at least 50,000

Case Study

A 22-year-old male presents to the trauma bay after receiving a gunshot to the left upper abdomen. He is awake and alert, complaining of abdominal pain. His HR is 134 and BP 88/67.

Primary survey:

- *Airway: patent*
- *Breathing: breath sounds are equal bilaterally, no tracheal deviation*
- *Circulation: Palpable radial and pedal pulses. 1 PIV is in place*
- *Disability: Moves all extremities on command. Sensation grossly intact. Glasgow Coma Scale 15.*
- *Exposure: Log rolled and CXR obtained*

Secondary survey:

- *Abdomen diffusely tender, left upper quadrant wound, palpable missile in subcutaneous tissue in a left middle back*
- *Abrasion on L knee, R foot*
- *Ecchymosis on L thigh*

AMPLE history:

- *Allergies: None*
- *Meds: None*
- *PMH: None*
- *Last meal: 1 hour ago, +ETOH*
- *Event: Patient was shot in attempted robbery*

Emergency physician administered 1 L of Lactated Ringer's.

Now, patient's vitals are HR is 142 and BP 78/51. He is diaphoretic, the abdomen feels more distended.

Please evaluate the patient's status.

This patient is bleeding internally and has severe hemorrhaging shock: very tachycardic and hypotensive, not responding to 1 L of IV fluid bolus. He needs emergent surgery.

The patient is going to OR for an emergent exploratory laparotomy.

What is your anesthetic plan?

This patient has a "full stomach" and needs RSI with cricoid pressure. He needs better IV access immediately (2 large bore IV or a central line) for resuscitation with blood products that must be ordered STAT. Since there is no time to wait for a cross-matched blood, O-negative PRBC and AB plasma must be used. Beside standard ASA monitors,

the patient needs an arterial line to monitor his BP beat-to-beat and to draw labs. The OR should be warm, all infusions should be going through the warmers to avoid hypothermia.

Upon arrival to OR the anesthesiology residents quickly placed two 16 G IVs and started transfusion of 4 Units of O-negative PRBC. The patient was pre-oxygenated, and reduced dose of Ketamine (30 mg) administered for induction. After patient became unconscious, RSI with cricoid pressure was performed: Succinylcholine 70 mg was administered, no bag mask ventilation was attempted, and the patient was successfully intubated. Arterial line was placed immediately after induction.

Surgical incision revealed a large amount of blood in the abdomen. Patient's BP is 55/36, HR 148; temperature is 34.9 °C. Your first lab. values are pH 6.97, ionized Ca 0.9, Hct 21, BE - 15, Lactate 5.2.

What are your resuscitation goals?

This patient is in severe hemorrhaging shock, the bleeding is uncontrolled. You ask the surgeon to compress the aorta for temporary hemostasis while you are catching up with massive transfusion. You must call for a massive transfusion protocol which allows you to transfuse blood components (PRBC, FFP and Platelets) in a ratio 1:1:1.

While the surgeon is identifying the source of bleeding and trying to control it, your main goal is to minimize the "dose of shock" by restoring circulation and adequate perfusion of the brain and other vital organs, correct acidosis, prevent coagulopathy and hypothermia. Your resuscitative fluid of choice is blood, and crystalloids should be limited. You transfuse PRBC, FFP and Platelets in ratio 1:1:1, the volume and speed of transfusion is targeted to maintain SBP 80–90 mmHg and HR of less than 120 bpm, pH between 7.10 and 7.25, and Hematocrit greater than 25%. You need to administer Ca chloride to compensate for transfusion related hypocalcemia. Running viscoelastic test such

as TEG will allow you to early detect and to correct coagulopathy. You also want to see some urinary output and adequate pulse oximetry tracing as a proof of ongoing tissue perfusion.

The surgeon tells you that he gained a temporary control of the bleeding. Patient's injuries are quite extensive: completely shattered spleen, 2 holes in tributary of the left renal vein, transverse colon and multiple small bowel enterotomies. Given the patient's condition: severe hemorrhagic shock, hypothermia, coagulopathy and acidosis, he will proceed with the damage control surgery.

What is damage control surgery?

A severely injured patient lacks the physiological reserve to survive prolonged definitive or reconstructive surgery. The goal of damage control surgery is to avoid "operating the patient to death". It limits prolonged surgical procedures and increased blood loss. Life-threatening conditions are addressed first: ligation of bleeding vessels, packing for diffuse bleeding, rapid excision of badly injured organs, control of contamination: stapling bowel injuries without anastomosis. Definitive closure is deferred. The abdomen is left opened until patient is appropriately resuscitated and stable.

The surgeon informs you that he has just ligated left renal vein and performed splenectomy. Thus, surgical hemostasis is achieved. Estimated blood loss is over 4.0 L. Patient intraoperatively received: 16 U of PRBC, 15 U FFP, and 3 pooled units of Platelets.

Patient's vitals are improving to BP 96/61 mm Hg, HR 122 bpm, T 36.1 °C. Lab values: pH 7.28, BE – 8, Lactate 3.1, Hct 27%, ionized Ca 1.18.

The surgeon is performing hemicolectomy followed by small bowel resection without anastomosis. He is planning to leave the abdomen open and to transfer the patient to the ICU for further resuscitation.

Are you going to change your resuscitation goals?

Once hemostasis is achieved, the next goal would be to continue restoration of circulating blood volume with additional fluid and blood products as well as to promote vasodilation and subsequent tissue perfusion with anesthetic agent or narcotics administration.

You will be targeting your anesthetic management toward stabilization of vital signs and laboratory parameters: SBP >100 mm Hg, HR < 100 bpm, Hematocrit >20%, normal UO, pH, BE and lactate.

You need to prepare to transport this patient intubated to the ICU with sedation and analgesia provided by propofol and fentanyl infusions.

This patient returns to OR 24 hours later for colon and small bowel anastomosis and abdominal closure. The bullet lodged in his back is to be removed as well. He is gradually advanced to a general diet and transitioned to oral pain medications. The patient is discharged home on postoperative day 7.

Acknowledgement The authors are grateful to Roy G. Soto for his contribution to the 2016 chapter "Trauma and Orthopedic Surgery" in the first edition of" Anesthesia Student Survival Guide".

References

1. Center for Disease Control and Prevention. Injury Prevention and Control. Available at: https://www.cdc.gov/injury/wisqars/overview/key_data.html. Accessed 7/16,2020
2. American College of Surgeons. Committee on Trauma (2018) ATLS advanced trauma life support for doctors: ATLS student course manual, 10th edn
3. Gaieski DF, Mikkelsen ME. Definition, classification, etiology, and pathophysiology of shock in adults. Up-to-date. https://www.uptodate.com/contents/definition-classification-etiology-and-pathophysiology-of-shock-in-adults. Accessed 6/11/2020

4. Dutton R (2007) Current concepts in Hemorrhagic shock. Anesthesiol Clin 25(1):23–34
5. Hagberg CA, Kaslow O (2015) Difficult Airway Management Algorithm in trauma updated by COTEP. ASA Newsl 2014(9):56–60. Trauma Anesthesia, C. Smith. 2nd edition. Cambridge University Press
6. Smith C (2015) Trauma anesthesia, 2nd edn. Cambridge University Press
7. Varon A, Smith C (eds) (2017) Essentials of trauma anesthesia, 2nd edn. Cambridge University Press
8. Dutton R (2012) Hemostatic resuscitation. BJA 109(51):139–146

Part VI

Postoperative Considerations

Acute Pain Management

29

Seiha T. Kim

Learning Objectives

- Discuss the different types of pain
- Review the basic neurophysiology of pain
- Describe the components of multimodal analgesia
- Provide an overview of interventional procedures for acute pain

Introduction

An acute pain service (APS) is typically composed of anesthesiologists with subspecialty training in either regional anesthesia and acute pain medicine (RAAPM) or chronic and interventional pain medicine.

S. T. Kim (✉)
Department of Anesthesiology, Wake Forest University School of Medicine, Winston Salem, NC, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_29

Basic Pain Sensation in the Normal Individual

The International Association for the Study of Pain (IASP) defines pain as an "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage." Sensation of pain can be divided into four steps: transduction, transmission, modulation, and perception. Each of these steps can be targeted by systemic medications or interventional procedures.

Transduction is the conversion of a noxious stimulus (mechanical, chemical, or thermal) into electrical energy by a nociceptor (pain receptor). Mechanical receptors respond to physical damage, thermal receptors respond to extremes of temperature, and chemical receptors respond to specific chemical mediators such as substance P, serotonin, potassium, bradykinin, histamine, prostaglandins, or leukotrienes. Polymodal nociceptors can respond to both noxious and non-noxious stimuli.

Transmission is the process by which this converted electrical signal is transported to the central nervous system via peripheral nerves. Peripheral nerves are typically classified by their primary function (motor or sensory), diameter and speed of conduction velocity (see Table 29.1). Pain pathways are typically mediated through **A-δ** and **C** fibers via the dorsal root ganglion and then transmitted through one of three major ascending nociceptive pathways (spinothalamic, spinoreticular, or spinomesencephalic) as shown in Fig. 29.1.

Modulation is the alteration (better or worse) of pain and can occur either peripherally at the receptor, at the level of the spinal cord, or in supraspinal structures (i.e. the brain stem, thalamus, or cortex). Synapses at the level of the spinal cord have multiple mediators and receptors that affect the electrical signal transmission, such as neurotransmitters (eg. serotonin, norepinephrine), prostaglandins, cannabinoid receptors, glutamate, NMDA receptors, GABA, and calcium.

Table 29.1 Classification of peripheral nerves

Fiber class	Diameter (μm)	Myelin	Conduction velocity (m/s)	Innervation	Function
A-α	12–20	+++	75–120	Afferent to skeletal muscle	Motor and reflexes
A-β	5–12	+++	30–75	Afferent from cutaneous mechanoreceptors	Vibration, light touch, and pressure
A-γ	3–6	++	12–35	Efferent to muscle spindles	Muscle tone
A-δ	1–5	++	5–30	Afferent pain and thermoreceptors	Pain ("fast," sharp, intense, lancinating); Touch; Temperature
B	<3	+	3–15	Preganglionic sympathetic efferent	Autonomic function
C	0.2–1.5	–	0.4–20	Afferent pain and thermoreceptors	Pain ("slow," dull, burning, achy); Touch; Pressure; Temperature; and Postganglionic autonomic signaling

Finally, the **perception** of pain takes place at the level of the thalamus, somatosensory cortex, anterior cingulate gyrus, insula, cerebellum, and frontal cortex. The thalamus and somatosensory cortex are thought to allow for the localization of pain, while the anterior cingulate gyrus is involved in the emotional response to the stimulus. The insula, cerebellum, and frontal cortex allow for one to remember and to learn from a painful experience and to develop avoidance behavior.

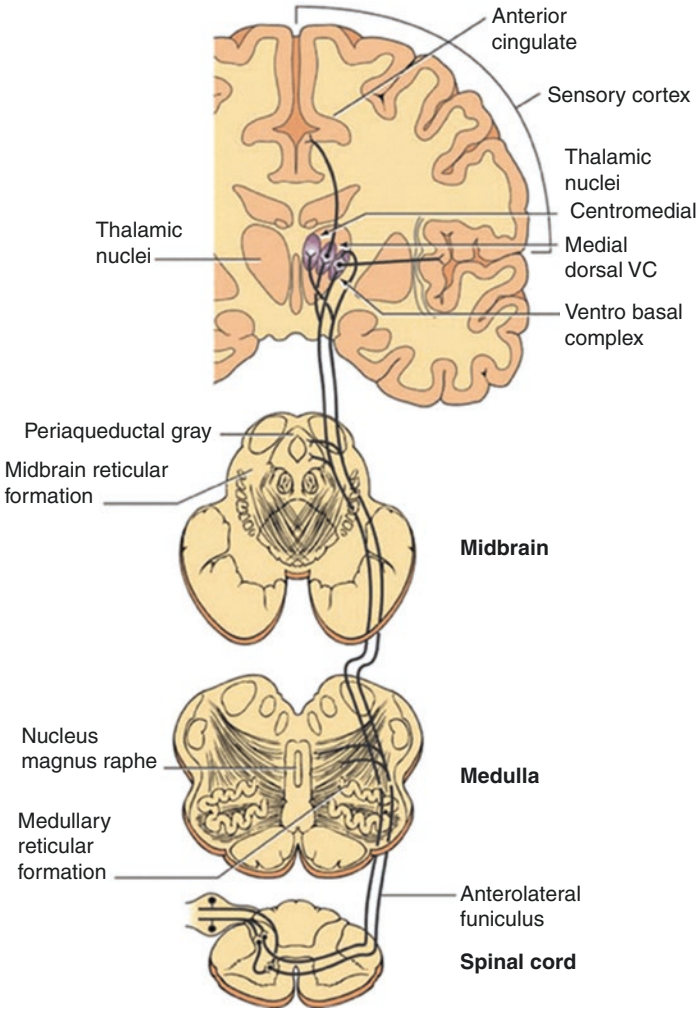


Fig. 29.1 Gross anatomy of pain pathways. (From Sorkin et al. [5]. Used with permission)

General Pain Definitions

It is important to have a basic understanding of the terminology used to express the type and description of pain a patient is experiencing.

Relative to the IASP definition of pain, **acute pain** specifically refers to pain due to tissue injury (eg. surgery, trauma, disease). Its biological function is to curb actions that could result in further or additional tissue damage. Typically this process is self-limiting following resolution of the insult and lasts up to 7–10 days. Postoperative pain that extends beyond this time period is known as persistent postsurgical pain (PPSP). Pain that exists after three months, regardless of etiology, is arbitrarily referred to as chronic pain.

Pain is typically classified as somatic or visceral in nature. **Somatic pain** is caused by the activation of nociceptors in the skin, subcutaneous tissues, muscles, bones, joints, and external mucous membranes. This pain is typically well localized and described as a sharp, throbbing, or stabbing sensation. **Visceral pain** arises from injury of the internal organs, is poorly localized, and typically described as dull, achy, or cramping.

The types of pain can be subdivided into four categories: nociceptive, inflammatory, neuropathic, and dysfunctional. **Nociceptive pain** occurs through suprathreshold stimulation of pain receptors (Table 29.2), and is typically seen in the acute setting of trauma or following surgery. There is usually no injury or changes to the nervous system in this setting. Nociceptive pain can also be chronic in nature due to certain pathologic states such

Table 29.2 General pain types

Nociceptive	Normal, acute pain from noxious stimuli in intact tissue; no peripheral or central sensitization
Inflammatory	Pain due to chemical mediators released by inflamed or injured tissues; no neural injury
Neuropathic	Pathophysiologic state of pain after neural injury resulting in peripheral & central reorganization
Dysfunctional	Diagnosis of exclusion; no pathologic insult can be elucidated

Table 29.3 Definition of abnormal pain descriptors

Allodynia	Non-painful stimulus leads to perception of pain.
Hyperalgesia	Painful stimulus leads to out-of-proportion perception of pain.
Paresthesia	Abnormal sensation (burning, tingling, "pins and needles"); can be spontaneous or evoked

as osteoarthritis where destruction of the joint can lead to stimulation of the nociceptors with movement.

Inflammatory pain is secondary to mediators (e.g. bradykinin, serotonin) released by injured tissues and inflammatory cells. These mediators lead to a decreased threshold for the perception of pain secondary to changes in the peripheral and central nervous system. This pain can either be acute (e.g. following trauma or surgery) or chronic (e.g. certain cancers or autoimmune diseases). The hypersensitivity will usually resolve upon removal of inflammation.

Neuropathic pain results from a lesion of the peripheral or central nervous system. These pathologic states can include diabetic neuropathy, thalamic strokes, and postherpetic neuralgia. All neuropathic pain syndromes can have positive (e.g. allodynia, hyperalgesia; see Table 29.3) and negative (i.e. weakness, sensory loss, decreased reflexes) signs and symptoms. Unlike other pain types, neuropathic pain will remain long after resolution of the inciting insult.

Dysfunctional pain is a diagnosis of exclusion where no noxious stimuli, inflammation, or pathologic lesion can be elucidated. Common diseases included under this heading include fibromyalgia, irritable bowel syndrome, and interstitial cystitis.

Treatment of Acute Pain

Since 2012 the American Society of Anesthesiologists (ASA) task force on acute pain management has recommended that multimodal analgesia (MMA) be utilized for the management of perioperative whenever possible. Key components of MMA include

acetaminophen, non-steroidal anti-inflammatory drug (NSAID), and regional analgesic techniques such as peripheral nerve blocks, neuraxial blocks, and (more recently) fascial plane blocks. Other non-opioid medications can be beneficial when indicated.

Multimodal Analgesia

Acetaminophen is an antipyretic, non-opioid analgesic whose mechanism of action is still not fully understood. It is believed to inhibit the cyclooxygenase (COX) enzyme centrally (rather than in the periphery) because it lacks significant anti-inflammatory activity. The COX enzyme and prostaglandins can be found in the spinal cord and play a role in the release of chemical mediators, such as substance P. It has additive analgesic effects when combined with NSAIDs. Acetaminophen is typically started preoperatively and the dose is 15 mg/kg (up to 1000 mg at a time). In the acute postoperative period, the dosing interval is every six hours scheduled with a maximum daily dose of 4000 mg to avoid liver toxicity. It is available in both per os (PO; by mouth) and intravenous (IV) formulations, and the data is equivocal when comparing the routes of administration and its effects on analgesia. Therefore most institutions reserve IV acetaminophen for patients unable to take PO medications.

NSAIDs inhibit the COX enzyme peripherally and can significantly reduce inflammation and pain. Despite the significant non-opioid analgesic effects, NSAIDs are not benign. Their known common adverse effects include increased bleeding risk, especially gastrointestinal bleed (GIB), increased risk of cardiovascular (CV) events, and kidney injury. NSAIDs are subdivided into nonselective (COX-1 and COX-2) and selective COX-2 inhibition, with selective COX-2 inhibitors (celecoxib is the only one available in the U.S.) displaying lower risk of GIB but higher risk of CV events compared to nonselective COX inhibitors. The use of NSAIDs is dependent on the type of surgery, patient specific factors, and institutional formulary.

The N-Methyl-d-aspartate (NMDA) receptor plays an important role in central sensitization. NMDA receptor antagonists,

especially ketamine, are being used more frequently in the perioperative period due to its potential effects on preventing chronic and/or neuropathic pain by dampening, or even inhibiting, central sensitization. Other drugs in this class include methadone, magnesium, memantine, and dexamethasone.

Gabapentin and pregabalin make up the gabapentinoids. Originally used as anticonvulsants, this class also has neuromodulating properties and is sometimes referred to as membrane stabilizers. Gabapentinoids bind to a specific subunit on presynaptic voltage-dependent calcium channels in the spinal cord and can reduce calcium influx and prevent neurotransmitter release. Their use in MMA is controversial due to equivocal analgesic benefit with a significant risk of somnolence.

Alpha-2 agonists are another class of medications gaining favor as a component of MMA. Their effects include decreased blood pressure and heart rate, sedation, anxiolysis, analgesia, and muscle relaxation. These actions are achieved by agonism of prejunctional alpha-2 receptors, which subsequently leads to inhibition of neurotransmitter release (e.g. norepinephrine). Caution must be exercised in using these agents because their intended effects can become adverse (sedation, bradycardia, hypotension) and might prolong time in the postanesthesia care unit (PACU). The most commonly used agents in this class for MMA are dexmedetomidine, clonidine, and tizanidine.

Opioids

Even though the Department of Health and Human Services declared the opioid epidemic a “public health emergency” in 2017, perioperative opioids are still an important tool in our armamentarium to treat acute pain. Even though our own bodies release endogenous opioids (endorphin, enkephalin, dynorphin) for analgesia and other effects, we should still be judicious with opioids. The CDC recommends limiting postoperative opioid use to 14 days or less, and some states have passed laws limiting postsurgical opioid prescriptions to a maximum supply of seven days.

Intraoperative IV opioids are used for reasons other than nociceptive pain, such as attenuation of the sympathetic response to laryngoscopy and as a cough suppressant for tolerance of the endotracheal tube (ETT). By utilizing MMA it is possible to minimize opioid administration to only these necessary indications while still providing adequate analgesia.

In the acute postoperative period, opioids are commonly administered IV or PO. Patient-controlled analgesia (PCA) is a form of IV opioid administration in which the patient doses himself or herself via a button connected to a programmable pump. This method is typically reserved for patients who are not allowed to take medications by mouth (either due to surgery or GI rest) or those with high opioid requirement due to their past medical history (e.g. chronic pain or substance abuse). A dose is chosen for each push of the button, followed by a lockout interval (time period during which any additional pushes of the button result in no medication to prevent overdose), and lastly a maximum total hourly amount. When the indication for PCA use has resolved, it is prudent to assess the patient's opioid use over the prior 24 hours in order to calculate a PO regimen that will meet this requirement.

An important term and concept in pain management is morphine milligram equivalents (MME). This allows for utilization of equianalgesic dosing ratios when converting from one form (e.g. IV to PO) or drug (e.g. oxycodone to hydromorphone) to another. For example, 15 mg of PO morphine means 15 MME and is equivalent to 10 mg of PO oxycodone (see Table 29.4).

Table 29.4 Equianalgesic doses of common opioids

	PO	IV
Morphine	15 mg	5 mg
Hydromorphone	4 mg	1 mg
Oxycodone	10 mg	n/a
Hydrocodone	15 mg	n/a
Codeine	100 mg	n/a

Regional Analgesic Techniques

Regional analgesia is the administration of local anesthetic to a specific nerve or plexus that can provide significant or complete analgesia. Ultrasound technology has both increased the number of available regional analgesic options and improved preexisting techniques. There are a multitude of single injection (up to 18–24 hours of pain relief) and continuous, catheter-based (up to seven days of pain relief) techniques.

Brachial plexus blocks can provide complete analgesia for upper extremity procedures. A lumbar plexus block combined with a sciatic nerve block can provide complete analgesia for lower extremity procedures. Fascial plane blocks, such as the transversus abdominis plane (TAP) block or erector spinae plane (ESP) block, can provide somatic pain relief of the abdomen or thorax, respectively.

Neuraxial techniques like thoracic epidural analgesia (TEA) or subarachnoid block (SAB, also known as "spinal") can provide both visceral and somatic pain relief in the thorax or abdomen. TEA requires placement of a catheter into the epidural space in order to provide continuous analgesia for up to seven days. The epidural catheter is connected to a pump similar to the PCA to allow for patient-controlled epidural analgesia (PCEA). One major difference from the PCA is that there is a continuous infusion of medication to supplement the PCEA so that the patient can get pain relief even if they are asleep. The TEA solution is typically composed of diluted local anesthetic and an extremely diluted opioid to allow for ambulation and prevent opioid overdose, respectively. With a SAB the cerebrospinal fluid (CSF) is dosed with a hydrophilic opioid like morphine to provide analgesia for 24–48 hours.

Acknowledgement Mark A.Hoeft who had contributed to the previous version of this chapter.

Resources and Suggested Further Reading

1. Benzon HT, Rathemell JP, Wu CL, Turk DC, Argoff CE (2008) Raj's practical management of pain, 4th edn. Mosby-Elsevier, Philadelphia
2. Bonica JJ, Loeser JD, Chapman CR, Fordyce WE (2001) The management of pain, 3rd edn. Lippincott, Williams & Williams, Philadelphia
3. Kandel ER, Schwartz JH, Jessell TM (2000) Principles of neural science, 4th edn. McGraw-Hill, New York
4. Longnecker DE, Brown DL, Newman MF, Zapol WM (2007) Anesthesiology, 1st edn. McGraw-Hill, New York
5. Sorkin L et al (1998) Atlas of anesthesia. Current Medicine Group, Philadelphia
6. Wardhan R, Chelly J (2017) Recent advances in acute pain management: understanding the mechanisms of acute pain, the prescription of opioids, and the role of multimodal pain therapy. F1000Res 6:2065. https://doi.org/10.12688/f1000research.12286.1. eCollection 2017
7. Helander EM et al (2017) Multimodal analgesia, current concepts, and acute pain considerations. Curr Pain Headache Rep 21(1):3. https://doi.org/10.1007/s11916-017-0607-y

Perioperative Acute and Chronic Pain Management

30

Justin Merkow

Key Learning Objectives

- Understand the basic neurophysiology of pain
- Understand the types of acute and chronic pain (i.e. nociceptive, inflammatory, neuropathic, and dysfunctional)
- Learn the common pain syndromes encountered in the pain clinic, and describe the basic treatment options

Introduction

Pain medicine is a subspecialty composed of anesthesiologists, neurologists, psychiatrists, as well as physical medicine and rehabilitation physicians. The field focuses on the management of

J. Merkow (✉)
Department of Anesthesia, University of Colorado Hospital, Aurora, CO, USA

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_30

patients with both acute and chronic pain arising from physiologic, structural, and psychological pathology.

Basic Pain Sensation in the Normal Individual

Pain, as defined by the International Association for the Study of Pain, is "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage." Sensation of pain can be divided into four steps: **transduction**, **transmission**, **modulation**, and **perception**. In **transduction**, the ability of the body to sense noxious stimuli (nociception) depends on the activation of nociceptors (pain receptors). These receptors are divided into thermal, mechanical, and polymodal nociceptors. Thermal receptors are excited by extremes of temperature, mechanical receptors respond to sharp objects that penetrate, squeeze, or pinch, while polymodal receptors respond to the destructive mediators of thermal, mechanical, and chemical stimuli. The chemical stimuli include potassium, serotonin, bradykinin, histamine, prostaglandins, leukotrienes, or substance P, which may lead to activation or sensitization of the polymodal nociceptors.

Following transduction, the nociceptor signal is translated into an electrical signal which allows for **transmission** of the stimuli via the peripheral nerves. Peripheral nerves are typically classified by their primary function (motor or sensory), diameter and speed of conduction velocity (see Table 30.1). Pain pathways are typically mediated through A delta and C fibers via the dorsal root ganglion and then transmitted through one of three major ascending nociceptive pathways (spinothalmic, spinoreticular, or spinomesencephalic) as shown in Fig. 30.1.

Modulation of pain (suppression or worsening of a painful stimulus) occurs either peripherally at the receptor, at the level of the spinal cord or in supraspinal structures (i.e. the brain stem, thalamus, or cortex). Finally, the **perception** of pain takes place at

Table 30.1 Classification of peripheral nerves

Fiber class	Diameter (μm)	Myelin	Conduction velocity (m/s)	Innervation	Function
A alpha	12–20	+++	75–120	Afferent to skeletal muscle	Motor and reflexes
A beta	5–12	+++	30–75	Afferent from cutaneous mechanoreceptors	Vibration, light touch and pressure
A gamma	3–6	++	12–35	Efferent to muscle spindles	Muscle tone
A delta	1–5	++	5–30	Afferent pain and thermoreceptors	"Fast", sharp, intense, lancinating pain, touch and temperature
B	<3	+	3–15	Preganglionic sympathetic efferent	Autonomic function
C	0.2–1.5	–	0.4–2.0	Afferent pain and thermoreceptors	"Slow", dull, burning, achy pain, touch, pressure, temperature, postganglionic autonomic

the level of the thalamus, somatosensory cortex, anterior cingulate gyrus, insula, cerebellum, and frontal cortex. The thalamus and somatosensory cortex are thought to allow for the localization of pain, while the anterior cingulate gyrus is involved in the emotional response to the stimulus. The insula, cerebellum, and frontal cortex allow for one to remember and to learn from a painful experience and to develop avoidance behavior.

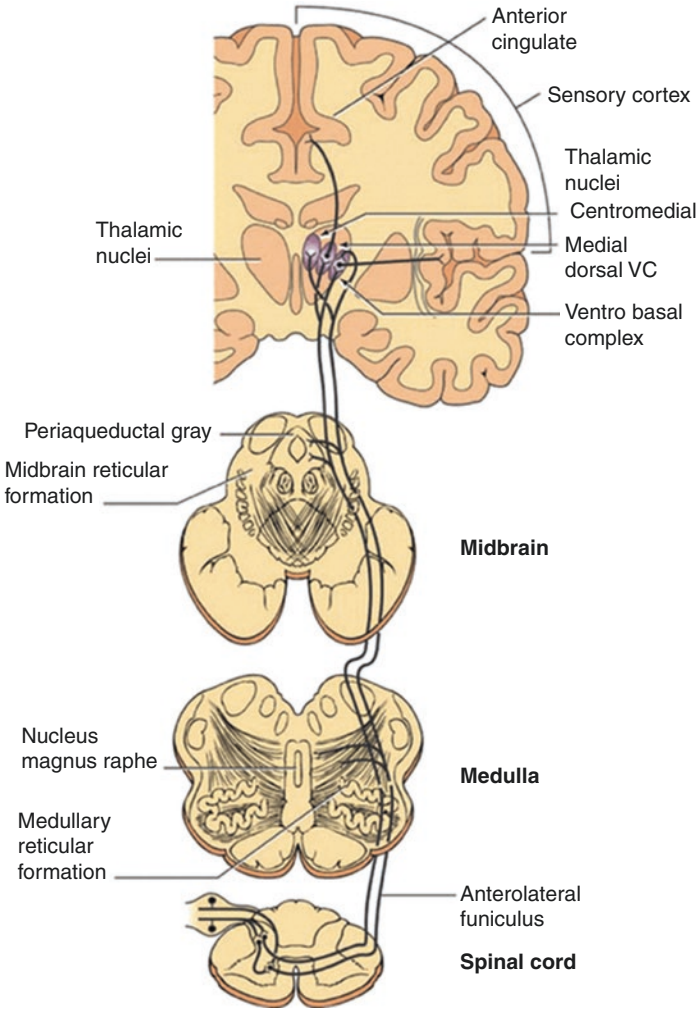


Fig. 30.1 Gross anatomy of pain pathways. (From Sorkin et al. [5]. Used with permission)

General Pain Definitions

When discussing acute and chronic pain, it is important to have a basic battery of definitions to express the type and description of pain a patient is experiencing.

Acute Versus Chronic Pain

The clinical definition of acute versus chronic pain is determined in a temporal fashion with an arbitrary timeframe of 3–6 months defining the cutoff point between acute versus chronic.

Acute pain can be defined as a noxious stimulus caused by injury or abnormal functioning of viscera or musculature. It is usually noted following posttraumatic, postoperative, obstetrical, and acute medical illnesses (i.e. myocardial infarction or nephrolithiasis). It is typically classified as **somatic** or **visceral** in nature. **Somatic pain** is caused by the activation of nociceptors in the skin, subcutaneous tissues, and mucous membranes. This pain is typically well localized and described as a sharp, throbbing or burning sensation. **Visceral pain** arises from injury of the organs and is typically described as dull, distention, achy and is poorly localized. Acute pain follows the pathways listed above and will resolve within seconds to weeks following resolution of the insult.

Chronic pain can be secondary to lesions of peripheral nerves, the spinal cord, or supraspinal structures. Chronic pain can be complicated by many psychological factors such as attention seeking behavior, emotional stresses that can precipitate pain (cluster headaches), and pure psychogenic mechanisms.

The types of acute and chronic pain are subdivided into four categories: **nociceptive**, **inflammatory**, **neuropathic**, and **dysfunctional**. **Nociceptive pain** occurs through suprathreshold stimulation of pain receptors and typically serves as a protective mechanism (Table 30.2). Typically, no injury or changes to the nervous system are seen in nociceptive pain. This type of pain is typically seen in the acute setting of trauma or following surgery. The pain type works as an adaptive mechanism to allow for pro-

Table 30.2 General pain types

Nociceptive pain	Normal, acute pain perception evoked by short-lasting noxious stimuli in intact tissue, in the absence of peripheral or central sensitization
Inflammatory pain	Pain following tissue injury but with no neural injury
Neuropathic pain	Pathophysiologic state of pain after neural injury resulting in peripheral and central reorganization

tection of the injured body part. Nociceptive pain can be chronic in nature as is seen in certain pathologic states such as osteoarthritis where destruction of the joint can lead to stimulation of the nociceptors with movement.

Inflammatory pain is secondary to mediators (e.g. bradykinin, serotonin) released by injured tissues and inflammatory cells. These mediators lead to a decreased threshold for the perception of pain secondary to changes in the peripheral and central nervous system. This pain can be either acute following trauma or surgery or chronic in the setting of cancer or osteoarthritis. Upon the removal of inflammation, the hypersensitivity will typically resolve.

Neuropathic pain is secondary to a lesion of the peripheral or central nervous system. These pathologic states can include diabetic neuropathy, thalamic strokes, and postherpetic neuralgia. All neuropathic pain syndromes have positive signs and symptoms (e.g. allodynia, hyperalagesia) and negative symptoms (i.e. weakness, sensory loss, and decreased reflexes). As opposed to inflammatory pain, neuropathic pain will remain long after the resolution of the inciting insult.

Dysfunctional pain is a diagnosis of exclusion where no noxious stimuli, inflammation or pathologic lesion can be elucidated. Common diseases included under this heading include fibromyalgia and irritable bowel syndrome.

Treatment of Pain

Acute Pain

Pain is often treated utilizing a *multimodal* approach, meaning multiple treatment methods may be combined to provide analgesia, with the hope of decreasing pain and opioid usage. The treatment of acute pain can often begin prior to the initial surgical insult. In the preoperative period, *preemptive analgesia* is often utilized to decrease or stop nociceptive input. Nonsteroidal anti-inflammatory drugs (NSAIDs) such as celecoxib (PO), ketorolac (IV), and ibuprofen (PO) or acetaminophen can be used preoperatively in combination with other medications such as gabapentin to prevent central sensitization. The main advantage of celecoxib and other cyclooxygenase-2 (COX-2) inhibitors over other NSAIDs include the decreased risk of gastrointestinal bleeding, but other adverse events such as myocardial infarction, stroke, allergic reaction to sulfa, and renal issues may be seen with the use of COX-2 inhibitors.

Preemptive analgesia can also be obtained through neuraxial and regional techniques, such as peripheral nerve blocks of the femoral nerve, and brachial plexus. In those patients with moderate to severe pain, opioid analgesics such as hydromorphone or morphine may be used in combination with acetaminophen or NSAIDs for analgesia. Surgeons may aid in providing pain relief through infiltration of local anesthetics such as lidocaine or bupivacaine at the surgical site (Table 30.3).

Table 30.3 Abnormal pain descriptor definitions

Allodynia	The perception of pain by a stimulus that is not normally painful
Hyperalgesia	The enhanced perception of pain by a normally painful stimulus
Dysesthesia	Abnormal sensations experienced in the absence of stimulation
Paresthesia	An abnormal sensation (e.g. burning, pricking, tickling, or tingling)

In those patients not able to take oral medications postoperatively, patient controlled analgesia (PCA) devices allow patients to deliver pain medication through the pressing of a button which allows the medication to be delivered via an intravenous route or an epidural catheter. These devices typically allow patients to deliver a predetermined amount of pain medicine at specific time intervals. There is a lockout period in which the patient can attempt to deliver pain medication, however, none will be given to prevent overdosing on opioid pain medication. A continuous (basal) rate may also be added to provide a baseline level of analgesia without the patient needing to administer the medication.

When assessing postoperative pain, a verbal numeric scale is typically used. The scale typically ranges from 0 to 10 with 0 representing no pain and 10 representing the worst pain imaginable. Important qualitative descriptors of pain to assess are the location, radiation, and the quality (sharp or dull) of the pain.

Chronic Pain

Treatment methods for chronic pain patients are multimodal and include the use of non-narcotic pain medications such as NSAIDs, opioid analgesics, antidepressants, anticonvulsants, and multiple interventional pain procedures. The most common interventional pain procedures are listed in Table 30.4. Additionally, physical therapy, psychiatric evaluation and treatment, and surgical intervention are often coordinated through the pain clinic. Pain physicians are also involved in end-of-life care issues.

Table 30.4 Common interventional pain procedures

Procedure	Target	Mechanism	Indicated pain syndrome
Epidural steroid injection	Nerve root	Injection of steroid to decrease inflammation surrounding the nerve root	Herniated discs, spinal stenosis, foraminal stenosis
Medial branch block	Medial branch of dorsal ramus	Local anesthetic injection	Diagnostic test to determine if the pain is facet mediated
Radiofrequency ablation	Medial branch of the posterior division of the spinal nerve	Coagulative destruction of the medial branch nerve	Therapeutic intervention if a diagnostic medial branch block indicates the targeted medial branch nerve is the pain generator
Trigger point injection	Trigger points	Relaxation and lengthening of the muscle fiber	Myofascial pain
Spinal cord simulator	Posterior column of spinal cord	1. Decreased nociceptive input and hyperexcitability through increased inhibitory neurotransmitters (i.e. GABA and adenosine) and decreased excitatory neurotransmitter (i.e. glutamate) 2. Increase coronary blood flow through alteration of sympathetic tone	Neuropathic pain, angina, peripheral ischemic pain
Intrathecal pumps	Intrathecal space	Decreasing systemic dose of medications such as opioids, thus decreasing side effects	Cancer pain patients

(continued)

Table 30.4 (continued)

Procedure	Target	Mechanism	Indicated pain syndrome
Neurolytic blocks	Celiac plexus, trigeminal ganglion, lumbar sympathetic chain	Destruction of nerve/ plexus via phenol, alcohol or RFA	Pallative care patients
Stellate ganglion block/ lumbar sympathetic	Stellate ganglion/ lumbar plexus	Local anesthetic blocking of sympathetic efferent nerves	Complex regional pain syndrome

Common Chronic Pain Medications Classifications

Opioids

The opioids are a diverse classification of mediation that typically provide analgesic effect via actions on the μ, δ, and κ opioid receptors. The receptors are most abundant in the dorsal horn of the spinal cord and also in the dorsal root ganglion and peripheral nerves. Various natural and synthetic formulations and routes of delivery exist for these medications, including oral, intravenous, buccal, transdermal, and intrathecal. The most common oral agents are listed in Table 30.5. The major side effects of opioids include constipation, nausea, vomiting, pruritus, sedation, and respiratory depression.

Some of the major challenges surrounding opioids include those of **tolerance**, **physical dependence**, **withdrawal**, and **addiction**. **Tolerance** is defined as a fixed dose of an opioid providing less analgesia over time that may lead to escalating doses of opioids to achieve the same pain relief.

Physical dependence is a physiologic state which is manifest by abruptly stopping opioid medications which then results in a withdrawal state. Opioid withdrawal presents with irritability, anxiety, insomnia, diaphoresis, yawning, rhinorrhea, and lacrima-

Table 30.5 Common oral opioid pharmacodynamics and dosing

Opioids	Half-life	Duration (h)	Equianalgesic oral doses (mg)	Initial dose (mg)	Dosing interval (h)
Codeine	3	3–4	80	30–60	4
Hydromorphone	2–3	2–3	2	2–4	4
Hydrocodone	1–3	3–6	10	5–7.5	4–6
Oxycodone	2–3	3–6	7	5–10	6
Methadone	15–30	4–6	10–20	20	6–8
Morphine	2–3.5	3–4	10	10–30	3–4
Propoxyphene	6–12	3–6	43–45	100	6
Tramadol	6–7	3–6	40	50	4–6

tion. As time progresses, the symptoms may include fevers, chills, myalgias, abdominal cramping, diarrhea, and tachycardia. Opioid withdrawal is self-limiting and can typically last 3–7 days.

As opposed to physical dependence, **addiction** is defined by opioid use resulting in physical, psychological, or social dysfunction and continued use of the opioid despite the overlying issues. Behaviors that are most indicative of addictive behaviors are buying street drugs, stealing money to obtain drugs, attempting to obtain opioids from multiple sources, acts of prostitution to obtain drugs, forging prescriptions, and selling prescription drugs.

Alpha-2-Agonist: (Tizanidine)

The alpha-2-agonist tizanidine is commonly used in pain medicine as a muscle relaxant. It causes less significant blood pressure changes compared to clonidine, but can lead to drowsiness.

Anticonvulsants: (Gabapentin, Carbamazepine, and Oxcarbamazepine, Pregabalin)

The anticonvulsants work through very diverse mechanisms of actions, including modulation of voltage-gated calcium channels,

sodium channels, GABA, and glutamine receptors. FDA-approved pain indications include trigeminal neuralgia (carbamazepine), post herpetic neuralgia (gabapentin, pregabalin), diabetic neuropathy (pregabalin), fibromyalgia (pregabalin), and migraine prophylaxis (divalproex, topiramate).

Tricyclic Antidepressants: (Nortiptyline, Amitriptyline)

Tricyclic antidepressants (TCA) contribute to the improvement in pain symptoms through their actions on multiple sites, including serotonergic, noradrenergic, opioidergic, NMDA receptors, adenosine receptors, sodium channels, and calcium channels. The effects of TCAs can include elevation of mood, normalization of sleep patterns, and muscle relaxation. These agents are used for the treatment of neuropathic pain syndromes such as postherpetic neuralgia, diabetic neuropathy, pain secondary to spinal cord injury, cancer-related neuropathic pain, and other pain syndromes such as low back pain, osteoarthritis, and fibromyalgia. The side effects of this class of medications can include dry mouth, drowsiness, dizziness, weight gain, orthostatic hypotension, and lethargy.

Serotonin-Norepinephrine Reuptake Inhibitors: (Venlafaxine, Duloxetine)

Serotonin-norepinephrine reuptake inhibitors (SNRI), as their class implies, block the reuptake of norepinephrine and serotonin. Duloxetine is the first antidepressant to have a specific pain indication (diabetic neuropathy) in the United States. These medications have also been demonstrated to be useful in the treatment of fibromyalgia. The side effect profile tends to be lower in the SNRIs than the TCAs.

Cancer Pain

Cancer pain is typically treated in a stepwise fashion via the World Health Organization (WHO) analgesic ladder with the goal of maintaining oral administration of analgesics to allow for the patient to have simplicity, independence, convenience, and lower cost. This is outlined in Fig. 30.2. Mild pain is treated with non-opioids such as NSAIDs and other adjuvants. As the patient's pain level increases or persists, opioids are added and titrated to the patient's comfort.

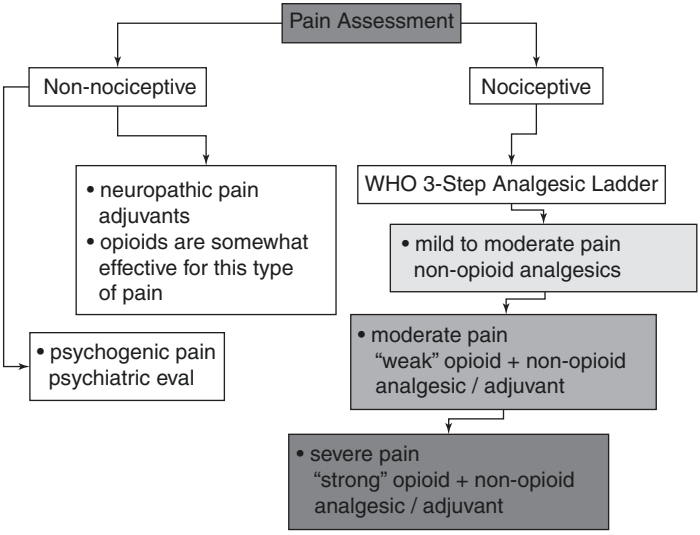


Fig. 30.2 Assessment of pain and World Health Organization analgesic ladder

Common Pain Syndromes

Spinal Stenosis

Spinal stenosis is a narrowing of the spinal canal secondary to congenital and acquired pathologies such as disc herniations, facet arthropathy, bone spurs, and ligamentous hypertrophy. It may often lead to low back pain and leg pain, which is worse with standing or walking downhill. Diagnosis can be made via MRI. Treatment ranges from epidural steroid injections, physical therapy, and NSAIDs to surgical decompression via laminectomy and other approaches.

Radicular Pain

The pathology behind radicular pain can be secondary to narrowing of the intervertebral foramina, which leads to compression of the exiting nerve roots. This may be caused by intervertebral disc herniation, osteophyte formation, or spondylolisthesis (a defect in the pars interarticularis). Symptoms typically follow a dermatomal distribution of the exiting nerve root and may manifest with pain, numbness, weakness, and reflex changes. Diagnosis is made through MRI and electromyography. Treatment ranges from epidural steroid injections, physical therapy, NSAIDs, and surgery.

Facet Arthropathy

Facet arthropathy is another cause of chronic low back pain. The facet joints are the articulating bodies of the spine and may develop arthritis over time. Pain may radiate into the scapula, buttocks, or posterior thighs. Diagnosis of the facet joint as the main cause of the patient's pain may be made through a medial branch block which entails injecting local anesthetic on the medial branch of the posterior primary division of the spinal nerve. If the patient receives pain relief, radiofrequency ablation may be used at a later time to ablate the nerve.

Discogenic Pain

Discogenic pain is a pathologic process involving the intervertebral disc and often presents in the center of the back, buttocks, or posterior thighs and is worse with mechanical loading, sitting, standing, and bending forward. The diagnosis can be made via a discogram that demonstrates a tear in the annulus fibrosis and concordant reproduction of pain in the back with injection into the disc. Treatment can include conservative treatment with physical therapy and NSAIDs, or more invasive and controversial procedures such as intradiscal electrothermal therapy or fusion.

Complex Regional Pain Syndrome

Complex regional pain syndrome (CRPS) type I and II (formally known as reflex sympathetic dystrophy and causalgia, respectively) are chronic pain syndromes that typically affect extremities after trauma. Local trauma to an extremity either without evidence of nerve damage (type I) or with evidence of nerve damage (type II) leads to the maintenance of pain secondary to sympathetic efferent nerves or circulating catecholamines. A typical extremity affected by CRPS can have edema, loss of range of motion, denudation of hair, a lower temperature and color changes compared to the opposite extremity and allodynia. Diagnosis of CRPS can be made with a sympathetic block of the stellate ganglion or of the lumbar sympathetic plexus. Treatment can consist of medication therapy, physical therapy, psychological therapy, education about the disease process, and regional sympathetic blocks.

Myofascial Pain

Myofascial pain is characterized by aching muscles, muscle spasms, stiffness, and weakness which is thought to occur secondary to ischemic microtrauma to a muscle. On exam, patients with

myofascial pain will note discrete areas of tenderness (trigger points) that are palpable over the affected muscle. Trigger points may be treated with injections of lidocaine, dry needling, or Botox injections into the trigger point.

Sacroiliac Joint Dysfunction

The sacroiliac (SI) joint may cause pain secondary to etiologies such as trauma, spine deformities, facet arthropathy, pregnancy, osteoarthritis, and inflammatory arthropathies. The typical pain distribution is around the SI joint, into the buttock and posterior thigh. Physical exam may demonstrate pain on movement of the joint and limited motion. Local anesthetic and steroid injections of the joint may help to elucidate if the SI joint is the true cause of the patient's pain. Radiofrequency ablation may be used to treat the patient's symptoms by ablating the nerves providing sensation to the joint.

Postherpetic Neuralgia

Acute herpes zoster is caused by reactivation of the latent varicella virus in the dorsal root ganglion. The typical course of the infection is that there is pain for 48–72 h prior to the rash. At this point, a vesicular rash appears in a dermatomal distribution and lasts for approximately 1–2 weeks. Following resolution of the acute herpes zoster, patients (usually patients greater than 50 years old) may experience sharp, lancinating pain secondary to post herpetic neuralgia. Typical treatment of post herpetic neuralgia involves anticonvulsants, antidepressants, and lidocaine patches.

Physical Therapy

Physical therapy has an important role in the treatment of the chronic pain patient to reduce disability, restore and increase function, and improve strength. Exercise may increase endurance

and muscle strength while at the same time decrease the patient's subjective experience of pain. Passive forms of physical therapy can include electrostimulation, heat and cold therapy, and ultrasound.

Psychological Therapy

Psychological evaluation of the patient may help to diagnose and treat psychiatric issues such as malingering, substance abuse and somatization disorders and other issues such as depression, anxiety, and sleep disorders contributing to the patient's pain disorder. Early diagnosis and treatment of psychological issues have demonstrated to effect a patient's pain level, ability to cope, return to work, and medication compliance.

Palliative Care

Palliative care focuses on providing pain relief and care of a terminally ill patient and his/her family over the remainder of the patient's life. It focuses on pain relief and symptomatic relief of nausea, vomiting, and dyspnea. Care may take place at home (usually through hospice) or in an inpatient palliative care unit, acute care hospital, or nursing home.

Case Study

A 32-year-old woman seeks consultation with you in the pain management clinic. Six months ago she sprained her left elbow and wrist in a fall while roller blading. After recovering uneventfully with splinting of her wrist and wearing a sling for 4 weeks, she has developed severe pain again. She describes it as burning and constant. She describes tingling, "electric shock" sensations over the affected area. It covers the dorsum of her hand, both sides

of her forearm, and the posterior aspect of the elbow and lower arm. She notes that she cannot type with her left hand and that she cannot lift her backpack with her left arm. She finds showering painful and keeps the arm out of the water; she avoids long-sleeved shirts because the fabric rubbing against her skin is painful. On examination, the limb is purplish and mottled, edematous, and cool to the touch. There is less hair than on comparable regions of her right arm. The nails of her left hand are thickened, discolored, and longer than those on her right. Lightly stroking the dorsum of her hand with a fingertip causes pain.

You perform the initial evaluation with your attending. You are asked to dictate the note describing the patient's pain presentation. Which of the four main types of pain will you characterize as hers?

The four main categories of pain are nociceptive, inflammatory, neuropathic, and dysfunctional. This patient's acute injury has long passed, so her pain is probably not nociceptive or inflammatory, and is likely neuropathic. The characteristics of the pain as well (type, pain descriptors) are also consistent with this classification. It is important not to characterize it as dysfunctional until other types have been excluded.

Which pain descriptors will you use to describe her symptoms?

The patient's pain can be described in her own terms (burning), and the location, intensity, and variation in the pain should be noted. For example, behavioral choices she makes (showering, dressing) should be noted. You will also ask her about variation during the day, effect of analgesics, document the duration of her symptoms, and the relationship to her injury. This patient has described *allodynia*, pain elicited by a normally nonpainful stimulus, and *dysesthesia* and *paresthesia*, abnormal sensations occurring spontaneously or in response to stimulation. You have verified allodynia on your exam (stroking her hand) but have not

demonstrated *hyperalgesia*, an exaggerated perception of pain in response to a normally painful stimulus, because you wisely did not attempt a painful stimulus.

What is your working diagnosis? How could you verify it?

The patient appears to have complex regional pain syndrome, type I, formerly known as reflex sympathetic dystrophy. We base this diagnosis on the pattern of her pain and its relationship to her injury: it followed local trauma without nerve damage (which might have made it type II, formerly causalgia), she has cutanous evidence of sympathetic excess and disuse atrophy, and she has allodynia. She thus meets the International Association for the Study of Pain's criteria for the diagnosis, which are sensitive but not specific for the disorder. Although not considered definitive, a strongly suggestive diagnostic test is a favorable response to sympathetic blockade of the affected extremity. You could perform a localized chemical sympathectomy of the limb by infusing phentolamine into the arm isolated by a tourniquet. More commonly, you could block the stellate ganglion on the affected side (see below). If evidence of sympathectomy is seen, for example by vasodilation and warming of the extremity, and if some pain relief is observed, the diagnosis is strongly supported.

What treatment would you offer her?

A stellate ganglion block is performed by injecting local anesthetic adjacent to the transverse process of C6, palpated medial to the carotid artery at the level of the cricoid cartilage in the neck. Fluoroscopic or ultrasound guidance is used and can improve the efficacy and possibly safety of the block. The spinal and epidural spaces lie close to the correct needle position, as do the carotid and vertebral arteries. If a stellate ganglion block is effective, the block can be repeated several times over the next few weeks. In a fortunate proportion of patients, the pain relief lasts far longer than the effect of the local anesthetic, and may actually lengthen

over time. Unfortunately, some patients do not experience progressively longer relief or even relief extending longer than the block, and other treatments will be needed. Multimodal therapy is recommended whether blocks are successful or not. First, the patient needs psychological counseling that her symptoms are not the result of direct tissue damage, and that she can and must begin to use the extremity more as analgesia allows. Physical therapy taking advantage of less painful periods is essential. Anxiety, depression, and sleep disorders should be addressed by counseling and likely medication. Other medications that may be helpful include those directed at neuropathic pain (such as antiepilepsy or antidepression drugs), opioids, and NSAIDs. The condition can be difficult to treat, so if one therapy fails, a different one should be tried in order to facilitate rehabilitation efforts. Spinal cord stimulation may also be an effective option if more conservative treatments fail.

Suggested Further Reading

1. Benzon HT, Rathemell JP, Wu CL, Turk DC, Argoff CE (2008) Raj's practical management of pain, 4th edn. Mosby-Elsevier, Philadelphia
2. Bonica JJ, Loeser JD, Chapman CR, Fordyce WE (2001) The management of pain, 3rd edn. Lippincott, Williams & Williams, Philadelphia
3. Kandel ER, Schwartz JH, Jessell TM (2000) Principles of neural science, 4th edn. McGraw-Hill, New York
4. Longnecker DE, Brown DL, Newman MF, Zapol WM (2007) Anesthesiology, 1st edn. McGraw-Hill, New York
5. Sorkin L et al (1998) Atlas of anesthesia. Current Medicine Group, Philadelphia

Postoperative Anesthesia Care Unit and Common Postoperative Problems

31

Tarun Bhalla, Evelyn Lee, R. Dean Nava Jr., and Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page 640 are reviewed before reading this chapter.

T. Bhalla (✉)
Department of Anesthesia and Pain Medicine, Akron Children's Hospital, Akron, OH, USA
e-mail: tbhalla@akronchildrens.org

E. Lee
Northeast Ohio Medical University, Rootstown, OH, USA
e-mail: elee5@neomed.edu

R. Dean Nava Jr.
Department of Anesthesiology, Northwestern Memorial Hospital, Northwestern University, Chicago, IL, USA

J. M. Ehrenfeld
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: jesse.ehrenfeld@vanderbilt.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_31

Key Learning Objectives
- Learn the key elements of a PACU sign-out
- Review the most common postoperative anesthetic complications
- Understand the criteria for discharge from the PACU

Admission

Upon patient admission to the PACU, standard postoperative anesthesia care unit (PACU) monitors are placed and an initial evaluation, including a set of vital signs is obtained. HR, ECG, BP, RR, oxygen saturation, pain level, temperature, mental status, and level of nausea all need to be evaluated. These should be documented every 5 min for the first 15 min, then at least every 15 min afterwards. Invasive monitors (e.g. CVP, arterial line, PA or Swan-Ganz) are used if indicated by patient condition. Capnography may be used if the patient has an artificial airway or if there is concern for respiratory depression.

A directed yet **thorough sign-out** to the PACU care team is paramount in the care of patients in the postoperative period. Table 31.1 shows an example of a typical sign-out an anesthesiologist would give to the PACU staff.

Table 31.1 Sample PACU sign-out

Preoperative history	Medications, allergies, past medical history
	Underlying diagnosis
	Premedications
Intra-operative history	Procedure
	Anesthesia type
	Medications & fluids given
	Estimated blood loss, urine output
	Intra-operative events/problems
	Vital sign ranges
Patient status	Airway (preop exam, airway management, ETT position)
	Size, location of lines, catheters and invasive monitors
	Level of consciousness
	Pain level
	Intravascular volume status
	Overall impression
Postoperative instructions	Acceptable ranges (blood loss, vitals, urine output)
	Potential cardiovascular or respiratory problems
	Labs or diagnostic studies (CXR, ECG) if necessary
	Location and physician contact information

Postoperative Respiratory Complications

The most frequent complication in the PACU is **airway obstruction.** Common causes include:

- the tongue falling against the posterior pharynx (most common)
- laryngospasm (see below)
- glottic edema
- secretions/vomit/blood in the airway
- external pressure on the trachea (e.g. neck hematoma)

A clinical sign of partial obstruction is sonorous respiration. A sign of complete obstruction is absent breath sounds and often paradoxical movement of the chest with respiration.

Treatment modalities include **supplemental oxygen**, **head lift**, **jaw thrust**, **oral or nasal airway**, or **reintubation**. If the

patient displays signs of extrinsic compression of trachea, such as an expanding hematoma with airway compromise, reopening of the wound and drainage is therapeutic and can be lifesaving.

Laryngospasm (uncontrolled contraction of the laryngeal cords) may also be seen in the PACU. Clinical indicators may include a high-pitched crowing or silence if the glottis is totally closed. This may be more common after airway trauma, repeated airway instrumentation or with copious secretions (including blood or vomit in airway). Management includes positive pressure mask ventilation, oral or nasal airway, suctioning, small dose of succinylcholine if refractory, intubation, and finally cricothyroidotomy or jet ventilation if the inability to intubate or ventilate is encountered.

Common causes of **hypoventilation** in the PACU are residual depressant effects of anesthetics (most common), residual neuromuscular blockade, splinting from pain, diaphragmatic dysfunction after thoracic or upper abdominal surgery, distended abdomen, tight abdominal dressings, and increased CO_2 production (e.g. shivering, sepsis, and hypothermia). The clinical signs may include prolonged somnolence, slow respiratory rate, shallow breathing with tachypnea, and labored breathing. The signs may not become prominent until the $PaCO_2 > 60$ or pH <7.25. Treating the underlying cause is the mainstay of therapy, but until that is accomplished, control of ventilation is essential. Intubation may be necessary (hemodynamically unstable, severely obtunded, etc.). Provide an opioid antagonist (naloxone in increments of 0.04 mg IV) if an opioid overdose is a possibility, administer a cholinesterase inhibitor if residual paralysis is suspected. If the patient is splinting, consider increasing pain control measures depending on respiratory rate and mental status.

Common causes of **hypoxemia** in the postoperative setting are increased intrapulmonary shunting due to decreased FRC (most common), pneumothorax, prolonged ventilation with small tidal volumes, endobronchial intubation, bronchial obstruction by blood or secretions leading to collapse, aspiration, bronchospasm, pulmonary edema, and atelectasis. The early signs usually involve restlessness, tachycardia, and ventricular or atrial dysrhythmias. The late signs usually include hypotension, obtundation, bradycardia, and cardiac arrest. The treatment generally includes supplemental O_2, and the patient may need a nonrebreather mask. If

symptoms persist, the patient may need intubation until the underlying cause is found and corrected. A chest x-ray should be ordered immediately. Treatment obviously depends on the underlying cause. A chest tube should be placed if a pneumothorax or hemothorax is discovered and bronchodilators (e.g. albuterol) given if bronchospasm is suspected. Consider administering diuretics if there is fluid overload and performing a bronchoscopy if there is severe atelectasis due to obstructive plugs or aspiration.

Postoperative Hemodynamic Complications

The most common causes of hemodynamic compromise in the recovery unit can be differentiated into problems associated with **preload**, left and right **ventricular function**, and **afterload**. Hypotension can result from one or more of these causes, as outlined in Table 31.2.

The clinical signs of **hypotension** include a 20–30% baseline decrease in blood pressure, disorientation, nausea, change in consciousness, decreased urine output, and angina. Treatment of hemodynamic compromise should include fluid bolus, vasopressor agents, pleural aspiration if tension pneumothorax is sus-

Table 31.2 Causes of hypotension

Decreased preload	Hypovolemia (most common)
	"Third spacing" (fluid sequestration)
	Bleeding
	Wound drainage
	Venodilation due to spinal/epidural anesthesia
	Pericardial tamponade
	Tension pneumothorax
	Air embolism
Left ventricular dysfunction (impaired contractility)	Severe metabolic derangements (acidosis, sepsis, hypoxemia)
	Myocardial infarction
	Volume overload
	Dysrhythmias
Arterial vasodilatation (decreased afterload)	Possible inflammatory response
	Anesthetic-related

pected, pericardiocentesis if a cardiac tamponade is suspected, and invasive monitoring (arterial line, CVP, or PA catheter) if necessary. The treatment depends on the patient's clinical picture and underlying cause.

Postoperative **hypertension** is a frequent occurrence in the PACU. Common causes include noxious stimuli (most common), incisional pain, irritation from the endotracheal tube, distended bladder, previous history of hypertension, fluid overload, metabolic derangements (hypoxemia, hypercapnia, and acidosis), and intracranial hypertension. Clinical signs and symptoms include headache, bleeding, vision changes, angina, and ST changes on ECG. Treatment includes correcting the underlying problem, draining the bladder, providing analgesia, and correcting metabolic derangements. Be aware of the patient's baseline preoperative blood pressure, and use that as a target for titration. Specific medical therapies other than analgesia are listed in Table 31.3 below.

Postoperative **tachycardia** is often mediated by parasympathetic output or caused by medications such as atropine, glycopyrrolate, and muscle relaxants (e.g. pancuronium). See Table 31.4 for differential diagnosis of tachycardia. Signs and symptoms may include hypertension or hypotension and angina. Treatment includes treating the underlying cause, fluid bolus, draining the bladder, and pain control. Symptomatic treatment may be necessary to allow offending medications to wear off. Cardiac arrhythmias are also common causes of tachycardia. If atrial fibrillation occurs, consider beta blockade, calcium channel blockers, and

Table 31.3 Suggested medical therapies for hypertension

Mild to moderate hypertension	Beta blockers (labetalol, esmolol, metoprolol)
	Calcium channel blockers (nicardipine)
	Nitro paste
	Hydralazine
Severe or refractory hypertension (consider intra-arterial BP monitoring)	IV antihypertensive infusions
	Nicardipine
	Nitroglycerine
	Nitroprusside

Table 31.4 Causes of postoperative tachycardia

Noxious stimuli	Pain, anxiety
	Endotracheal tube
	Distended bladder
Physiologic derangements	Acidosis
	Hypoxemia
	Hypotension and hypovolemia
	Hypoglycemia
	Increased intracranial pressure
	Myocardial ischemia
Medications	Beta adrenergic vasopressors
	Dopamine
	Dobutamine
	Bronchodilators
Anesthetics	Ketamine
	Isoflurane

potentially cardioversion if the patient becomes hemodynamically unstable.

The most common causes of postoperative **bradycardia** are increased parasympathetic flow or decreased sympathetic output, which may additionally manifest as hypotension concomitant with the bradycardia. In cases of suspected increased parasympathetic output, consider muscarinic blocking agents such as atropine and glycopyrrolate. In cases of decreased sympathetic output, beta-mimetic agents such as ephedrine are useful. Table 31.5 outlines the most common causes of postoperative bradycardia.

Myocardial ischemia should always be part of differential diagnosis in patients with hemodynamic compromise. Risk factors for myocardial ischemia include CHF, valvular disease, low ejection fraction, smoking history, anemia, hypertension, and emergency surgery. Causes may include tachycardia (decreases time in diastole, leading to coronary hypoperfusion), hypotension, and hypoxemia. Clinical signs are angina, ECG changes, and dysrhythmias. Work-up and treatment includes treating underlying causes (pain control, fluid bolus, and anxiolysis), oxygen, aspirin, nitroglycerine, beta blockade, and morphine. Cardiac enzymes (e.g. troponin levels) should also be checked.

Table 31.5 Common causes of postoperative bradycardia

Medications	Neostigmine
	Phenylephrine, norepinephrine
	Opioids
	Succinylcholine
	Beta blockers
	Local anesthetics
	Ganglionic blockers
	High spinal/epidural anesthesia
Physical causes	Carotid sinus massage
	Valsalva maneuver
	Gagging
	Rectal exam
	Increased ocular pressure
	Distended bladder
	Stimulation of pharynx
Metabolic derangements	Severe academia
	Hypoxemia

Postoperative Neurologic and Other Complications

The most common cause of **delayed awakening** is residual anesthetic, sedative, or analgesic. Less common causes include hypothermia, metabolic derangements, and stroke. Management includes treating underlying causes (e.g. apply a forced air warming blanket, correct metabolic disturbances) or medication reversal. Naloxone reverses opioid effects, although the patient may need repeated doses if the half-life of the opioid is longer than naloxone. Flumazenil reverses benzodiazepine effects.

Another common complication is **altered mental status and emergence delirium**. Exacerbating factors are listed in Table 31.6.

Emergence delirium (ED) usually resolves in 10–15 min. Management includes verbal reassurance, adequate analgesia, correcting metabolic derangements, providing supplemental oxygen, adjunctive agents, arm restraints, and physostigmine if reaction is related to scopolamine or atropine (*central anticholinergic*

Table 31.6 Causes of postoperative mental status changes

Hypoxemia
Metabolic derangements
Cerebral hypoperfusion
Extremes of age
Emotionally significant operations
Presence of intraoperative recall
Scopolamine or atropine
Substance abuse
Pain, nausea, pruritus

syndrome). Adjunctive agents include dexmedetomidine, fentanyl, ketamine, clonidine, and propofol. The risk of ED is lowest when propofol is used as a single-agent anesthetic compared with sevoflurane-based anesthetics. Dexmedetomidine is considered the agent of choice in the incidence of emergence delirium. It also has been shown to improve symptomatic coverage for PONV and chills. Recent studies favor treatment with ketamine, particularly in combination with dexmedetomidine. Historically, benzodiazepines were used as treatment for delirium, but studies have shown a strong correlation between preoperative administration of benzodiazepines and increased risk of ED. However, while preoperative administration has been correlated with a significant risk for ED, many studies have also shown lower incidences of ED with perioperative benzodiazepine administration.

Postoperative neuropathy is a less common injury that may present postoperatively. Spinal cord injury can occur with positioning during intubation or with hematoma after neuraxial anesthesia, but this is very rare. More commonly seen are peripheral nerve injuries. These stretch or compression injuries may involve the ulnar nerve (compression of ulnar nerve at the postcondylar groove of humerus), peroneal nerve (compression of nerve against fibular head while in lithotomy), femoral nerve (due to exaggerated lithotomy position with "candy cane" stirrups), brachial plexus (due to over abduction of arms past 90° in the supine position or the neck being too far to one side), and long thoracic nerve (occurs with pneumonectomies, leading to winged scapula and

paralyzed serratus anterior muscle). Most symptoms resolve in 6–12 weeks, although permanent injuries may occur.

Corneal abrasions can be caused by ocular drying (eyes open during procedure), contact with eye during facemask ventilation or intubation, or the patient scratching his or her own eye upon awakening (hence the reason we ask the patient not to rub his or her eyes on the way to the recovery room). Signs and symptoms include excessive tear formation, photophobia, and decreased visual acuity. Treatment includes artificial tears, eye closure, and ocular antibiotics. Most corneal abrasions heal within 72 h.

The most common cause of **postoperative weakness** is residual neuromuscular blockade. Other causes include cerebrovascular accident and preexisting neuromuscular disorders (e.g. myasthenia gravis, Eaton–Lambert syndrome, periodic paralysis, and muscular dystrophies). This is clinically evident with poor respiratory effort, shallow breathing, rapid respiratory rate, and subjective skeletal muscle weakness reported by the patient. Treatment includes administration of neuromuscular reversal agents or reintubation until the weakness resolves. Sugammadex has been increasingly utilized for reversing neuromuscular blockade and has been shown to work as well as neostigmine. Studies show that sugammadex works faster than neostigmine in reversing neuromuscular blockade and is associated with less postoperative weakness comparatively. Although the use of sugammadex is safe to administer to pediatric patients, recent studies have reported concerns about sugammadex being associated with residual weakness. Sugammadex may lead to residual neuromuscular block without the appropriate nerve stimulating monitoring. While sugammadex is able to quickly and predictably reverse neuromuscular blockade, there are safety concerns of the drug in relation to hypersensitivity reactions and cardiac arrhythmias which can result in life-threatening events. The risk of such events is likely low, but ongoing vigilance and further research is needed.

Postoperative Nausea and Vomiting (PONV)

Up to 20–30% of surgical patients experience some degree of postoperative nausea and vomiting (PONV). Risk factors are listed in Table 31.7:

Treatment includes a number of modalities. An essential part of therapy is treating underlying factors (e.g. hypotension, hypoglycemia, elevated ICP, and GI bleeding). When nausea and vomiting occur postoperatively, treatment should be administered

Table 31.7 PONV contributing factors

Patient-related
Young women
Hiatal hernia
Obesity
History of postoperative nausea
History of motion sickness
Non-smokers have higher risk
Surgery-related
ENT, abdominal, gynecologic procedures
Extraocular muscle traction
Middle ear irritation
Peritoneal, intestinal irritation
Dental procedures
Anesthesia-related
Gas in stomach due to facemask ventilation
Use of nitrous oxide (controversial)
Use of parenteral opioids
Use of etomidate
Hypotension after spinal/epidural anesthesia
Postoperative care-related
Use of parenteral opioids
Postoperative oral fluid intake

with an antiemetic from a pharmacologic class that is different from the prophylactic drug initially given. If no prophylaxis was given, the recommended treatment is a low-dose serotonin receptor antagonist. **Serotonin receptor blockers**, such as ondansetron 0.1 mg/kg (max 4 mg) IV, at the end of surgery have few side effects and are commonly used. **Dexamethasone**, a steroid, is also a useful antiemetic, although its exact mechanism of action is unclear. It is given as a 4–8 mg IV dose just after induction. **Droperidol** is useful for breakthrough nausea but may lead to sedation and currently has an FDA mandated black box warning due to Q-T interval prolongation. Prior to treatment with droperidol, a 12- Lead ECG should be obtained from patients, and it should not be given to high-risk patients. Compazine, metoclopramide, and phenergan are also available medications (see Chap. 7, Pharmacology of Adjunct Agents). Multimodal therapy (i.e. drugs from several different classes) and prevention is most effective in the treatment of PONV. Non-pharmacological techniques such as acupressure, acupuncture, and transcutaneous electrostimulation have been used in addition to pharmacologic therapy and have been able to control emetic symptoms. By combining pharmacologic therapy and non-pharmacologic alternatives, prevention of PONV can be more effective without increasing side effects or potential for adverse drug interactions. Aromatherapy has also recently been used and has been shown to have a similar effectiveness to placebo, though the findings are still uncertain.

Pain Control

A plan for controlling postoperative pain depends on both patient and surgical factors. Pain medications can be given via intravenous, intramuscular or oral route. The intravenous route is often preferred because medications can be given in smaller doses, have more reliable uptake, and are more easily titrated. Common opioids and their basic properties are listed in Table 31.8. Patients who had a regional block placed may require fewer supplemental medications. Patients who have an epidural placed for

Table 31.8 Commonly used opioids in the PACU

Drug	Duration	Typical bolus dose
Fentanyl	Short acting	25–100 mcg IV
Hydromorphone (Dilaudid)	Intermediate to long duration	0.2–1 mg IV
Meperedine (Demerol)	Intermediate to long duration	50–100 mg IV/SC/IM
Morphine	Intermediate to long duration	2–5 mg IV

postoperative pain may receive both the local anesthetic and the opioid via the epidural catheter.

Non-steroidal anti-inflammatory drugs (NSAIDs), acetaminophen, and COX-2 Inhibitors are other classes of medications that are also very useful in the postoperative setting. Potential benefits include reducing opioid requirements, decreasing the incidence of nausea and vomiting, minimal effect on platelet function (COX-2 inhibitors), and fewer gastrointestinal side effects.

Ketorolac (Toradol) is a popular analgesic, but potentially deleterious side effects include platelet dysfunction and nephrotoxicity. It should be used with caution in patients with renal dysfunction, the elderly or those with increased risk of bleeding.

Hypothermia and Shivering

Hypothermia and shivering can result from a number of causes. Distributive heat loss, evaporation from skin prep, impaired function of normal thermoregulation from anesthetics and the higher rate of heat loss from patients with burns, traumatic injuries, or cachexia can all lead to a significant drop in body temperature and subsequent shivering. The physiologic impairments of both hypothermia and shivering are detailed below in Table 31.9.

The treatment of hypothermia and shivering includes forced air warming devices, patient reassurance, and meperidine in severe cases of shivering.

Table 31.9 Effects of hypothermia and shivering

Hypothermia
Increased oxygen consumption, carbon dioxide production
Elevates peripheral vascular resistance
Impairs platelet function, decreased clotting factors
Increased infection rates
May lead to cardiac dysrhythmias
Shivering
Increased oxygen consumption (up to 200%)
Increased carbon dioxide production (up to 200%)
Impairs monitoring devices
May lead to myocardial ischemia
May precipitate ventilatory compromise

Discharge Criteria

Discharge from the PACU is based on an array of clinical factors outlined below:

General Condition

The patient should be oriented to time, place, situation, and follow commands. Patient should be non-cyanotic and non-pallorous, and muscle strength needs to be appropriate. Nausea, pain, and any other major early postop complications should be absent or under control.

Hemodynamics

The patient's blood pressure should be within 20% of baseline preop value. The heart rate and rhythm should be stable for at least 30 min before discharge is considered. It is important to look out for common complications such as cardiac dysrhythmias and myocardial ischemia. Volume status also needs to be stable and hypo- or hypervolemia corrected.

Respiratory Status

A patient's respiratory rate should be around 10–25 breaths/min. Causes of either tachypnea or respiratory depression should be investigated prior to discharge. Secretions need to be coughed up and cleared adequately and the work of breathing acceptable.

Airway

Swallow and gag reflexes should be intact. No obstruction, stridor, or retraction should be present. Artificial airways should no longer be needed prior to discharge to the floor.

Pain Control

The patient should be able to identify and localize pain, and the analgesia for that pain should be adequate. The opioid requirement should be no shorter than every 15 min, and postoperative analgesia orders need to be appropriate for the situation.

Renal Function

It is important to monitor urine output (UO), with UO >0.5 cc/kg/h in catheterized patients usually considered adequate. In patients without a urinary catheter, voiding prior to discharge is no longer required, unless they had a spinal or have had problems with voiding in the past.

Labs and Diagnostic Tests

If checked, hematocrit needs to be appropriate compared to fluid losses sustained during surgery. Other labs should be checked as indicated, and electrolytes, glucose, coagulation labs, platelets,

and hematocrit corrected as needed. Other diagnostic tests, such as ECG and chest x-ray are obtained depending on specific patient indications (chest pain, hypoxia) and need to be evaluated prior to discharge home or to the floor.

Case Study

A 45-year-old woman has just undergone total abdominal hysterectomy. She is generally healthy, does not smoke or drink alcohol, and has not had general anesthesia ever before. She emerged from general anesthesia (thiopental, vecuronium, sevoflurane, and fentanyl) uneventfully. You accompany the patient to the PACU, assist the nurse with settling the patient, and obtain initial vital signs on arrival: BP 148/90, HR 77, SpO298% on facemask oxygen at 6 L/min.

Describe the elements of the report you will now give to the PACU nurse.

You begin with a brief summary of the patient's past medical history, the procedure performed, and a summary of the anesthetic course. You will tell the nurse about preoperative sedation (drugs, total dose, and time), antibiotics, induction agents, mask ventilation and intubation ease or difficulty, maintenance drugs, neuromuscular blockade, and reversal given. You will summarize opioids and other analgesics given and tell the nurse the last dose, amount, and time. You will summarize "ins and outs" by giving estimated blood loss, fluids given, and blood products given. Finally, you will discuss anything special: intraoperative problems, special drugs given (insulin, steroids, antiemetics, etc.), special concerns or requests the patient may have expressed, and plan for postop care if not routine.

After completing your report you leave the bedside to complete your paperwork. Before you return to the operating room, approximately 5 min after your initial arrival in the PACU, the nurse calls you back to the bedside. The patient is agitated, thrashing around in bed and not answer-

ing questions or following instructions to lie back and relax. What will be your initial steps in assessing the patient? What is the differential diagnosis?

Although this may be simple emergence delirium you must rule out other more serious problems, including hypoxia or hypercapnia. Check the patient's vital signs, especially looking for hypoxia or extreme hypertension. Make certain that the patient has a patent airway and is breathing, by physical examination. Make certain that the patient is agitated, not seizing.

You exclude emergencies and conclude the patient is experiencing emergence delirium. How will you respond?

Attempt to speak to the patient and calm her. If you are unable to do so, a small dose of short-acting sedative, such as midazolam, 1–2 mg, is reasonable. You and/or the nurse will still need to reassess the patient after getting her more calm.

The patient improves. One hour later you are called back to the PACU. The patient is complaining of pain. How will you assess the patient? What intervention will you recommend? Would your approach be different if the patient had undergone laparoscopic myomectomy and was scheduled to be discharged home later today?

You should speak to the patient and attempt to understand the origin of her pain. Is it incisional? Opioids are usually very effective in this setting. Although individual patient responses may modify your approach (for example, if you noted either unusual sensitivity or resistance to opioids intraoperatively), hydromorphone (Dilaudid), 0.2–0.4 mg boluses, or morphine, 3–5 mg boluses, titrated to effect, are common choices. If the patient is to be discharged home, it may be more prudent to use short-acting opioids such as fentanyl, 50–100 mcg boluses. In both cases you may also consider adjunctive drugs such as the NSAID ketorolac, 30 mg, if not contraindicated by the presence of renal disease or severe bleeding.

The pain is under control 30 min later, but the patient now complains of nausea. How will you respond?

This patient has moderately high risk for PONV, as a nonsmoking female who has received significant opioids (the fourth risk factor in the simplest assessment scale is previous history of PONV or motion sickness). If she has not received any prophylactic antiemetics, ondansetron, 1–4 mg IV, is a reasonable first choice. If she already received this drug for prevention of PONV, then an agent from another class is more prudent. Options include droperidol or haloperidol, prochlorperazine (Compazine), hydroxyzine (Vistaril), promethazine (Phenergan), metoclopramide (Reglan) or scopolamine. The latter is typically given as a transdermal patch, which takes several hours to reach a peak effect.

When can the patient be discharged from the PACU? How would your criteria differ if the patient were being discharged home after laparoscopy instead?

The patient should be oriented to person, place, time, and situation. Her pain and nausea should be under reasonable control, but it is not necessary for her to be completely pain free or to be completely without nausea. These symptoms may persist for hours or even days in the case of postoperative pain. The point is to have reached a stable and tolerable equilibrium. She should be fluid replete, as indicated in part by acceptable urine output, and if bleeding has been significant, her hemoglobin should be in a range not requiring transfusion (generally higher than 7 g/dL). Her vital signs should be stable and there should be no respiratory problems other than a possible requirement for supplemental oxygen. If she is to be discharged home, she should have no oxygen requirement, and she should be able to ambulate with minimal assistance. She must have a competent adult to accompany her home.

Suggested Further Reading

1. Barash PG, Cullen BF, Stoelting RK (eds) (2006) Clinical anesthesia, 5th edn. Lippincott, Williams and Wilkins, Philadelphia
2. Morgan GE, Mikhail MS, Murray MJ (eds) (2006) Clinical anesthesiology, 4th edn. McGraw-Hill, New York
3. Practice advisory for the prevention of perioperative peripheral neuropathies: a report by the American Society of Anesthesiologists Task Force on Prevention of Perioperative Peripheral Neuropathies (2000) Anesthesiology 92:1168–1182
4. American Society of Anesthesiologists Task Force on Postanesthetic Care (2002) Practice guidelines for postanesthetic care: a report by the American Society of Anesthesiologists Task Force on Postanesthetic Care. Anesthesiology 96:742–752
5. Gan TJ, Meyers T, Apfel CC et al (2003) Consensus guidelines for managing post-operative nausea and vomiting. Anesth Analg 97:62–71
6. American Society of Anesthesiologists Task Force on Acute Pain Management (2004) Practice guidelines for acute pain management in the perioperative setting: an updated report by the American Society of Anesthesiologists Task Force on Acute Pain Management. Anesthesiology 100:1573–1581
7. Moore AD, Anghelescu DL (2017) Emergence delirium in pediatric anesthesia. Paediatr Drugs 19(1):11–20
8. Viswanath O, Kerner B, Jean Y-K, Soto R, Rosen G (2015) Emergence delirium: a narrative review. J Anesthesiol Clin Sci 4(1):2
9. Carron M, Zarantonello F, Tellaroli P, Ori C (2016) Efficacy and safety of sugammadex compared to neostigmine for reversal of neuromuscular blockade: a meta-analysis of randomized controlled trials. J Clin Anesth 35:1–12
10. Lorinc AN, Lawsom KC, Niconchuk JA, Modes KB, Moore JD, Brenn BR (2020) Residual weakness and recurarization after Sugammadex Administration in pediatric patients: a case series. A&A Pract 14(7):e01225
11. Naguib M, Brull SJ, Arkes HR (2013) Reasoning of an anomaly: residual block after sugammadex. Anesth Analg 117(2):297–300
12. Honing G, Martini CH, Bom A, van Velzen M, Niesters M, Aarts L, Dahan A, Boon M (2019) Safety of sugammadex for reversal of neuromuscular block. Expert Opin Drug Saf 18(10):883–891
13. Gan TJ, Diemunsch P, Habib AS, Kovac A, Kranke P, Meyer TA, Watcha M, Chung F, Angus S, Apfel CC, Bergese SD, Candiotti KA, Chan MT, Davis PJ, Hooper VD, Lagoo-Deenadayalan S, Myles P, Nezat G, Philip BK, Tramèr MR, Society for Ambulatory Anesthesia (2014) Consensus guidelines for the management of postoperative nausea and vomiting. Anesth Analg 118(1):85–113

14. Tateosian VS, Champagne K, Gan TJ (2018) What is new in the battle against postoperative nausea and vomiting? Best Pract Res Clin Anaesthesiol 32(2):137–148
15. Cao X, White PF, Ma H (2017) An update on the management of postoperative nausea and vomiting. J Anesth 31(4):617–626
16. Kiberd MB, Clarke SK, Chorney J, d'Eon B, Wright S (2016) Aromatherapy for the treatment of PONV in children: a pilot RCT. BMC Complement Altern Med 16(1):450

Introduction to Critical Care

32

Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xxxi are reviewed before reading this chapter.

Key Learning Objectives

- Review basic concepts of oxygen balance in the body
- Understand the diagnosis and treatment of common conditions encountered in the intensive care setting such as shock, sepsis, and acute respiratory failure
- Learn the basic principles, indications, and complications associated with hemodynamic monitoring techniques such as arterial line, CVP and pulmonary artery catheter
- Discuss the basic modes of mechanical ventilation
- Review other supportive therapies in the ICU

J. M. Ehrenfeld (✉)
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: jehrenfeld@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_32

Initial Assessment of the Critically Ill Patient

In a seriously ill patient, it is often necessary to provide resuscitation before making a definitive diagnosis. Begin with the ABCs (Airway, Breathing, and Circulation) and focus on stabilization as the work-up and diagnosis are ongoing. Ensure a patent airway and stable vital signs, while proceeding further to work-up with history, physical exam, laboratory and radiographic testing, and other diagnostic procedures.

Oxygen Balance

When managing critically ill patients, it is important to have an understanding of oxygen balance, including oxygen delivery to the tissues and oxygen consumption by the tissues.

Oxygen Transport

Oxygen transport involves the loading of blood with oxygen in the lungs, delivery of oxygen from the blood to tissues, and return of unused oxygen to the cardiopulmonary circulation. The amount of oxygen contained in arterial blood can be defined by the arterial oxygen content (CaO_2) equation:

$$CaO_2 = \left[Hb \times 1.34 \times SaO_2\right] + \left[PaO_2 \times 0.003\right]$$

where Hb = hemoglobin concentration, SaO_2 = % hemoglobin saturation with oxygen, and PaO_2 = partial pressure of dissolved oxygen.

Global oxygen delivery (DO_2) to the body depends on this arterial oxygen content (CaO_2) as well as cardiac output (CO):

$$DO_2 = CaO_2 \times CO$$

Global oxygen consumption (VO_2) is the total oxygen consumption by all of the body's organs and tissues. Normal oxygen consumption is ~3 ml/kg/min O_2. The amount of oxygen that is returned to the cardiopulmonary circulation from the venous side is termed the mixed venous oxygen saturation (SvO_2). The oxygen extraction ratio (O_2ER) is defined as oxygen consumption divided by oxygen delivery:

$$O_2ER = \left(VO_2 / DO_2\right) \times 100$$

Under normal conditions, the body extracts approximately 30–35% of the delivered oxygen and the rest is returned to the heart as the mixed venous oxygen. *Thus, normal mixed venous oxygen saturation is 65–70%.*

The body is capable of increasing oxygen extraction for brief periods during exercise or stress up to a maximum O_2ER of about 70%. Any further or prolonged increase in oxygen consumption (or decrease in oxygen delivery) will result in cellular hypoxia, anaerobic metabolism, and the production of lactic acid.

Recall from the above arterial oxygen content equation that hemoglobin concentration (Hb) and hemoglobin saturation (SaO_2) influence the oxygen content. The relationship between partial pressure of oxygen in the blood and hemoglobin saturation is defined by the oxyhemoglobin dissociation curve (Fig. 32.1). The position of this curve is affected by pH, temperature, $PaCO_2$, and 2,3-diphosphoglycerate (2,3-DPG). Shifting of the curve to the left or right will alter the ability of hemoglobin to bind oxygen. As the curve shifts to the right, hemoglobin has less affinity for oxygen, and thus more oxygen will be released to the tissues. As the curve shifts to the left, hemoglobin binds oxygen more tightly and releases less to the tissues. During periods of stress (such as metabolic acidosis), the curve is shifted to the right to allow more oxygen to be delivered to the tissues.

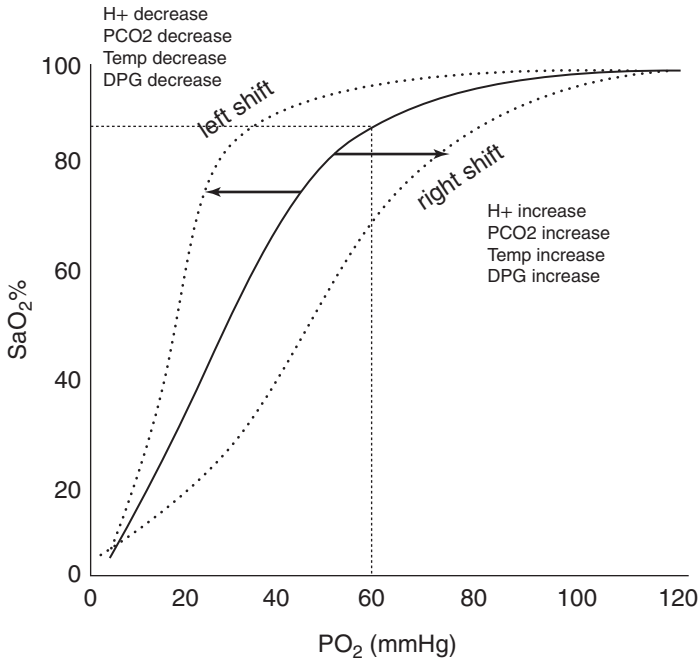


Fig. 32.1 Oxyhemoglobin dissociation curve. This curve defines the relationship between partial pressure of oxygen in the blood and the percent of hemoglobin that is saturated with oxygen. The position of this curve is influenced by factors such as H+ concentration, PaCO2, temperature, and 2–3-diphosphoglycerate (DPG). (Image Courtesy J. Ehrenfeld)

Markers of Oxygen Balance and Tissue Perfusion

Lactate

When the body's oxygen balance is such that oxygen demand exceeds oxygen supply, cells become hypoxic and convert to anaerobic metabolism. Lactic acid (lactate) is a by-product of anaerobic metabolism and can be measured in the blood. Elevated lactate levels are associated with tissue hypoperfusion and poor oxygenation. Although other factors can affect lactate levels, the presence of elevated lactate can therefore be used as an indirect marker of poor tissue perfusion and shock.

Central Venous and Mixed Venous Blood Oxygen Saturation

When a central venous catheter is in place, blood can be drawn from the superior vena cava (distal port) and sent to the lab for measurement of central venous blood oxygen saturation. Central venous blood oxygen saturation ($ScvO_2$) correlates well with mixed venous blood oxygen saturation (SvO_2) in most circumstances, and can be used to reflect tissue oxygenation. Normal $ScvO_2$ is approximately 70% (compared to normal SvO_2 of approximately 65%). Lower than normal $ScvO_2$ or SvO_2 is an indication of poor tissue oxygenation and the need for improved oxygen delivery and perfusion. The advantage of using $ScvO_2$ is that it does not require a pulmonary artery catheter (versus SvO_2 which is drawn from the pulmonary artery).

Hemodynamic Monitoring (Also See Chap. 11)

Goals

The goals of hemodynamic monitoring in the critically ill patient are to optimize perfusion and oxygen delivery to tissues, ensure rapid detection of changes in clinical status, and monitor for response to treatment. Although noninvasive monitors (such as a blood pressure cuff) are associated with less risks and complications, it is often necessary to use invasive monitoring techniques to achieve these goals.

Invasive Arterial Blood Pressure Monitoring

A common cause of admission to the intensive care unit is hypotension, which may be due to any number of etiologies (see section "Shock" below). Blood pressure monitoring with a noninvasive cuff may be adequate, but if the blood pressure is significantly low, it may be undetectable or inaccurate by a cuff.

In addition to being the most accurate form of blood pressure monitoring, arterial cannulation allows continuous beat-to-beat monitoring. It also serves as a site for obtaining lab measurements of oxygenation, ventilation, and acid–base status. The most common sites for arterial cannulation are radial or femoral arteries, but other arteries may be used if necessary (see Chap. 15, IV, Arterial & Central Line and Gastric Tube Placement Techniques).

Complications associated with arterial cannulation and precautions to decrease the incidence of complications are listed in Table 32.1.

Volume status can be assessed by evaluating the arterial pressure height during controlled mechanical ventilation. Positive pressure ventilation will lead to significant systolic variation (>10 mmHg) of the blood pressure in patients who are hypovolemic (Fig. 32.2).

Table 32.1 Complications associated with arterial cannulation

Complication	Precautions to decrease risk
Hematoma	Avoid multiple needle punctures/attempts Apply pressure if artery punctured
Bleeding	Caution in coagulopathic patients Apply pressure to bleeding site
Thrombosis	Avoid multiple needle sticks Use continuous flush system Avoid prolonged catheterization
Vasospasm	Avoid multiple or traumatic punctures/attempts at cannulation
Air embolism	Caution when flushing catheter
Nerve damage	Avoid sites in close proximity to nerve
Infection	Use sterile technique Avoid prolonged catheterization
Intra-arterial drug injection	Keep venous and arterial lines well-organized, separated, and clearly labeled
Ischemia	Avoid traumatized sites Avoid prolonged catheterization Place pulse oximeter on ipsilateral side to verify perfusion

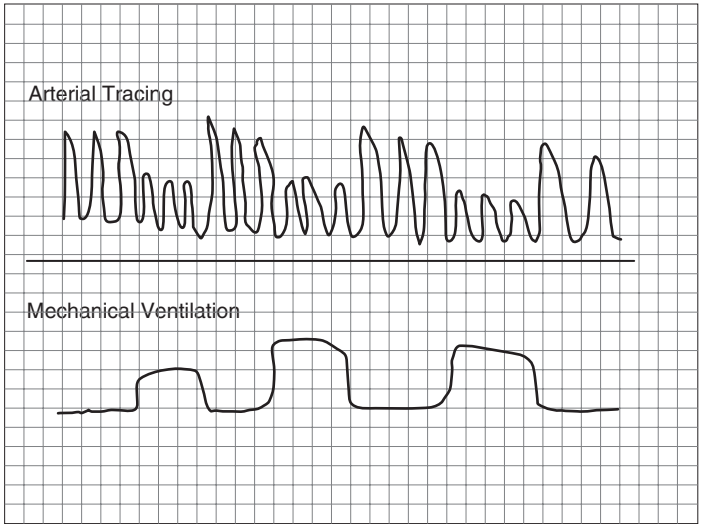


Fig. 32.2 Arterial blood pressure tracing showing systolic pressure variation with three consecutive breaths during changes in mechanical ventilation. During the three respective breaths, the systolic blood pressures drop. (Courtesy, J. Ehrenfeld)

Cardiac Output

Recall that global oxygen delivery (DO_2) to the tissues is dependent on the oxygen content of blood (CaO_2) as well as cardiac output (CO). Cardiac output is equal to the product of heart rate (HR) and stroke volume (SV):

$$CO = HR \times SV$$

The variables that affect stroke volume include **preload, afterload, and contractility**. *Preload* is an estimate of left ventricular volume at the end of diastole. The Frank-Starling curve shows the relationship between preload and stroke volume (Fig. 32.3). In general, increases in preload lead to greater stroke volume. However, a point on the Frank-Starling curve is eventually reached where further increases in preload do not increase stroke volume and may instead lead to decreased stroke volume (as in congestive

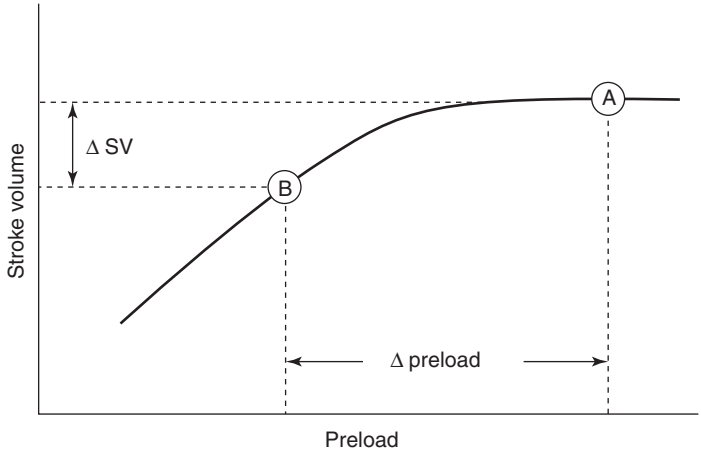


Fig. 32.3 Frank-Starling curve. This curve shows the relationship between preload (end-diastolic volume) and stroke volume. Increases in preload lead to increased stroke volume until a point is reached where further increases in end-diastolic volume lead to congestive heart failure (point B to point A). (Courtesy, J. Ehrenfeld)

heart failure). Because it is difficult to measure ventricular volume, ventricular pressure is commonly used to estimate volume and thus preload. Use of a central venous catheter enables monitoring of right atrial pressure or central venous pressure (CVP), which is an estimate of right ventricular preload. In a patient without significant pulmonary hypertension or valvular disease, it can be assumed that right ventricular preload correlates with left ventricular preload because the same blood volume that enters the right heart will traverse to enter the left heart. By way of this assumption, CVP is often used as an estimate of left ventricular preload.

Afterload refers to the myocardial wall tension that is required to overcome the opposing resistance to blood ejection. Right ventricular afterload is clinically represented by the pulmonary vascular resistance (PVR) and left ventricular afterload is clinically represented by the systemic vascular resistance (SVR). SVR may

be calculated from the following equation when cardiac output measurements are obtained:

$$\mathrm{SVR} = \left[\left(\mathrm{MAP} - \mathrm{CVP}\right) / \mathrm{CO}\right] \times 80$$

where MAP = mean arterial pressure.

Contractility refers to the ability of the myocardium to contract and eject blood from the ventricle. Contractility depends on preload and afterload so these variables should be optimized first in order to improve contractility. Contractility can be directly measured with the use of echocardiography to estimate ejection fraction. However, once preload and afterload are optimized, contractility is often indirectly represented by cardiac output. If cardiac output remains low despite improvements in preload and afterload, the use of inotropic pharmacologic agents may be initiated to improve contractility.

Central Venous Pressure Monitoring

As described above, invasive CVP monitoring allows continuous measurement of right heart pressures, which can be used to reflect preload. Normal CVP during positive pressure ventilation ranges from 6 to 12 mmHg. A low CVP with hypotension and tachycardia most often corresponds to hypovolemia. Persistent hypotension following a fluid challenge and higher than normal CVP indicates cardiac congestion (as may occur with cardiac tamponade, tension pneumothorax, or myocardial ischemia).

Cannulation sites for CVP placement include subclavian, internal jugular, and femoral veins (also see Chap. 15, IV, Arterial & Central Line and Gastric Tube Placement Techniques). Complications associated with the placement of a central line are presented in Table 32.2. To reduce the number of cannulation attempts and the risk of inadvertent arterial puncture, direct visualization with ultrasound guidance should be used when possible during placement of a central line.

Table 32.2 Complications associated with central venous and pulmonary artery catheterization

Complication	Precautions to decrease risk
Hematoma	Avoid multiple needle punctures/attempts Apply pressure if vein or nearby artery punctured
Bleeding/hemorrhage	Caution in coagulopathic patients Apply pressure to bleeding site
Air or thrombotic embolism	Caution with infusions Use head-down tilt and avoid open catheter to air Avoid prolonged catheterization and use continuous flush
Carotid artery puncture/cannulation	Use appropriate landmarks ± sonographic visualization Use small finder needle; transduce pressure to verify venous
Pneumothorax/ hemothorax[a]	Use appropriate landmarks Avoid multiple needle sticks No risk with femoral vein Risk with internal jugular < risk with subclavian
Infection/bacteremia/ endocarditis	Use strict sterile technique[b] Avoid prolonged catheterization
Nerve trauma	Use appropriate landmarks and avoid sites in close proximity to nerves
Thoracic duct damage/chylothorax	Avoid left subclavian and internal jugular when possible
Complete heart block	Extreme caution placing PAC in patient with LBBB
Cardiac dysrhythmias	Use ECG monitoring while placing catheter and avoid prolonged placement of wire/catheter in atria/ventricles
Pulmonary ischemia/ infarction	Do not keep PAC continuously wedged Minimize balloon inflation time
Pulmonary artery rupture Myocardial perforation	Do not over-wedge PAC; avoid balloon hyperinflation Always inflate balloon before advancing catheter, but never inflate balloon against significant resistance Always deflate balloon before withdrawing catheter

PAC pulmonary artery catheter, *LBBB* left bundle branch block, *ECG* electrocardiogram.

[a]A chest xray should always be performed after catheterization to verify correct positioning and absence of pneumothorax/hemothorax

[b]Strict sterile technique includes handwashing, sterile gloves, gown, mask, hat, patient drape, and sterile prep with chlorhexidine

Pulmonary Artery Catheter

As described above, left Pulmonary artery catheter (PAC)heart pressures may be estimated from right heart pressures in most circumstances and CVP may be used to approximate pulmonary capillary wedge pressure (PCWP). However, when left ventricular function is impaired, or significant valvular disease or pulmonary hypertension is present, the use of a pulmonary artery catheter (PAC) may be indicated for more accurate estimations of left heart pressures. Use of a PAC allows continuous monitoring of pulmonary artery pressures, intermittent monitoring of PCWP, and thermodilution for estimation of cardiac output and calculation of systemic vascular resistance. PCWP is used as the best estimation of left ventricular end-diastolic volume (preload), analogous to CVP estimation for the right ventricle.

The PAC can also be used to obtain blood samples for mixed venous oxygen saturation (SvO_2) in order to evaluate oxygen balance. Risks associated with PAC placement include those associated with central line placement as well as additional risks (Table 32.2). Table 32.3 in the next section shows how the use of a PAC can help in the determination of common hemodynamic disturbances in shock.

Table 32.3 Hemodynamic disturbances in shock

Shock type	Central venous pressure or pulmonary capillary wedge pressure	Cardiac output	Systemic vascular resistance
Hypovolemic	Decreased	Decreased	Increased
Cardiogenic	Increased	Decreased	Increased
Distributive	Depends on volume status (initially decreased)	Normal or increased	Decreased
Obstructive	Increased	Decreased	Increased

Shock

Shock is a disorder of impaired tissue perfusion and results when oxygen delivery is inadequate to meet the demands of oxygen consumption or when tissues are unable to adequately utilize delivered oxygen. Hypotension is often present in shock, but shock can also occur without hypotension due to compensatory mechanisms that serve to augment blood pressure. Many other clinical signs of shock may be present, including altered mental status, organ dysfunction such as low urine output, cold extremities, acidosis, tachycardia, tachypnea, and any other sign of impaired perfusion. If not rapidly treated, shock can lead to irreversible tissue injury, organ failure, and death.

Classification of Shock

Shock is classified into four main categories. Although this classification can be useful in the diagnosis and management of shock, patients may simultaneously suffer from more than one category of shock. Table 32.4 shows the four main types of shock and lists examples of each.

Table 32.4 presents the most likely hemodynamic disturbances that are associated with each type of shock.

Table 32.4 Classification of shock and examples

Shock type	Examples
Hypovolemic	Dehydration, hemorrhage
Cardiogenic	Acute myocardial infarction, congestive heart failure
Distributive	Sepsis, anaphylaxis, neurogenic shock
Obstructive	Cardiac tamponade, tension pneumothorax

Management of Shock

The primary goal in the management of shock is to restore perfusion and oxygen delivery to vital tissues before organ failure develops. This goal is accomplished by improving hemodynamics (including blood pressure and cardiac output) and optimizing oxygen balance. Specific therapy depends on the type of shock. In general, patients with shock will require invasive monitoring to assist in the diagnosis and to monitor response to treatment. Many patients will also require endotracheal intubation and mechanical ventilation, particularly if their work of breathing is increased by metabolic acidosis. Fluid therapy is indicated in almost all forms of shock (with the exception of congestive heart failure and cardiogenic shock) as a means of increasing preload, cardiac output, and blood pressure. *A reasonable blood pressure goal for most patients is a mean arterial pressure (MAP) ≥ 65 mmHg*. In patients with a history of hypertension or who already manifest signs of organ failure, a higher blood pressure may be necessary to optimize tissue perfusion. Beyond fluids, vasoactive agents can be utilized in order to augment blood pressure. Other therapy can be used to improve each of the components of oxygen delivery while at the same time trying to reduce oxygen demand. It is important to search for and treat the underlying cause of shock while continuing resuscitation. Measures of tissue perfusion, including $ScvO_2$ (or SvO_2 if a pulmonary artery catheter is in place) and lactate can be followed to assess the response to treatment and guide further therapy.

Vasoactive Agents Commonly Used in Shock

Vasoactive agents are indicated for management of patients with shock who do not respond adequately to fluid therapy. These medications may include vasopressors, vasodilators, chronotropes, and/or inotropes. Many of the vasoactive medications used to treat shock have more than one mechanism of action. Table 32.5 lists some of the commonly used vasoactive agents along with their mechanism of action (also see Chap. 7).

Table 32.5 Commonly used vasoactive agents in shock

Agent	Mechanism of action (receptor)
Dopamine	Chronotropy (β1), Inotropy (β1) > Vasoconstriction (α at higher doses)
Dobutamine	Chronotropy (β1), Inotropy (β1) > Vasodilation (β2)
Epinephrine	Chronotropy (β1), Inotropy (β1) > Vasoconstriction (α at higher doses)
Norepinephrine	Vasoconstriction (α) > Chronotropy (β1), Inotropy (β1)
Phenylephrine	Vasoconstriction (α1)
Vasopressin	Vasoconstriction (V1)

Septic Shock

Septic shock is a form of distributive shock caused by infection and should be managed in concordance with the formal guidelines that have been devised by the **Surviving Sepsis Campaign**. In addition to the management principles used to treat any form of shock, it is crucial to search for and control the source of infection with the early initiation of broad-spectrum antibiotics and if necessary, surgical debridement. An overview of the management of septic shock is presented in Table 32.6.

Acute Respiratory Failure

Acute respiratory failure (ARF) is another Acute respiratory failure (ARF)common disorder leading to intensive care unit admission. Respiratory failure may develop from primary pulmonary disorders or as a result of other systemic disorders. Clinical signs of acute respiratory failure may include altered mental status, tachypnea, increased work of breathing, use of accessory respiratory muscles, decreased oxygen saturation, cyanosis, and other nonspecific systemic signs such as tachycardia and hypertension. ARF may be divided into two types – oxygenation failure (hypoxemic respiratory failure) or ventilation failure (hypercapnic respi-

Table 32.6 Overview of the management of septic shock

1. Resuscitation
(a) Hemodynamic goals
MAP ≥65 mmHg Urine output ≥0.5 ml/kg/h CVP 8–12 mmHg (12–15 mmHg if mechanically ventilated) $ScvO_2 \geq 70\%$ (or $SvO_2 \geq 65\%$)
(b) Begin with fluid resuscitation if the patient is hypotensive or has elevated lactate > 4 mmol/L Minimum 30 mL/kg crystalloid Consider colloid (albumin) if patient requiring considerable fluid Avoid hydroxyethyl starches Continue fluid resuscitation as long as patient shows hemodynamic improvement
(c) Add a vasopressor if the patient is not responding appropriately to fluid resuscitation
Use an arterial line if vasopressors are required Norepinephrine is the first-line vasopressor Vasopressin may be added to norepinephrine if needed Epinephrine if additional agent needed
(d) Consider administration of steroids only if the patient has a poor response to fluids and vasopressor therapy
(e) Consider inotropic support with dobutamine if not meeting hemodynamic goals with above measures (especially if evidence of myocardial dysfunction) (f) Consider a blood transfusion if Hb<7 g/dl
2. Diagnosis – try to obtain cultures before giving antibiotics
(a) Blood cultures (b) Sputum culture (c) Urine culture (d) Culture other sites as indicated by history and physical exam (e) Imaging studies (chest radiograph and other studies as indicated by history and exam)
3. Source control
(a) Evaluate for a focus of infection that can be drained or surgically debrided (b) Consider foreign bodies as a possible infectious source (such as central lines)

(continued)

Table 32.6 (continued)

4. Antibiotic therapy
(a) It is vitally important to start antibiotics within the first hour of hypotension
(b) Initiate broad-spectrum antibiotics
(c) Follow cultures daily and de-escalate antibiotics as appropriate
(d) Treat for 7–10 days (unless extenuating circumstances)
(e) Stop antibiotics if shock determined to be caused by a noninfectious source
5. Other supportive care (see sections "Acute Respiratory Distress Syndrome" and "Supportive Care in the ICU") – low tidal volume ventilation, glucose management, thromboprophylaxis, ulcer prophylaxis, nutrition

ratory failure). Patients may also have combined oxygenation and ventilation failure.

Hypoxemic Respiratory Failure

Hypoxemic respiratory failure is usually a result of mismatched alveolar ventilation (V) and perfusion (Q). Many disease processes can result in areas of alveolar hypoventilation relative to perfusion (termed low V/Q). This is otherwise known as an intrapulmonary shunt (Fig. 32.4). Examples of such disease processes that lead to intrapulmonary shunting include pneumonia, atelectasis, pulmonary edema, aspiration, and pneumothorax. As blood flows to poorly ventilated alveoli, it is unable to pick up adequate amounts of oxygen and thus returns poorly oxygenated blood to the heart. This poorly oxygenated blood dilutes oxygenated blood, causing systemic hypoxemia.

Other causes of hypoxemia include increased dead space (see below), decreased partial pressure of inspired oxygen (such as in areas of high altitude with low inspired oxygen tension), left-to-right cardiac shunting, alveolar hypoventilation, and diffusion abnormalities.

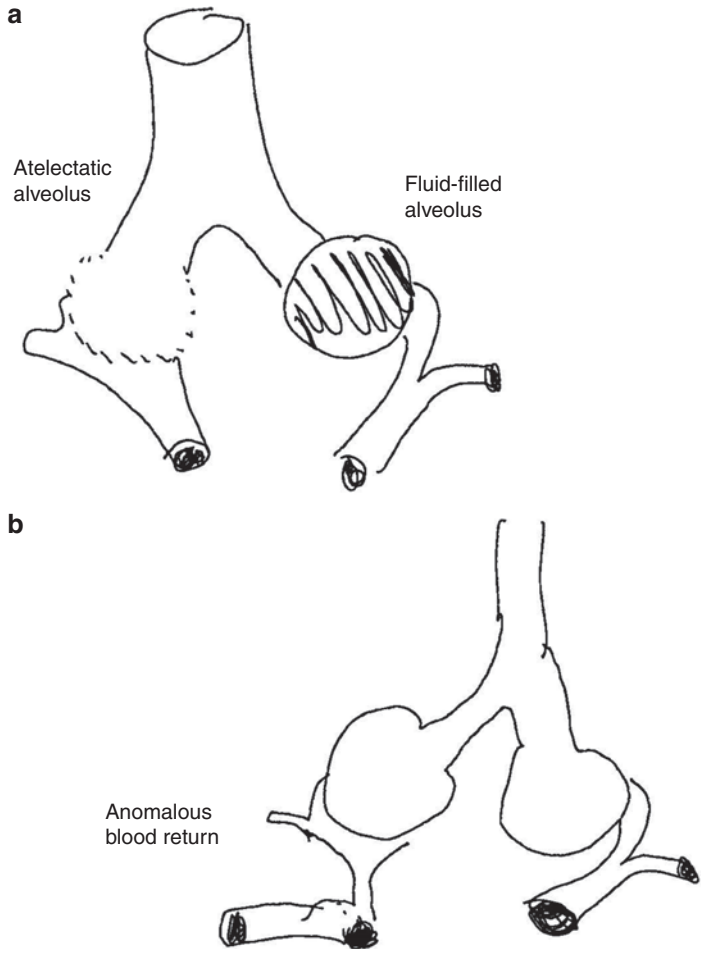


Fig. 32.4 Examples of intrapulmonary shunt. (**a**) Collapsed and fluid-filled alveoli are examples of intrapulmonary shunt. (**b**) Anomalous blood return of mixed venous blood bypasses the alveolus and thereby contributes to the development of intrapulmonary shunt. (Image Courtesy J. Ehrenfeld)

Hypercapnic Respiratory Failure

Hypercapnic respiratory failure results from any disorder than leads to decreased alveolar minute ventilation. Minute ventilation (Va) is defined by the following equation:

$$\mathrm{Va} = \mathrm{f} \times \left(\mathrm{Vt} - \mathrm{Vd} \right)$$

where f = respiratory rate, Vt = tidal volume, and Vd = dead space.

Therefore, decreased minute ventilation can result from decreases in respiratory rate or tidal volume (such as occurs with sedation and anesthesia) and/or increases in dead space ventilation. Dead space ventilation includes any area of the respiratory tract that is ventilated but not perfused. If alveoli are underperfused, CO_2 cannot diffuse out of the blood via gas exchange and is therefore returned to the circulation, resulting in hypercapnia. Dead space may be anatomic or physiologic. Anatomic dead space results from airways that normally do not participate in gas exchange such as the trachea and bronchi. Physiologic dead space results from alveoli that are ventilated, but not adequately perfused. Physiologic dead space can occur from poor cardiac output resulting in inadequately perfused alveoli. Another example of physiologic dead space occurs with pulmonary embolus, where blood flow to an area of the lungs is obstructed.

Management of Acute Respiratory Failure

While the cause of respiratory failure is being investigated, it is important to ensure a patent airway and support of oxygenation and ventilation. Supplemental oxygen should be provided and if necessary, the patient should be intubated and managed with mechanical ventilation. Appropriate diagnostic tests include history and physical exam, arterial blood gas measurement, chest radiograph, and additional testing based on these findings and the likely etiology of the respiratory failure.

Acute Respiratory Distress Syndrome (ARDS)

Acute lung injury (ALI) is a complex process of injury to the lungs involving cytokines and damage to the alveolar-endothelial barrier, which leads to increased pulmonary microvascular permeability and edema. Diagnostic criteria for ARDS have been defined by an international consensus committee and include:

- Acute process (within 1 week of clinical insult)
- Severe hypoxemia ($PaO_2/FiO_2 < 300$ mmHg)
- Bilateral diffuse pulmonary infiltrates seen on chest radiograph
- Evidence of noncardiogenic pulmonary edema

Further, the severity of ARDS is classified by the PaO2/FiO2 ratio as follows: PaO2/FiO2 ratio < 300 is mild ARDS, PaO2/FiO2 ratio < 200 is moderate ARDS, and PaO2/FiO2 ratio < 100 is severe ARDS. Increased severity correlates with increased mortality rates. There are many possible etiologies that lead to ARDS, including both pulmonary and extra-pulmonary causes. In addition, it is known that mechanical ventilation can cause or exacerbate lung injury by volutrauma (overdistention of alveoli), barotrauma (high plateau pressures), and/or atelectrauma (shear stress of opening and closing of alveoli). The ARDS Network found that mortality is significantly reduced when patients with ARDS are ventilated with lower tidal volumes. There has also been much study and debate regarding optimal pressures, levels of PEEP, and modes of ventilation in ARDS. Management of ARDS includes supportive care while treating the underlying cause and avoiding further ventilator-induced lung injury. In addition, salvage therapies may be indicated for patients with such severe ARDS that they cannot maintain adequate oxygenation to support tissue and organ function. Such therapies include the use of alternative modes of ventilation, prone positioning, inhaled nitric oxide, and extracorporeal membrane oxygenation. While these therapies can improve oxygenation and provide temporary support, none of them have been shown to influence the mortality associated with ARDS.

Mechanical Ventilation

When patients develop respiratory failure such that they cannot maintain adequate oxygenation and/or ventilation, it is often necessary to provide mechanical ventilation.

Indications for mechanical ventilation include:

- hypoxemic respiratory failure
- hypoventilatory (hypercapnic) respiratory failure
- need for sedation or neuromuscular blockade
- need for hyperventilation to control intracranial pressure
- airway protection

Commonly Used Modes of Ventilation

Assist-Control Ventilation (Also Known as CMV, Continuous Mandatory Ventilation)

Assist-control ventilation may be delivered with volume-cycled breaths (**volume control**) or time-cycled breaths (**pressure control**). The patient may trigger breaths or breathe over the set rate, but the machine guarantees the minimum number of breaths that are preset. Regardless of whether each breath is patient-triggered or machine-triggered, the patient will receive the full preset tidal volume or preset applied pressure. This serves to decrease the patient's work of breathing. During volume control ventilation, a preset tidal volume is delivered to the patient at a set rate. The peak pressure may vary per breath depending on the patient's lung mechanics and compliance. Pressure control ventilation involves a preset inspiratory time and applied pressure instead of a preset tidal volume. Thus, the tidal volume will vary with each breath. Figure 32.5 shows pressure, volume, and flow tracings for pressure control versus volume control.

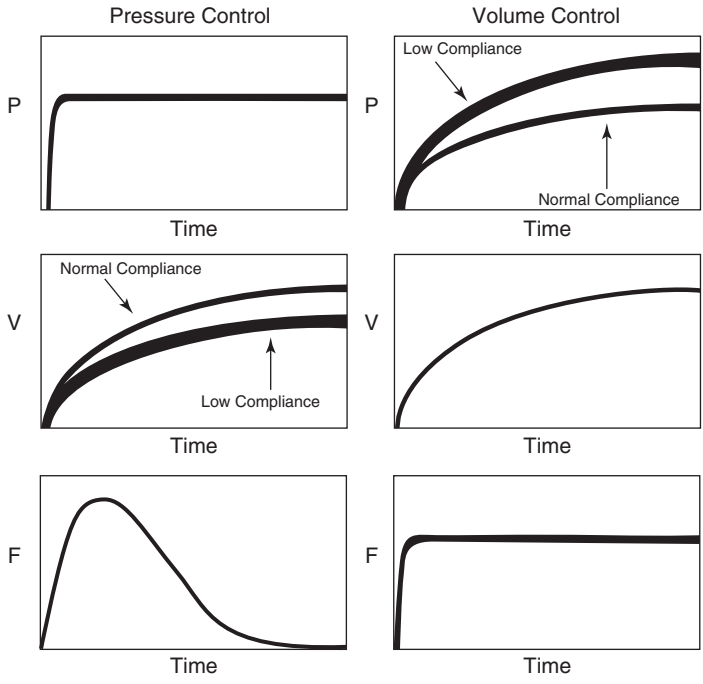


Fig. 32.5 Graphical representation of pressure (P), volume (V), and flow (F) versus time for Pressure Control Ventilation and Volume Control Ventilation. Note in Pressure Control, the pressure stays constant as the tidal volume varies based on lung compliance. Note in Volume Control, the flow and volume remain constant while pressure varies based on lung compliance. (Image Courtesy J. Ehrenfeld)

Intermittent Mandatory Ventilation (IMV)

Intermittent mandatory ventilation delivers Intermittent mandatory ventilation (IMV)either volume-cycled or time-cycled breaths at a preset rate. The patient may breathe spontaneously beyond the preset rate, but patient-triggered breaths beyond the set rate are not supported by the machine. Synchronized intermittent mandatory ventilation (SIMV) delivers the preset machine

breaths simultaneously with the patient's inspiratory efforts to avoid patient-ventilator dyssynchrony.

Pressure Support Ventilation

Pressure support ventilation allows the patient to breathe spontaneously, but provides a preset level of inspiratory pressure with each triggered breath. Inspiratory pressure provided by the machine decreases the patient's work of breathing, but still allows the patient to trigger all breaths and thus control the respiratory rate. Most modern ventilators will provide a back-up ventilatory rate if the patient becomes apneic, but it is important to ensure that apnea alarms and back-up rates are set appropriately.

Positive End-Expiratory Pressure

Positive end-expiratory pressure (PEEP) may be applied during any of the above mechanical ventilatory modes. PEEP functions to keep alveoli open at the end of expiration, thereby reducing atelectasis. PEEP minimizes the cyclic opening and closing of alveoli and reduces shear force which may cause damage to alveoli. By keeping terminal alveoli open, PEEP serves to increase the number of functional lung units that are participating in gas exchange and therefore improves oxygenation.

Inspiratory Pressures

During positive pressure mechanical ventilation, pulmonary pressure increases to a maximum at the end of inspiration. This maximum pressure is known as peak inspiratory pressure (Pi) and reflects airway resistance as well as the elastic properties of the alveoli and chest wall. If an inspiratory hold is applied at the end of inspiration, the flow of gas will stop and allow the pressure to drop to a level known as plateau pressure (Pplat). Plateau pressure reflects only the elastic properties of the alveoli and chest wall and

is thus the best measure of alveolar pressure. The difference between peak inspiratory pressure and plateau pressure (Pi–Pplat) reflects the resistance of the upper airways.

Initiating Mechanical Ventilation

The mode of mechanical ventilation that is chosen is less important than ensuring that the main goals of mechanical ventilation are met. These goals include support of oxygenation and ventilation, synchrony between patient and ventilator, and avoidance of injurious pressures or volumes. Initially, the fraction of inspired oxygen (FiO_2) should be set to 1.0 and can later be titrated down to maintain adequate patient oxygenation. Initial tidal volume should be set at 8–10 ml/kg in patients with normal lung compliance. If the patient has poor lung compliance or is at high risk for ARDS, then tidal volumes should be reduced to 6 ml/kg to avoid volutrauma or barotrauma. If using pressure control ventilation, the initial peak pressure should be set less than 30 cm H_2O to ensure that plateau pressures remain less than 30 cm H_2O. The set pressure can then be titrated to maintain tidal volumes as above. Initial respiratory rate can be set at 10–15 breaths/min and should be adjusted based on the results of arterial blood gas measurements. PEEP should be used to keep alveoli open at the end of expiration. PEEP of 5 cm H_2O is a reasonable starting level and may be titrated up depending on the patient's underlying pathology or oxygenation requirements.

AutoPEEP

AutoPEEP describes the patient's intrinsic positive alveolar pressure that develops at the end of expiration and is caused by incomplete expiration of the tidal volume. AutoPEEP most commonly occurs in patients with obstructive lung disease because they have more difficulty expiring all of the tidal volume before the next breath is initiated. With each breath, more air becomes trapped in the alveoli, leading to a "stacking" of breaths and thus increasing

dead space. This increased dead space increases the patient's work of breathing. Strategies to reduce autoPEEP include lowering the respiratory rate or tidal volume to allow more time for expiration or less volume that needs to be expired, decreasing the inspiratory: expiratory ratio to allow more time for expiration, and applying extrinsic PEEP to equalize the autoPEEP and remove the pressure gradient.

Noninvasive Positive-Pressure Ventilation (NIPPV)

It is possible to Noninvasive positive-pressure ventilation (NIPPV) deliver mechanical ventilation without endotracheal intubation in the form of a bilevel positive airway pressure (BiPAP) or continuous positive airway pressure (CPAP) mask. BiPAP uses two levels of positive airway pressure to deliver pressure support during inspiration and PEEP during expiration. These pressures are typically referred to as inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP). Continuous positive airway pressure (CPAP)CPAP delivers a constant pressure during the entire respiratory cycle such that the patient will spontaneously breathe at an elevated baseline pressure without additional pressure support during inspiration. Note that both forms of NIPPV require the patient to be breathing spontaneously. Therefore, NIPPV is best used in an awake, cooperative patient. NIPPV is contraindicated in patients who are not spontaneously breathing, unable to cooperate, have a high risk of aspiration, or have facial trauma which precludes the use of a tightly-fitting mask. If a patient does not respond favorably to NIPPV within a few hours, intubation and invasive mechanical ventilation may be required.

Ventilator-Associated Pneumonia

Although mechanical ventilation is life-saving when patients develop respiratory failure and cannot support their own oxygenation and ventilation, it is also known that endotracheal intubation

with mechanical ventilation is an independent risk factor for the development of pneumonia. Ventilator-associated Ventilator-associated pneumonia (VAP) is defined as pneumonia that arises after a patient has been intubated >48 h. VAP is a major contributor of morbidity and mortality in the intensive care unit, and the risk of developing VAP is directly proportional to the length of time the patient is intubated. The pathogenesis of VAP is multifactorial but thought to be associated with aspiration of oropharyngeal bacterial pathogens around the endotracheal tube cuff as well as infected biofilm that develops in the endotracheal tube. In addition to being in the intensive care unit and having been intubated for >48 h, patients who develop VAP often have many risk factors for infection with multidrug-resistant organisms. Methicillin-resistant *Staphylococcus aureus* and gram-negative organisms (such as *Pseudomonas aeruginosa*) are frequent pathogens in VAP. If possible, lower respiratory tract samples should be obtained for microbiologic culture prior to initiation of broad-spectrum antibiotics. However, if this is not possible in a timely fashion, antibiotic therapy should not be delayed because the failure to initiate prompt appropriate therapy is associated with increased mortality. Significant research efforts continue to focus on reducing risk factors and developing preventive strategies for VAP, but the best possible way to avoid VAP is to treat the underlying cause of respiratory failure and extubate the patient as soon as possible. Guidelines for the management of VAP have been published by the American Thoracic Society and the Infectious Diseases Society of America.

Supportive Care in the ICU

In addition to the Critically ill patientsmanagement and treatment of primary underlying disorders, there are supportive and prophylactic measures that have been shown to improve outcomes and help prevent complications associated with critical illness.

Measures to Prevent Nosocomial Infections Include

1. Staff education and appropriate hand disinfection
2. Use of sterile technique and precautions during procedures
3. Isolation of patients with multidrug-resistant organisms
4. Head of bed elevation to 30–45° for prevention of aspiration
5. Oral hygiene with chlorhexidine rinse for intubated patients
6. Avoidance of inappropriate use of antibiotics
7. Sedation and ventilator weaning protocols

Sedation Management

Although patients with critical illness often suffer from anxiety and emotional distress, studies have shown that constant deep sedation prolongs ventilator time, increases the incidence of infection, and may lead to worsening delirium. Therefore, the use of sedation protocols as well as daily awakening or lightening of sedation is recommended in the intensive care unit to avoid oversedation. Unless absolutely clinically indicated, neuromuscular paralysis should be avoided as it leads to longer time on the ventilator and is a significant risk factor for the development of prolonged weakness.

Glucose Management

Hyperglycemia is common in critically ill patients, and it is known that severe hyperglycemia is associated with increased morbidity and mortality in certain groups of patients. However, it is also known that intensive insulin therapy to maintain strict normoglycemia increases the risk of hypoglycemia, which is also associated with increased morbidity and mortality. Based on the most recent data, the optimal target range for blood glucose in critically ill patients is <180 mg/dl.

Thromboprophylaxis

Patients in the intensive care unit often have many risk factors for the development of venous thromboemboli, including:

- prolonged immobility
- venous stasis
- polytrauma
- burns
- spinal cord injury

Malignancy

- obesity
- presence of central venous catheters
- hypercoagulability associated with the perioperative period

Thrombosis of the deep veins can lead to significant morbidity, including embolism of blood clots to the pulmonary vasculature (PE). The majority of clinically significant pulmonary emboli arise from the proximal deep veins in the leg. Because a significant pulmonary embolism is often fatal, prevention of these deep vein thromboses is important. Specific guidelines have been published by the American College of Chest Physicians regarding thromboprophylaxis. In general, all patients in the intensive care unit should receive mechanical prophylaxis (in the form of early ambulation or intermittent pneumatic compression boots) and unless contraindicated, a form of pharmacologic prophylaxis should also be instituted.

Stress Ulcer Prophylaxis

Patients with critical illness often develop gastrointestinal mucosal damage that can progress to clinically significant gastrointestinal bleeding, which increases mortality. Strategies for the

prevention of stress ulcers decrease the incidence of such bleeding in intensive care unit patients. However, it is important to identify those patients who have risk factors for stress ulcer formation because the indiscriminate use of prophylaxis in all ICU patients may increase the risk of nosocomial pneumonia. Patients with any of the following risk factors should receive stress ulcer prophylaxis:

- Mechanical ventilation >48 h
- Coagulopathy or therapeutic anticoagulation (does not include patients only receiving thromboprophylaxis)
- Use of steroids
- History of active peptic ulcer disease
- Traumatic brain injury
- Major burns
- Severe infection or shock

Recommended prophylaxis may be provided by the administration of either a proton pump inhibitor or an H2-receptor antagonist.

Nutrition

Malnutrition is common in critically ill patients and has detrimental effects on organ function, immune function, wound healing, ventilator weaning, and has been shown to increase mortality. In patients who cannot meet their nutritional needs orally, enteral nutrition is preferable to parenteral nutrition. Enteral nutrition has been shown to have important advantages as well as a lower incidence of complications as compared to parenteral nutrition. Current recommendations support the initiation of early enteral nutrition (within 24–48 h of admission) in critically ill patients who are expected to be unable to tolerate an adequate oral diet, unless there is a contraindication. Contraindications to enteral

nutrition include intractable emesis, severe diarrhea or malabsorption, severe gastrointestinal bleeding, peritonitis, mesenteric ischemia, intestinal obstruction, short bowel syndrome, or severe shock. In these situations, it may be necessary to initiate Total parenteral nutrition (TPN), especially if the patient is significantly malnourished.

TPN is reserved only for these patients (who have a contraindication to or cannot tolerate enteral feeding) because it is associated with added risks. TPN must be administered into a central vein and as such, confers the risks associated with central venous cannulation and bloodstream infections. In addition, TPN is associated with mucosal atrophy of the gastrointestinal tract which disrupts the normal barrier function of the gut and is associated with bacterial translocation from the bowel lumen into the circulation. Other complications associated with TPN include hepatic dysfunction, cholestasis, and acalculous cholecystitis.

Ethical Decisions and End-of-Life Care (Also See Chap. 31, Ethical Issues in Anesthesia)

Many patients cared for in the intensive care unit are unable to participate in decisions about their own medical care and are dependent on advance directives or surrogate decision-makers. Healthcare professionals must be able to adequately communicate among themselves and with patients' families in order to set realistic goals that are consistent with patient and family desires. Sometimes it is determined by the team of healthcare professionals that further medical therapy is unlikely to be beneficial to the patient and this may lead to ethical issues, such as whether aggressive medical care should be continued and/or how end-of-life care should be facilitated. Many intensive care units now have Palliative Care teams to assist with end-of-life care.

Case Study

You are called to the PACU emergently to see a 57-year-old patient who has just undergone an aorto-bifemoral bypass graft procedure. On arrival to the bedside, the nurse informs you that the case proceeded uneventfully and the patient arrived in the PACU 1 h ago. The patient underwent general endotracheal anesthesia and was extubated in the OR. Vital signs on arrival to PACU were normal, but the blood pressure has been progressively declining and the heart rate has been rising since then. Five minutes ago, the patient's blood pressure was 68/40 with heart rate 128. Now the nurse notes that she cannot obtain a blood pressure and cannot feel a pulse. The patient has a peripheral IV infusing lactated Ringer's and an arterial line in the right radial artery. No blood pressure is seen on the arterial tracing.

What will be your initial response (first 30 s) on arrival?

In any "code" situation, remember ABC's: Airway, Breathing, and Circulation. These always precede "D" (drugs, discussion, debate…)! From the nurse's report and lack of vital signs, this patient appears to be in full cardiac arrest. You will check for a pulse (the lack of arterial pulsations on an otherwise working arterial line trace is confirmatory), and check for breathing by either auscultation or direct inspection.

The patient is found to be apneic and pulseless. What will you do next?

Call for help by activating the "code" team or other system in place in your particular hospital. (Some institutions treat arrests in the OR and PACU differently than on regular nursing units). Open the airway and begin ventilation by bag and mask with 100% oxygen (Airway, Breathing). Ask the nurse, an assistant, or other personnel to begin chest compressions (Circulation). Ensure that someone has secured a defibrillator and emergency medications. Assess the patient's rhythm on the ECG.

The patient is found to be in ventricular fibrillation (VF). What will you do next?

Current Advanced Cardiac Life Support (ACLS) guidelines recommend immediate DC shock. Any device can be used, including a monophasic defibrillator at 360 J (note that progressive increase in energy is no longer recommended). Alternatively, and possibly more efficacious, one can use a biphasic device at whatever power the machine is designed for (typically 120–200 J). An automatic defibrillator may also be used at the machine-specific setting. CPR is then immediately resumed for five cycles (or about 2 min) before the next step. The rhythm is checked again during CPR and a second shock (at equal or higher energy if a biphasic device is being used) is given if the rhythm is still VF. Any time after the first or second shock, epinephrine, 1 mg IV (alternative vasopressin 40 U) is also given. CPR is always continued for 2 min after a shock or drug dose, to maximize the chances of return of spontaneous circulation. Reintubation is also recommended early in the sequence to facilitate ventilation and allow for continuous chest compressions.

After your initial intervention, sinus rhythm reappears. Inspection of the arterial tracing shows minimal pulsatile activity, and manual blood pressure measurement confirms that the blood pressure remains unobtainable. What are your next steps?

The patient has pulseless electrical activity (PEA), likely profound hypotension, as demonstrated by the arterial waveform and lack of noninvasive blood pressure reading. Vasopressors and CPR are continued without interruption while reversible causes are sought. Some recommend vasopressin if it has not already been given. There are several etiologies and a mnemonic, "H and T's" is sometimes helpful:

- Hypovolemia
- Hypoxia
- Hydrogen ions (acidosis)
- Hypokalemia/hyperkalemia
- Hypoglycemia
- Hypothermia
- Toxins
- Tamponade, cardiac
- Tension Pneumothorax
- Thrombosis (coronary or pulmonary)
- Trauma

In this patient, hypovolemia from internal bleeding should be high on the differential diagnosis. Thromboembolism and pneumothorax are also possible, though less common. Auscultation of the chest will rule out tension pneumothorax, and echocardiography (usually transesophageal) may diagnose massive pulmonary embolism. The electrolyte, acid/base, and other etiologies are also possible, and history and laboratory studies (recent or sent as part of the evaluation now) may be helpful. You will alert the surgeon immediately if you suspect an anastomotic leak and/or internal hemorrhage as the etiology, as immediate reoperation will be necessary. Continue ACLS until return of spontaneous circulation, after which aggressive fluid administration and vasopressors can temporize until definitive intervention can take place.

Suggested Further Reading

1. Acute Respiratory Distress Syndrome Network (2000) Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 342:1301

2. American Dietetic Association (2007) Critical illness evidence-based nutrition practice guideline. Executive summary: critical illness nutrition practice recommendations. American Dietetic Association, Chicago
3. American Thoracic Society, Infectious Disease Society of America (2005) Guidelines for the management of hospital-acquired pneumonia, ventilator-associated pneumonia and healthcare-associated pneumonia. Am J Respir Crit Care Med 171:388
4. Dellinger RP, Levy MM, Rhodes A et al (2013) Surviving sepsis campaign: international guidelines for management of severe sepsis and septic shock: 2012. Crit Care Med 41(2):580
5. Geerts WH, Berggvist D, Pineo GE et al (2008) Prevention of venous thromboembolism: American College of Chest Physicians evidence-based clinical practice guidelines (8th ed). Chest 133(6):381S
6. Hess DR, Kacmarek RM (2002) Essentials of mechanical ventilation, 2nd edn. McGraw-Hill, New York
7. Rivers E, Nguyen B, Havstad S et al (2001) Early goal-directed therapy in the treatment of severe sepsis and septic shock. N Engl J Med 345:1368
8. Society of Critical Care Medicine (2007) Fundamental critical care support, 4th edn. Society of Critical Care Medicine, Mount Prospect

Enhanced Recovery After Surgery and the Perioperative Surgical Home

33

Ashley L. Talbott

Key Learning Objectives

- Understand the purpose of Enhanced Recovery After Surgery (ERAS) pathways
- Define the Perioperative Surgical Home (PSH)
- Highlight the goals of the ERAS guidelines and PSH in each phase of perioperative care
- Recognize the anesthesiologist's role in addressing the national opioid crisis

A. L. Talbott (✉)
Department of Anesthesiology, Wake Forest University School of Medicine, Winston Salem, NC, USA
e-mail: atalbott@wakehealth.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_33

Enhanced Recovery After Surgery

The Enhanced Recovery After Surgery (ERAS) Society was established in 2001 by a group of European surgeons who desired to standardize the perioperative care of patients in an effort to decrease morbidity and mortality and improve recovery after surgery [1]. The mission of the ERAS Society is to develop evidence-based perioperative guidelines for the management of surgical patients with intention to reduce perioperative stress and accelerate recovery after surgery. ERAS protocols have been published across all different surgical subspecialties including thoracic, cardiac, colorectal, bariatric, gynecologic, urologic, head and neck and orthopaedic surgery. These guidelines are unique to the surgical procedure and are recommendations based on the best available evidence as determined by good quality meta-analyses, randomized controlled trials and large cohort studies [2]. Although each surgical specialty has specific ERAS protocols, many of the ERAS pathways highlight similar goals and recommendations. These interventions are aimed at preoperative optimization, intraoperative pain management and maintenance of homeostasis, and postoperative early mobility with continued focus on pain control.

The Perioperative Surgical Home

The Perioperative Surgical Home (PSH) is a multidisciplinary, collaborative and patient-centered model of care for surgical patients. The anesthesiologist is the primary physician in the PSH model and is responsible for coordinating the care of the patient throughout his or her perioperative experience. As the leader of the PSH, the anesthesiologist assumes care of the patient from the time a surgical diagnosis is recognized and focuses on positive outcomes and high patient satisfaction. The PSH is patient-centric, physician-led and team based [3]. Surgical care is frequently episodic and fraught with gaps in communication between the various members of the care team. It often represents a lengthy and confusing journey for a patient through diagnosis, surgery and

rehabilitation [4]. The ERAS pathways were developed with the goal of improving surgical outcomes and patient experience, but are often difficult to implement without a clearly defined perioperative leader. The PSH shares many of the same values and goals of the ERAS guidelines, but also seeks to improve the patient experience by prioritizing continuity of care and communication throughout the preoperative, intraoperative and postoperative journey (Fig. 33.1).

The Perioperative Surgical Home starts with the decision to have surgery. The patient is then sent for preoperative evaluation by an anesthesiologist in an effort to identify and optimize any coexisting medical problems. A comprehensive review of medical history at this time provides the patient and surgeon with a formal risk assessment based on the patient's medical conditions and the inherent risk of the specific surgical procedure. Assessment of comorbidities and the patient's functional status identifies the need for any additional testing or consults that may impact the management of the patient perioperatively. There is also an opportunity for preoperative conditioning, disposition planning and patient education at the time of the preoperative evaluation. The

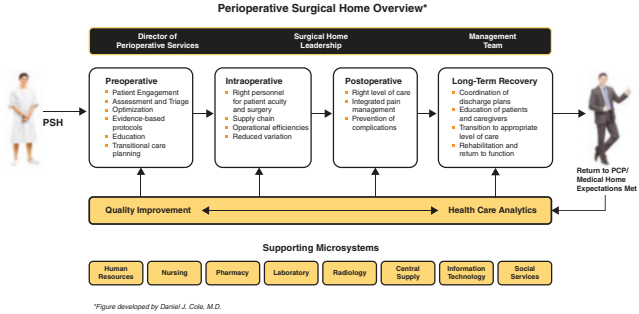


Fig. 33.1 Perioperative surgical home overview. (Public access? Also printed by Springer Publishing)

emphasis intraoperatively is on patient safety and evidence-based anesthetic techniques to optimize patient outcomes. Postoperatively, goals shift to pain control, early mobility, rehabilitation and prevention of postoperative complications such as postoperative nausea and vomiting, myocardial infarction, stroke, pulmonary embolus, and infection. Ultimately, care is transferred back to the primary care physician with an overall decrease in complications, morbidity and mortality resulting in a better patient outcomes [3].

ERAS guidelines complement the concept of a perioperative surgical home. Similar to the perioperative surgical home, ERAS protocols are multimodal and multidisciplinary in nature. Preoperative emphasis on patient education, nutrition, optimization of general medical conditions such as correcting anemia, prewarming and preemptive oral analgesia mirror many of the goals of the preoperative assessment within the PSH (Fig. 33.2). An intraoperative focus on regional anesthesia whenever possible, normothermia, normovolemia, blood conservation and antibiotic prophylaxis highlights the emphasis on patient safety and evidence-based anesthetic techniques that improve patient outcomes. ERAS guidelines recommend postoperative use of multimodal opioid-sparing techniques, postoperative nausea and vomiting (PONV) prophylaxis, early mobilization and early oral intake [5].

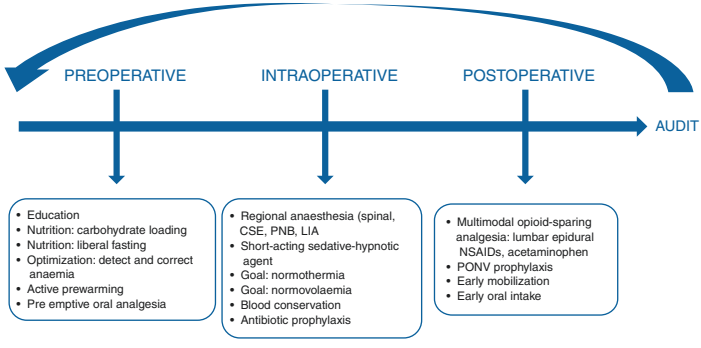


Fig. 33.2 An example ERAS protocol for total joint arthroplasty. (With permissions from BJA)

The PSH model is a coordinated system of perioperative care that requires institutional support and multidisciplinary engagement in order to be successful. The anesthesiologist leads the team with endorsement from surgical and hospital management [3]. The expected metrics of the PSH are to improve operational efficiencies, improve allocation of resources, decrease hospital length of stay and readmission, and reduce morbidity and mortality resulting in overall enhancement of patient care. The concept of a PSH essentially expands the role of an anesthesiologist from a consultant in the treatment of acute pain into a more comprehensive physician leader in the overall perioperative management of surgical patients. The PSH emphasizes continuity, coordination, and integration of perioperative care with a greater focus on patient-centeredness and shared decision making, ultimately aiming to reduce healthcare costs and maximize the quality of patient care [4]. The PSH enhances the visibility and value of the anesthesiology department within the hospital, and affords anesthesiologists the opportunity to expand their clinical practice and depth of expertise.

Preoperative Assessment

The first phase of the Perioperative Surgical Home, the preoperative assessment, begins after the decision has been made by the patient and the surgeon to proceed with surgery. The preoperative visit empowers the patient to participate in his or her perioperative care by engaging in conversations about past medical history, assessment of risk and optimization prior to surgery. The primary goals of preoperative assessment include:

- Documentation of the condition(s) for which surgery is indicated
- Assessment of patient's overall health status
- Perioperative risk determination
- Optimization of the patient's medical conditions in order to reduce surgical and anesthetic perioperative morbidity and mortality

- Perioperative medication management
- Patient education about surgery, anesthesia, intraoperative and postoperative pain control in hopes of reducing anxiety and facilitating recovery
- Reduction of costs, shortening hospital stay, reduction of cancellations and increase of patient satisfaction [6]

The assessment of a patient's overall health status may include preoperative labs such as complete blood count to evaluate for anemia or thrombocytopenia, basic metabolic panel to identify any electrolyte abnormalities or reduced renal function, and albumin as an indicator of overall nutritional status. Preoperative tests may include an electrocardiogram to look for arrhythmias or signs of ischemia, pulmonary function studies in patients with obstructive or restrictive lung disease, sleep study if concern for obstructive sleep apnea, echocardiogram to assess for valvular abnormalities or congestive heart failure, and stress testing if concern for inducible ischemia. The primary goal of the preoperative risk assessment is to prevent major adverse cardiac events such as myocardial infarction and malignant dysrhythmias that may lead to significant morbidity or even perioperative death. Determination of a patient's functional status helps guide need for additional testing.

The preoperative assessment is an excellent opportunity to optimize a patient's medical conditions prior to surgery in order to mitigate intraoperative and postoperative morbidity and mortality. Through a comprehensive review of systems and focused history and physical exam, the anesthesiologist may uncover undiagnosed medical issues such as sleep apnea, congestive heart failure, poorly controlled hypertension or diabetes, chronic kidney disease and previously unidentified risk factors for acute coronary syndrome. Identification of new problems allows for further investigation, referral for additional testing and/or consults from other specialists, and medical management prior to surgery. Occasionally, surgery may be postponed or cancelled due to the discovery of acute cardiopulmonary issues that may need to be addressed prior to an elective surgery. The PSH anesthesiologist

helps follow up on test results and recommendations from consulting physicians and often serves as the liaison between the consulting services and the surgeon.

The patient's home medications are reviewed at the preoperative visit and instructions for each medication are discussed. The PSH anesthesiologist helps determine management of anticoagulants and antiplatelet medications based on anesthetic plan and surgical risk of bleeding. Anticoagulation is typically held perioperatively, but timing becomes significantly more important if there is a plan for neuraxial anesthesia. Additionally, higher risk patients such as those with recent drug eluting stents or mechanical heart valves may require bridging with enoxaparin. Many of the decisions on perioperative medication management are standardized and evidence-based, and failure to adhere to the medication instructions can result in case cancellations or intraoperative complications such as hypotension, bleeding and arrhythmias. Lastly, the preoperative assessment serves to explain the anesthetic plan to the patient, answer any questions, assuage any fears and help to mentally and emotionally prepare the patient for his or her surgery.

The ERAS protocols also begin in the preoperative period. Common preoperative goals in most ERAS pathways include preoperative smoking cessation, reduction of alcohol consumption, recognition and treatment of preoperative anemia, preoperative physical conditioning when appropriate, optimization of nutrition, PONV prophylaxis and preoperative fasting recommendations [2]. Preoperative anemia is associated with increased risk of transfusion, length of stay, infection, morbidity and readmission rates. Preoperative anemia should be identified, investigated and corrected when possible. Recent anesthetic guidelines recommend the intake of clear fluids until 2 hours prior to surgery to maintain normovolemia during the period of preoperative fasting. It is also important to address any preoperative opioid use and introduce the concept of perioperative multimodal analgesia as an opioid-sparing technique. Most non-steroidal anti-inflammatory drugs (NSAIDs) are usually held preoperatively to decrease risk of surgical bleeding, but often resumed in the immediate preoperative period and continued postoperatively [7]. The preoperative

use of acetaminophen is encouraged when appropriate. Optimal pain management is a prerequisite of ERAS and combined use of oral analgesics of different classes with different modes of action has been shown to yield additive pain relief.

Intraoperative Goals

The next phase of the PSH, intraoperative management, focuses on patient safety and evidence-based anesthetic techniques to optimize outcomes [3]. Monitoring vital signs, temperature and volume status, maintaining adequate depth of anesthesia, using regional and neuraxial anesthesia when appropriate, treating intraoperative pain and promptly addressing intraoperative complications are all standards of care for anesthesiologists. Adhering to these basic principles of anesthesia minimizes the stress response of surgery and promotes improved outcomes. ERAS pathways highlight the value of regional and neuraxial anesthesia and promote the use of infiltration of local anesthesia when peripheral nerve blocks, subarachnoid blocks and epidurals are not possible [7]. All ERAS guidelines encourage the use of multimodal analgesia perioperatively to treat pain and minimize opioid use.

Other intraoperative recommendations common in most ERAS pathways include continued emphasis on PONV prophylaxis, intraoperative active warming to maintain normothermia, prophylaxis against venous thromboembolism (VTE), antimicrobial prophylaxis and skin preparation, perioperative fluid management and blood conservation. Prevention of intraoperative hypothermia has been shown to reduce rates of wound infection, decrease cardiac morbidity and reduce intraoperative bleeding [2]. VTE prophylaxis is achieved with compression stockings, intermittent pneumatic compression devices or pharmacological prophylaxis. The use of intravenous antibiotics is imperative to reduce the risk of surgical-site infections. Antibiotic selection is case-specific, dosed 30–60 minutes prior to incision and repeated intraoperatively as necessary. When possible, cleansing the skin with chlorhexidine-gluconate prior to incision is preferred [2]. The dif-

ferent ERAS pathways provide case-specific guidelines for intraoperative fluid management, but generally promote goal-directed treatment with crystalloid and/or colloid, and highlight the importance of blood conservation when possible.

Postoperative Management

The objectives of the PSH and ERAS guidelines in the postoperative phase of care are to optimize pain control, encourage early mobility and rehabilitation and prevent postoperative complications [3]. The use of multimodal opioid-sparing analgesia continues in an effort to treat acute postoperative pain effectively without the side effects and risk of addiction that come with heavy opioid use. Prolonged opioid use in and after surgery is a leading risk factor for longer term addiction and should be avoided. Epidural analgesia, peripheral nerve blocks and local infiltration of anesthesia all improve pain control and decrease need for opioids. Acetaminophen is a core component of multimodal analgesia in ERAS pathways as it reduces acute postoperative pain and has a favorable side-effect profile [7]. Multiple studies have also shown that NSAIDs decrease pain and reduce supplemental opioid use in patients with preserved renal function and no other contraindication to their use. There is conflicting evidence on the utility of gabapentanoids in addressing the neuropathic component of acute postoperative pain. Gabapentin or pregabalin may be considered as another option for opioid-sparing multimodal analgesia in patients with refractory pain. Adequate pain control through the use of multimodal analgesia and limited opioids allows for early ambulation, engagement in rehabilitation and improved outcomes.

The PSH also plays an important role after surgery in the management of chronic medical conditions. In addition to pain management, the goal of the anesthesiologist in the postoperative period is to prevent major adverse cardiac events such as myocardial infarction, stroke, flash pulmonary edema, malignant dysrhythmias and decompensated heart failure. Careful evaluation of perioperative medications, volume status, vital signs and concern-

ing signs or symptoms allows for prompt recognition and treatment of any major cardiopulmonary complications.

Both the PSH and ERAS protocols continue to emphasize PONV prophylaxis during the postoperative period. PONV affects 25–35% of all surgical patients and is a leading cause of patient dissatisfaction and delayed discharge from the hospital [2]. Consideration of risk for PONV preoperatively and intraoperative techniques to reduce PONV help mitigate the risk of PONV postoperatively. If nausea and vomiting persist, multimodal pharmacologic agents should continue to be dosed postoperatively to control symptoms.

Addressing the Opioid Epidemic

Through the use of multimodal analgesia and regional anesthesia, as well as the emphasis on early mobility, anesthesiologists have a unique perioperative opportunity to address concerns about opioid epidemic and empower patients with education and tools to prevent and address acute postoperative pain [8]. It is important for all physicians to understand the patient's opioid consumption during the pre-anesthetic evaluation, as well as his or her risk for substance use, misuse or abuse (Fig. 33.3). Preoperatively, it may be appropriate to maintain opioid therapy to avoid withdrawal, while being aware that these individuals may require significant doses of opioids during the postoperative phase. Some patients may be candidates to titrate down home opioid use in preparation for surgery. It is imperative to have discussions with patients and their families above the risks, benefits and alternatives to opioid therapy preoperatively. Awareness is key. Multimodal analgesia and opioid-sparing techniques are essential in the perioperative care of surgical patients. The use of acetaminophen, NSAIDs,

Fig. 33.3 The Perioperative Opioid Pathway. (Modified from ASA Monitor)

alpha-2 agonists, lidocaine infusions, magnesium infusions and regional anesthesia all help to decrease opioid use. Every decision in the hospital regarding pain management has an impact on the long-term management of pain. It is important to educate patients on how to safely use opioids in the postoperative period to treat acute pain, and empower them to stop using within 7–10 days. Encourage patients to dispose of opioids by returning to pharmacy or other "take back" programs. The PSH anesthesiologist guides patients through postoperative pain, and ensures reconnection with both the surgeon and the primary care physician to ensure no persistent pain or addiction. It is also important to understand the guidelines and regulations for prescribing opioids at the local, state and federal levels.

Summary

ERAS pathways are designed to standardize the perioperative care of patients by recommending evidence-based clinical practices that aim to reduce perioperative stress, decrease morbidity and mortality and improve recovery after surgery. The PSH is a multidisciplinary, team-based initiative led by anesthesiologists with similar goals of improving patient care and decreasing adverse perioperative outcomes. The PSH model integrates the ERAS guidelines into the perioperative care of surgical patients. Anesthesiologists are physician leaders in perioperative medicine as well as experts in risk assessment, optimization of medical comorbidities, pain management and prevention of postoperative complications. The PSH concept highlights the value of anesthesiologists as champions of patient-centered, collaborative, comprehensive perioperative care. The success of the anesthesiologist-led PSH depends on institutional support, strong interdisciplinary communication and a commitment to continuous quality improvement to ensure excellence in patient care.

References

1. ERAS Society. 15 September 2020. [Online]. Available: erassociety.org
2. Gustafsson U, Scott M, Schwenk W, Lobo D, Fearon K, Ljungqvist O (2012) Guidelines for perioperative care in elective colonic surgery: Enhanced Recovery After Surgery (ERAS) Society recommendations. Clin Nutr 31(6):783–800
3. American Society of Anesthesiologists Perioperative Surgical Home. 15 September 2020. [Online]. Available: www.asahq.org
4. Zaccagnino MPM, Bader AMM, Sang CNMCDJM (2017) The perioperative surgical home: a new role for the acute pain service. Anesth Anal 125(4):1394–1402
5. Soffin E, YaDeau J (2016) Enhanced recovery after surgery for primary hip and knee arthroplasty: a review of the evidence. Br J Anaesth 117(53):iii62–iii72
6. Zambouri A (2007) Preoperative evaluation and preparation for anesthesia and surgery. Hippokratia 11(1):13–21
7. Wainwright TEA (2019) Consensus statement for perioperative care in total hip replacement and total knee replacement surgery: Enhanced Recovery After Surgery (ERAS) Society recommendations. Acta Orthop 91(1):3–19
8. Naidu RKM, Chen L-LM (2017) The perioperative opioid pathway. ASA Monitor 81:12–15

Part VII

Special Topics

Professionalism, Teamwork, and Interaction with Other Specialties

34

Britlyn D. Orgill and Rebecca D. Minehart

Key Learning Objectives
After reading this chapter, learners will be able to

- Define professionalism and its importance for the practice of anesthesiology
- Describe factors that may be involved in maintaining public trust in anesthesiologists
- Identify common communication pitfalls
- Apply a communication strategy for speaking up to share concerns

During medical school, students are expected to learn a vast amount of complex medical information, requiring hours of concentration and diligent study. However, becoming a doctor requires more than book knowledge, and there is much that can be

B. D. Orgill · R. D. Minehart (✉)
Harvard Medical School, Boston, MA, USA

Department of Anesthesia, Critical Care and Pain Medicine, Massachusetts General Hospital, Boston, MA, USA
e-mail: borgill@mgh.harvard.edu; rminehart@mgh.harvard.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_34

learned from patients and other healthcare team members themselves. For anesthesiologists, time spent in the operating room managing physiology and participating in procedures is vital and is complimented by the development of strong interpersonal and self-management skills. Anesthesiology is a unique profession, and the training must provide a balance between the development of technical expertise and critical thinking with communication and leadership skills. The anesthesiologist must be skilled at quickly demonstrating empathy and establishing trusting relationships with patients and their families, many of whom feel frightened, anxious, and vulnerable. The anesthesiologist must also be able to perform complex procedures under pressure while simultaneously remaining vigilant and responsive to the changing needs of the patient and the operative team.

A career in anesthesiology is not limited to the operating room. Anesthesiologists may choose to work in pain clinics, labor floors, intensive care units, hospital administrative offices, as well as direct patient safety initiatives, or improve educational efforts. Given the vast array of opportunities awaiting the anesthesiologist, it is not surprising that training must include an emphasis on professionalism, communication, and mutual respect for multiple specialties.

Defining Professionalism

Professionalism can be hard to define and encompasses multiple aspects of an anesthesiologist, both as an individual and more broadly as applied to the profession. What is usually notable for most people is when professionalism is lapsed or absent, "*unprofessional.*" In 2012, the American Board of Medical Specialties defined medical professionalism as "a belief system about how best to organize and deliver health care, which calls on group members to jointly declare ("profess") what the public and individual patients can expect regarding shared competency standards and ethical values, and to implement trustworthy means to ensure that all medical professionals live up to these promises" [1]. It embodies the knowledge, technical ability, critical thinking, and

interpersonal skills of the provider, and each aspect may alternately enhance or diminish how anesthesiologists are perceived by their patients and the public. An editorial denoted the following as important qualities of professionalism within the field of anesthesia: humility, emotional intelligence, self-awareness, servant leadership, kindness, and altruism [2]. While fully defining professionalism is challenging, the concepts and examples shown below in Table 34.1 represent a synthesis of several definitions.

The professional challenges associated with becoming an anesthesiologist mirror many of those encountered in other fields. For instance, the anesthesiologist-in-training must develop a strong understanding of the concepts and theories within anesthesiology and gain expertise in technical procedures. However, there are also unique challenges within anesthesiology that are frequently underappreciated by those outside of the field. For example, the importance of communication is often downplayed, yet excellence within anesthesiology requires strong leadership and communication skills in addition to technical prowess and sound medical judgment.

For anesthesiology, professionalism at a minimum implies competence in anesthesia knowledge. The basic curricular elements considered necessary for certification in anesthesiology are defined by the American Board of Anesthesiology (ABA) and the Accreditation Council for Graduate Medical Education (ACGME). A board-certified anesthesiologist is a physician who has com-

Table 34.1 Professionalism: essential attributes for anesthesiologists

1. Competence in the fundamental elements necessary for the safe delivery of anesthesia, including both technical and nontechnical aspects
2. Assumes responsibility for the care of individual patients and as such contributes to the wellbeing of society in general
3. As a profession, anesthesiologists have the right to train, admit, discipline and dismiss its members for failure to sustain competence or observe the duties and responsibilities
4. Exhibits the following humanistic qualities including altruism, accountability, excellence, duty, honor and integrity, and respect for others

pleted specialized post graduate training in anesthesiology and exhibited an acceptable depth of knowledge in written and oral examinations. The standards for certification examinations are set by the ABA and are constantly reviewed and updated to reflect advances within the field and its specialties.

The anesthesiology profession has a responsibility for the care of individual patients and towards society in general, and this must be prioritized over competing interests, such as the surgeon, the OR schedule, and even oneself. Anesthesiologists have long been recognized as leaders in patient safety, and in 1985 the American Society of Anesthesiologists (ASA) was the first medical society to create a foundation dedicated to patient safety. The Anesthesia Patient Safety Foundation (APSF) was established to raise awareness within the profession and dedicate resources to improve the understanding of safe anesthetic practice. Since that time the ASA and APSF have sponsored numerous research projects and helped to establish guidelines and recommendations that have significantly improved patient safety. Anesthesiologists have also been instrumental in the advancement of the electronic medical record, team training, and medical simulation.

Anesthesiologists belong to a profession, and as such accept the responsibility to train, admit, discipline, and dismiss members who fail to sustain competence or observe expected duties and responsibilities. The public trusts that through education and training anesthesiologists will have acquired a certain level of clinical competence and technical expertise to care for patients and will maintain this competence throughout their practice.

Finally, for individual anesthesiologists, professionalism also implies the presence of humanistic qualities that are central to the physician in the role of healer. These key elements of professionalism include altruism, accountability, excellence, duty, honor and integrity, and respect for others. The basic need for these traits does not differ for anesthesiologists compared to other physicians from other specialties.

While the above descriptions of professionalism encompass a brief overview of its most important aspects, we will next focus on specific aspects of professionalism by considering two applications of it: individual professionalism and team professionalism.

Individual Professionalism

For the purposes of this chapter, we will consider individual professionalism as achieving and maintaining competence in skills and knowledge for the safe administration of anesthetic care, demonstrating empathy towards patients, and cultivating one's professional identity to uphold the public's trust in anesthesiologists and healthcare professionals as a whole. As much of anesthesiology training addresses gaining competence in skills and knowledge, we will concentrate on the empathy and professional identity to address these underappreciated professionalism considerations.

Maintaining and Demonstrating Empathy

Empathy, or the ability to understand and share the feelings of another [3], is a crucial ingredient for any doctor-patient relationship. Empathy can be further classified as *emotional empathy*, where one experiences feelings along with the patient, or *cognitive empathy*, in which one develops an ability to consider or adopt another person's perspective [4]. These distinctions have important implications for an anesthesiologist's resilience and burnout, as emotional empathy seems to track with higher rates of emotional exhaustion (or "compassion fatigue") [4], while cognitive empathy in the form of "perspective-taking" may actually increase one's creativity and curiosity [5]. Such empathy can be challenging to maintain; Hojat et al. found that empathy declines in medical students in their third year [6]. However, training in empathy can increase one's abilities over time, making this a skill that may be actively developed and maintained [7]. The largest impact for keeping up one's empathy is that patients may perceive physicians as being more competent when they display empathy [8], which may lead to better trust and a more therapeutic relationship. By building stronger connections with patients, anesthesiologists can make a difference in many lives through brief but emotionally powerful interactions, upholding the profession's commitment to humanistic care.

Cultivating One's Professional Identity as a Physician: Social Media Pitfalls and Substance Use Disorders

Becoming a physician is a noble calling, and one that entails a lifelong duty of service to patients and the community. Medical students already have important responsibilities to patients to help provide them the best care, often investing in time learning about the patients, their loved ones, and their social or cultural circumstances influencing their care choices. The transition from student to resident physician is a welcome one, but comes with additional challenges, including societal expectations for physicians outside of the hospital setting. While we advocate strongly for work-life balance to maintain overall wellbeing, some considerations deserve attention as they may impact patients' perceptions of the medical community. We will focus on a few specific responsibilities medical students have as citizens within the medical community.

Social media is an integral part of today's culture. Many medical students, trainees, and staff physicians have accounts on social media platforms which can serve a variety of purposes, including personal profiles to connect with friends and family as well as professional profiles to interact with and educate the public. Caution should be exercised when posting to these websites and applications as anything shared online is potentially public information. Sharing protected health information without the patient's explicit permission is considered a HIPAA violation subject to disciplinary action. When taking a picture at work, ensure no patients or patient information is in the background, and refer to the hospital's media policy prior to posting. In addition to information posted online being potentially accessed by patients, residency programs may choose to search for social media posts while assessing candidates. Prior to posting, consider what patients or colleagues might think if they were to see it as unfortunately, even deleting a post does not fully erase its footprint. The American Medical Association published a guideline on profes-

sionalism in the use of social media in 2011, which is a useful resource [9].

Physicians, especially anesthesiologists, are stewards of medications, including opioids and other potent substances which play an intimate role in the ability to care for patients. Unfortunately, physicians are not immune to substance abuse disorder and addiction. An estimated 10–15% of the general population is thought to be at risk for substance use disorder, and it is estimated that physicians are at a similar level of risk. Anesthesiologists have ready access to a variety of drugs with abuse potential [10]. In addition to alcohol, which is the most common substance abused, anesthesiologists are at risk for abusing opioids, benzodiazepines, propofol, ketamine, and inhalational anesthetics [10]. While there are indications that the incidence of substance use disorders among anesthesiology residents may be rising, Fitzsimons et al. reported that random urine testing in one program was associated with reduced rates of substance use disorder reporting among anesthesiology residents [11]. Some telltale signs of a physician who may have a substance use disorder are periods of mood instability, irritability, increased time spent at the hospital (even when off-duty), and erratic patterns of accepting or requesting breaks during anesthetic care [10]. Chillingly, many instances of substance use disorder go unrecognized, as physicians are highly creative, intelligent, and resilient to many challenging circumstances and can hide their conditions adeptly. Reporting suspicious behavior to a supervisor or a leader in the department is critical, as they can take further steps to determine if there is a problem at hand.

For physicians suffering from substance abuse (or with professional behaviors), many state societies have established programs to assist and treat. State societies work closely with state licensing boards to ensure the development of fair and safe regulations for patients and practicing physicians. A survey of US anesthesiology residencies showed that 80% of programs had experience with impaired residents, and that 19% of programs had at least one pretreatment death [12]. Although it can be uncomfortable and intimidating to "report" someone, speaking up may save a life.

Team Professionalism

Anesthesiologists frequently work in teams with other medical professionals including other physicians, nurses, and technologists. We will review a few key tenants of team professionalism including modeling best communication practices and promoting effective teamwork through employing crisis resource management principles.

Best Communication Practices: Closed-Loop Communication and Speaking-Up

Excellent team performance hinges upon effective and respectful communication. In the high-stakes environment of the operating room, clearly understanding the situation and how others need to work together to treat that patient forms the basis of good clinical care. Two components of communication bear emphasis: *closed-loop communication* and *speaking up*. We will explore these further in the following passages.

When ordering at a fast-food restaurant, your order will be repeated back to you before you pay, ensuring its accuracy. Closed-loop communication similarly ensures that requests are fulfilled as desired, in the order and at the exact time they are needed. Closed-loop communication in full is described as: (1) a request; (2) a repeating back of the request to ensure understanding; (3) an announcement of when the request was fulfilled; and (4) an acknowledgement of the request as fulfilled. As detailed, and perhaps cumbersome, as this may seem, closed-loop communication has been shown to help tasks be completed faster, which is especially important in urgent or emergent situations [13]. A hypothetical example of closed loop communication between Imani, an anesthesia resident who is securing a patient's airway through direct laryngoscopy, and Dr. Chen, her attending, follows:

- Imani [focusing on the patient's airway and not looking at her attending]: "Dr. Chen, can you pass me the bougie?"

- Dr. Chen: "Yes, getting the bougie, Imani—" [retrieves bougie and places it in Imani's right hand as she continues to optimize her view with the laryngoscope]; "here's the bougie."
- Imani: "Thanks—I have the bougie" [advances bougie into airway]

In this brief exchange, notice how Imani addresses Dr. Chen by name, instead of saying "can someone get me a bougie." Also note how Dr. Chen acknowledges that she has heard what she was asked to do, and then how Imani then confirms having the bougie. This serves to not only confirm between the two of them that this critical task was completed but also updates the rest of the operating room team (also looking on and scanning the situation) that perhaps this patient's airway was more challenging than expected, and other equipment may be needed or requested. This exchange is brief, polite, and effective. Looking for examples of closed loop communication during rotations in the operating room can help build awareness of this crucial behavior.

Despite excellent intentions, miscommunication often occurs, and unfortunately, can lead to serious patient complications. See Table 34.2 for common causes of communication failure.

Often, when communication is failing, situations may cause unease where one person perceives that something is not right but feels uncomfortable raising concerns for fear of revealing inadequate knowledge, being wrong, or challenging superiors [14]. Keeping silent about concerns (or even creative solutions to problems) puts the team and patient at risk for ineffectiveness and inefficiencies yet speaking up remains challenging for even experienced providers [15]. Despite many challenges, a conversational tool known as Advocacy/Inquiry, adapted from the aviation and organizational behavior fields, has proven effective at facilitating team members share their points of view and concerns while remaining respectful and curious to others' opinions [14, 15].

There are two parts to Advocacy/Inquiry: a verbal (or spoken) and a nonverbal (or body language) component. The verbal part of Advocacy/Inquiry pairs a person's unbiased observations (the "data", or "I see/hear") with their honest assessment of the situa-

Table 34.2 Common causes of communication failure

Interruptions: Up to 1/3 of communication events in the operating room are interrupted. This can lead to confusion, loss of information or failure to complete the communication
Fear: Medical students, residents and nurses are frequently afraid of being chastised, of offending their superior, or of looking incompetent if they ask questions or communicate the wrong information
Stress/conflict: It has been estimated that open conflict occurs between clinicians in the operating room in about 10% of cases. This is similar to the rate seen in the cockpit of commercial aircraft. However, these conflicts are resolved about 80% of the time in the cockpit, versus only 20% in the operating room
Too much communication: Up to 100 communication events occur per procedure in the operating room and resource nurses must manage an average of 74 communication events per hour
Noise: The average noise level in the operating room is 57 dB, but it can reach much higher

tion (the "I think") and finishes with an open-ended question (the "I wonder") to generate conversation. This clear type of communication, however, must be delivered in a way that conveys genuine respect, curiosity, support for the other person, and humility in order to maintain the team's respectful interactions. This type of emotional control over normal human tendencies to judge others' behaviors as "wrong" takes practice but can be achieved. One such example might be that Imani, the anesthesia resident, notices her attending, Dr. Chen, is about to give a medication that seems contraindicated in a patient they are caring for as a team.

- Imani (respectfully but firmly): "Dr. Chen, before you give that cefazolin, I have a question–"
- Dr. Chen (with syringe in hand, bent next to patient's intravenous line): "What's wrong?"
- Imani (with a curious and respectful tone): "Dr. Chen, I see you're about to give cefazolin to this patient, but I thought he had an allergy to penicillin antibiotics." [the "I see" statement] "I'm worried this patient will have a reaction to the cefazolin too—that he'll become hemodynamically unstable." [the "I

think" statement] "Can you help me understand how you see things?" [the "I wonder" statement]

By phrasing the statements in this way, Imani has efficiently raised her concerns, and has more effectively maintained her relationship with Dr. Chen because she has left herself open to learning how Dr. Chen sees the situation. Dr. Chen may reveal additional information about allergy testing (the patient may no longer be considered "allergic," or may not be specifically allergic to cefazolin), may not be giving cefazolin (it could be that Imani misread the label from afar), may not have meant to give cefazolin in this setting (and may be grateful for Imani's speaking up), or any other number of possibilities. Had Imani accused Dr. Chen of trying to harm the patient, their interactions going forward would undoubtedly be strained. This type of speaking up while maintaining a curious and respectful tone can be used with any team member, and the directness and honesty helps build trust.

Teamwork

Formal team training, based on the concepts of Crew Resource Management, has been recommended to improve communication and to decrease or mitigate the impact of error. Crew Resource Management was developed during the 1980s by military aviation after investigations identified poor communication and ineffective coordination of the team as leading causes of aviation accidents and led to the development of Crisis Resource Management (CRM) in medicine. While CRM has evolved through several generations, the tenets have remained largely unchanged. Salas et al. have defined a "Big Five" in CRM-based teamwork [16]:

- Leadership: A leader who will ensure the proper functioning of the team must be identified (this is not always the same as the clinical leader).
- Mutual performance monitoring: Team members must monitor each other's actions to ensure that plans are followed and to prevent or mitigate errors.

- Back-up behavior: Based in part on the performance monitoring, team members must assist each other when needed. This includes advocating for patient safety.
- Adaptability: Team members must be able to meet and communicate in order to change plans as the clinical situation dictates.
- Team orientation: Team members must understand and trust that the safest way to care for patients is to ensure proper functioning of the team. This is contrary to traditional medical teaching, which emphasizes that a physician has a moral responsibility directly to his/her patients.

These five behaviors are then supported by closed-loop communication, team structure to ensure role clarity, the development of shared mental models (which means ensuring that all team members have the same understanding of the patient plans) [17], and maintenance of situational awareness (which is an individual awareness of all factors on the unit that could influence the safe conduct of patient care). The operating room lends itself to the team training model.

Anesthesiologists have led the development of simulation-based courses for teaching CRM-based teamwork concepts to groups of anesthesiologists. In simulation-based team training, the clinician (or clinicians) is placed in a simulated clinical environment (see Chap. 37). Classroom-based team training employs didactic education techniques along with low-level simulation, exemplary vignettes, and videos to teach and practice the CRM concepts. Irrespective of the team training method employed, it is important to have an implementation plan designed to transfer the teamwork skills from the classroom or simulator to the clinical arena. Many tools have been developed to assess individuals and teams on their use of these teamwork skills, including the Anaesthetists' Non-Technical Skills (ANTS) system [18]. ANTS was published in 2003 and has skills divided into four categories: task management, team working, situation awareness, and decision making and has been adopted by surgeons as NOTSS [19].

Putting It All Together

The public trusts that through education and training an anesthesiologist will have acquired a level of clinical competence and expertise matched with the ability to communicate effectively and compassionately. The trust exhibited between the anesthesiologists, surgeons, other healthcare providers and the public represents the very essence of professionalism.

Case Study

Peter is one of your favorite anesthesiology residents. He loves the art and science of anesthesiology and is incredibly skilled at taking care of patients in addition to having test scores at the top of his class. He enjoys "big" cases and always volunteers for trauma, cardiac, and messy "whomps." You have seen him at a couple of social events where he is the life of the party. He drives a sports car, regales his friends with stories of his travel adventures, and is in a happy long-term relationship. He is generous and a team player, always the first to offer to cover another resident's call or stay late and finish cases so others can go home. Today, you witnessed an event that seemed totally out of character. Peter's second assigned case for the day, a large abdominal aortic aneurysm repair was moved to another room with a different anesthesia team because the first case in his room was running late. He was irritable as he dropped off his first patient in the PACU. Then, he sought out the floor leader and lambasted him (a senior attending) for "taking my case away." Then, Peter found the resident in the room where the case was transferred and demanded to switch assignments (they had put a breast biopsy procedure in his Peter's room). However, the resident refused to switch as she had already placed the large bore IV access and arterial line. Peter told the patient that he was more experienced and a better clinician than the resident now assigned

to him, and then asked the patient if he would not prefer Peter as his anesthesiology resident. The frightened patient was speechless. Peter stormed out of the preoperative area and told the floor leader that he was sick and needed to be sent home.

What lapses in professionalism have you witnessed?

Peter appears to have personalized a decision made on behalf of patient care and OR efficiency with reactions that are out of line. He spoke up to the floor leader with a disrespectful and incurious tone. He disparaged a colleague in front of a patient and feigned an illness. He placed his own interests above those of the patient, the surgeons, his colleagues, the OR, and hospital.

Later, you are discussing the event with another resident and a nurse in the PACU. Both tell you that they are not surprised. "Peter has been pretty volatile lately," they agree. Another resident says that Peter has recently ended his relationship with his girlfriend and "is always at the hospital. He sleeps here even when he isn't on call, which doesn't make sense since he has a great apartment." How does this knowledge influence your view of the event you witnessed?

Anyone can have a bad day, but Peter is exhibiting a dangerous and worrisome pattern of behavior. Placed in context, his irritability, problems with his personal life, tendency to spend excess time at work, volunteering for big cases and staying late and taking extra call may be indicative of substance abuse, psychiatric illness, or both. It is not unusual for behavior such as his to go unappreciated by any one individual, and it is often not until a crisis occurs that behaviors are clear enough and lead to intervention.

Several weeks later, Peter is on call with you. He is paged for a case but does not respond to several pages. You are sent to his call room to wake him up and ask him to come to the OR. You knock on his door with no response. You knock more loudly and finally enter the room with your own key. You find Peter in bed, apparently asleep, with the lights and

television on. You wake him with great difficulty and when rising he is groggy and somewhat incoherent. He sits up and quickly gathers his belongings into his backpack while muttering something about being exhausted. You believe you have seen several glass ampoules in his bag. What will you do?

The temptation may be to do nothing, especially if you are not sure what you saw and are afraid of getting someone "in trouble." However, you have a responsibility to patients, to the hospital, to the profession, and perhaps most importantly, to Peter, to report this to someone who can help, such as the medical school clerkship director, program director, clinical director, or department chair. This person can then further assess the situation including talking with Peter. Peter should be confronted directly and firmly. If he has not been abusing substances, he may be offended but will be able to quickly clear himself of any suspicion. If he has been abusing substances, then denial, anger, and avoidance are likely. Drug testing may be required emergently, as allowing time to pass may obscure the window of opportunity. Peter should ideally not care for patients until the issue is resolved.

Peter is found to have fentanyl and hydromorphone in his bag and tests positive for opioids in his urine. He admits to having been diverting drugs from the OR for about 3 months, beginning after his relationship began to unravel. Would random drug testing of all residents have prevented this situation?

Possibly; there is some single-center data to indicate this may have some influence but this has not proven to be a widespread approach [20]. A survey of anesthesia programs found an approximate prevalence of substance abuse of 1% among faculty physicians and 1.6% among residents [21]. Thus, drug testing would unnecessarily test many, many non-using anesthesiologists to discover one who was using. Moreover, the tests (especially for drugs other than opioids)

are expensive, prone to misleading results (for example, poppy seed ingestion can lead to a positive opioid test), and circumventable (for example, substituting clean urine. Drug testing alone cannot solve or prevent substance use disorders. Education, awareness, and strong support systems within and outside the department are paramount.

Is this problem more common in anesthesiology?

This is debatable. Earlier studies showed that among physicians admitted for inpatient substance abuse therapy, anesthesiologists were overrepresented relative to their prevalence among all physicians. This study may have been confounded by better detection of abuse in the specialty. For example, the mean time to discovery when one is abusing fentanyl is only 3 months because tolerance develops so rapidly that the anesthesiologist is not able to divert enough drug (often more than 1000 mcg or 20 ml per dose) to maintain the addiction. Subsequent work, using different methodology, contradicted this early result and found the incidence to be no higher among anesthesiologists than other physicians. Nonetheless, the daily direct handling of abusable drugs, the ability to mask diversion of drugs (by the use of other agents, such as beta blockers, in patients to mimic the effects of the stolen drugs), and the high stress environment of the OR are all possible reasons for anesthesiologists to become drug abusers. An intriguing but unproven hypothesis holds that exposure to trace quantities of opioids, induction agents, and inhalation agents in the OR can sensitize the anesthesiologist's brain and predispose it to addiction [22].

Peter undergoes several weeks of inpatient detoxification and rehabilitation. Should he re-enter the operating room as an anesthesia resident?

This is one of the most controversial topics in the fields of anesthesiology and addiction medicine. The direct exposure to drugs in the OR may prove to be a temptation that cannot be overcome by a recovering addict and therefore Peter may

be safer if he chooses a different medical specialty or career path. Conversely, many have recommended that properly motivated recovering abusers be allowed carefully monitored reintroduction into the field, and a significant fraction of those who do so are successful. Unfortunately, the presenting symptom of relapse is all too often death. Therefore, many have called for a "one-strike and you're out" policy, with compassionate counseling towards another field of medicine. Although only a tiny fraction of anesthesiologists succumbs to drug abuse, vigilance among all in the field is a professional responsibility.

References

1. American Board of Medical Specialties. ABMS Definition of Medical Professionalism (Long Form). 2012. Available at: https://www.abms.org/media/84742/abms-definition-of-medical-professionalism.pdf. Accessed 31 Aug 2020
2. Chestnut DH (2017) On the road to professionalism. Anesthesiology 126(5):780–786
3. Empathy. In: Oxford Languages Dictionary, 2020. Accessed 31 Aug 2020
4. Samra R (2018) Empathy and burnout in medicine—acknowledging risk and opportunities. J Gen Int Med 33(7):991–993
5. Parker SK, Axtell C (2001) Seeing another viewpoint: antecedents and outcomes of employee perspective taking. Acad Manag J 44(6):1085–1100
6. Hojat M, Vergare MJ, Maxwell K et al (2009) The devil is in the third year: a longitudinal study of erosion of empathy in medical school [published correction appears in Acad Med. 2009;84(11):1616]. Acad Med 84(9):1182–1191
7. Riess H, Kelley JM, Bailey RW, Dunn EJ, Phillips M (2012) Empathy training for resident physicians: a randomized controlled trial of a neuroscience-informed curriculum. J Gen Int Med 27(10):1280–1286
8. Kraft-Todd GT, Reinero DA, Kelley JM, Heberlein AS, Baer L, Riess H (2017) Empathic nonverbal behavior increases ratings of both warmth and competence in a medical context. PLoS One 12(5):e0177758

9. Shore R, Halsey J, Shah K, Crigger BJ, Douglas SP (2011) AMA Council on Ethical and Judicial Affairs (CEJA). Report of the AMA Council on Ethical and Judicial Affairs: professionalism in the use of social media. J Clin Ethics 22(2):165–172
10. Samuelson ST, Bryson EO (2017) The impaired anesthesiologist: what you should know about substance abuse. Can J Anaesth 64(2):219–235
11. Fitzsimons MG, Baker K, Malhotra R, Gottlieb A, Lowenstein E, Zapol WM (2018) Reducing the incidence of substance use disorders in anesthesiology residents: 13 years of comprehensive urine drug screening. Anesthesiology 129(4):821–828
12. Collins GB, McAllister MS, Jensen M, Gooden TA (2005) Chemical dependency treatment outcomes of residents in anesthesiology: results of a survey. Anesth Analg 101(5):1457–1462
13. El-Shafy IA, Delgado J, Akerman M, Bullaro F, Christopherson NAM, Prince JM (2018) Closed-loop communication improves task completion in pediatric trauma resuscitation. J Surg Educ 75(1):58–64
14. Pian-Smith MCM, Simon R, Minehart RD, Podraza M, Rudolph J, Walzer T, Raemer D (2009) Teaching residents the two-challenge rule: a simulation-based approach to improve education and patient safety. Sim Healthcare 4:84–91
15. Raemer DB, Kolbe M, Minehart RD, Rudolph JW, Pian-Smith MCM (2016) Improving anesthesiologists' ability to speak up in the operating room: a randomized controlled experiment of a simulation-based intervention and a qualitative analysis of hurdles and enablers. Acad Med 91(4):530–539
16. Salas E, Sims DE, Burke S (2005) Is there a "Big Five" in teamwork? Small Group Res 36(5):555–599
17. Gardner AK, Scott DJ, AbdelFattah KR (2017) Do great teams think alike? An examination of team mental models and their impact on team performance. Surgery 161(5):1203–1208
18. Fletcher G, Flin R, McGeorge P, Glavin R, Maran N, Patey R (2003) Anaesthetists' Non-Technical Skills (ANTS): evaluation of a behavioural marker system. Br J Anaesth 90(5):580–588
19. Yule S, Flin R, Paterson-Brown S, Maran N (2006) Non-technical skills for surgeons in the operating room: a review of the literature. Surgery 139(2):140–149
20. Fitzsimons MG, Baker K, Malhotra R, Gottlieb A, Lowenstein E, Zapol WM (2018) Reducing the incidence of substance use disorders in anesthesiology residents: 13 years of comprehensive urine drug screening. Anesthesiology 129:821–828
21. Booth JV, Grossman D, Moore J, Lineberger C, Reynolds JD, Reves JG, Sheffield D (2002) Substance abuse among physicians: a survey of academic anesthesiology programs. Anesth Analg 95:1024–1030
22. Bryson EO, Silverstein JH (2008) Addiction and substance abuse in anesthesiology. Anesthesiology 109(5):905–917

Quality Assurance, Patient and Provider Safety

35

Carolyn Pinkerton and Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xxxiii are reviewed before reading this chapter.

Key Learning 5.2.Objectives

- Learn about the need for and history of patient safety
- Discuss anesthesia-related patient safety data
- Understand national initiatives to improve patient safety

Anesthesiologists are responsible for taking their patients safely through the stresses of surgery, while preserving and protecting their vital functions. They become the **advocates for the anesthetized patient**, who has been rendered unconscious. Patient safety is of utmost concern, and the field of anesthesiology has long been recognized as a leader in patient safety efforts.

C. Pinkerton (✉) · J. M. Ehrenfeld
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: cpinkert@mcw.edu; jehrenfeld@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_35

The History of Patient Safety

In its early days, anesthesia was perceived to have a high risk of mortality, and medical liability insurance premiums reflected this perception. However, a concerted effort led by the American Society of Anesthesiologists (ASA), in collaboration with several other groups, has resulted in paying greater attention to patient safety and the issues of preventable adverse outcomes. The Anesthesia Patient Safety Foundation (APSF) was formed in 1985 with the vision that "no patient shall be harmed by anesthesia," and has been a champion for patient safety ever since. Significant advances in monitoring during anesthesia, such as pulse oximetry, have subsequently been responsible for a decline in adverse events [1].

Quality Assurance

Quality has been described in literature as the product of two factors: the science and technology of health care and the actual application of that science and technology in practice. Quality assurance (QA) refers to the process of determining whether patient services meet or exceed expected standard. QA helps maximize the quality of patient care, so that all patients receive the care they deserve [2].

In the United States, there is room for improvement in the quality of healthcare. The amount of money spent on healthcare in the U.S. is staggering. According to the National Health Expenditure Accounts (NHEA), which are the official estimates of total health care spending, U.S. health care spending approaches $3.6 trillion or $11,172 per person [3]. Despite this, Americans actually have poorer health outcomes compared to many countries with similar economies. A report published by the National Research Council and the Institute of Medicine from 2013 compared health outcomes in the United States with those of 16 comparable high-income countries. They discovered that compared to other countries, Americans overall have shorter life expectancies. Furthermore, Americans have the highest infant mortality rate,

highest rate of death from violence, highest rate of obesity and diabetes, and highest rate of lung disease compared to peer countries [4].

Healthcare quality and patient safety go hand-in-hand. Issues around safety in healthcare were brought to the forefront of public attention in 1999 with the publication of the Institute of Medicine's report entitled "*To Err is Human.*" This famous document estimated that medical errors occur in approximately 7% of all patients, and that between 44,000 and 98,000 deaths occur annually in the US as a result of medical error. This is almost three times the fatality rate on US highways [5].

While several external organizations such as The Joint Commission and state licensing Boards evaluate healthcare quality, the primary responsibility for patient safety and quality of healthcare provision rests upon anesthesia providers.

The ASA Closed Claims Study

The ASA Closed Claims Study, which began in 1985, has played an important role in the identification of anesthesia-related adverse events. This project is an ongoing, detailed analysis of closed anesthesia liability claims to identify significant patterns of injury. At the time of publication of a recent review, the database contained nearly 9000 cases, the majority of which are from 1980 to 2001 [6]. Most of these earlier data involve healthy adults undergoing nonemergency surgery under general anesthesia. These data provide an important opportunity to identify how anesthesia care contributes to adverse outcomes, since outcomes are not confounded by disease processes.

It is evident that adverse outcomes occur in a small number of specific categories. The top three groups of adverse outcomes identified in decreasing frequency are **death, nerve damage, and brain damage.** The significance of identifying these large groups of injuries is that research and interventions can be more effectively directed at a few large areas of clinical practice, potentially resulting in substantial improvements in patient safety. In the past, this technique was used successfully by the American Society of

Anesthesiologists to focus attention on monitoring standards and specific guidelines for high-frequency adverse events, leading to the promulgation of the ASA Standards for Basic Anesthetic Monitoring (Table 35.1).

The publication of guidelines by the ASA for managing issues with high rates of adverse outcomes has led to a significant decline in these adverse outcomes. For example, difficult airway management during induction of anesthesia has long been regarded as one of the most challenging issues in anesthesia patient safety. However, an analysis of claims associated with difficult airway management during induction of anesthesia shows a marked, sta-

Table 35.1 ASA Standards for Basic Anesthetic Monitoring [7]

Standard 1: Qualified anesthesia personnel shall be present in the room throughout the conduct of all general anesthetics, regional anesthetics, and monitored anesthesia care	
Standard 2: During all anesthetics, the patient's oxygenation, ventilation, circulation, and temperature shall be continually evaluated	
Oxygenation	Oxygen analyzer for inspired gases
	Observation of the patient
	Pulse oximetry
Ventilation	Auscultation of breath sounds
	Observation of the patient
	Observation of the reservoir bag
	Capnography (carbon dioxide monitoring)
Circulation	Continuous ECG display
	Heart rate and BP recorded every 5 min
	Evaluation of circulation
	Auscultation of heart sounds
	Palpation of pulse
	Pulse plethysmography
	Pulse oximetry
	Intraarterial pressure tracing
Temperature	Monitor temperature when changes are intended, anticipated, or suspected

tistically significant decrease in the incidence of death and brain damage (62% vs. 35%, $p < 0.05$) in the period after the publication of the ASA Difficult Airway Algorithm (1993–1999), when compared with period before the publication of the airway guidelines (pre-1993) [8]. The most recent ASA Difficult Airway Algorithm has been reproduced in Appendix A.

Challenges Facing the Anesthesia Provider

The operating room is a unique environment and presents challenges to even the most vigilant anesthesiologist. Environmental factors such as noise, multiple alarms, and continuous movement through the operating room of members of the team can all distract attention. Human factors like fatigue and sleep deprivation can also affect monitoring and cognitive tasks. In addition, with the emphasis on enhanced productivity, "production pressure" may force errors and compromise patient safety.

Automated information systems that provide automated anesthesia recordkeeping have become increasingly popular. They have been shown to be of great benefit in support of patient care and safety, and enhancement of clinical quality improvement programs. These systems are increasingly being implemented in various anesthesia departments to support several functions, including real-time clinical decision support [9, 10].

Steps to Ensure High Quality Anesthesia Care and Patient Safety

In order to optimize patient safety and ensure high quality care, the following principles should be taken into consideration by the anesthesia practitioner.

1. *Make patient safety a priority.* Be an advocate for your patient, always.
2. *Thorough planning*. **Follow the Scouts motto of "Prepared for Life."** Practice meticulous preoperative planning and formulate a plan for intraoperative as well as postoperative care.

Have a back-up plan in mind. However, at times, it may not be possible to plan far ahead because of the unpredictable nature of the operating room environment. Even when under pressure, slow down, think things through rationally and clearly and formulate a plan of action.

3. *Vigilance.* Monitoring the patient involves not only electronic monitoring but also astute clinical observation. Chest rise, mucus membrane color, furrowing of the brow are just a few signs that can provide a wealth of information about the patient. Be aware of what is happening in the operating room at all times and keep an eye on what's going on across the drapes. Listen out for indicators of potential problems like for the increasingly frequent sound of the suction catheter heralding an increase in blood loss.
4. *Teamwork* is essential for efficiency and excellence. Make a point to **introduce yourself** to the other members of the team, for it is through the collective efforts of the team striving together toward a common goal that high standards of patient care can be met.
5. *Detailed, accurate record keeping* is a medico-legal requirement. During "Adverse Events" there is often no time to fill out the chart. You *must* however do so later despite any emotional distress you may be feeling. Keep it brief, factual, and accurate. Remember, if something is not documented, it didn't happen.
6. *Postoperative patient checks* allow anesthesia providers to document the overall impact of the care they provide. This feedback is critical to understand the downstream effects of the clinical decisions made in the operating room.

Common Perioperative Complications

Difficult Airway

As previously discussed, difficult or failed airway management is a major contributor of patient morbidity and mortality in anesthesia. In recent years, however, technology including newer video

laryngoscopes and supraglottic airways have decreased the frequency of these events. A 2018 study of 421,581 anesthetics in a regional community anesthesia practice found the rates of problematic airways decreased fourfold between 2002 and 2015. From 2011 to 2016, the rates of difficult and failed intubation were 1.6 per 1000 and 0.06 per 1000 patients, respectively [11]. Thankfully, brain damage and death are very rare outcomes of difficult airway management. One contemporary series describing closed claims from 2000–2012 identified characteristics of patients with difficult or failed airways leading to adverse events. Compared to malpractice claims filed in earlier years, patients with these challenging airways were found to be sicker overall (ASA III to V). Furthermore, these events were more likely to occur in emergency operations and in "out of operating room" locations. Lastly, although the rates of these events have decreased through the years, the rate of death when there is a difficult or failed airway was found to be higher than before [12].

Dental Trauma

Dental injuries are a common complication during anesthesia. A review of the literature reveals retrospective data quoting a perioperative dental damage rate range from 0.02% to 0.07%. However, other prospective series report much higher incidences, up to 12% [13]. Perioperative dental damage is the most common of all medicolegal complaints related to anesthesia, comprising one third of all anesthetic claims. In the perioperative period, most dental injuries (50%–75%) occur during tracheal intubation. Obtaining a dental history and oral examination as part of the preoperative anesthesia assessment can alert one to those patients at high risk of dental injury. It is important to inquire about the presence of crowns, fixed partial dentures or bridges, and porcelain veneers, as teeth with dental work tend to be more fragile. Patients with poor dentition with risk factors for difficult intubation have the highest risk, however even sound teeth can be damaged. The use of mouthguards during intubation is controversial, as this may limit available space and make laryngoscopy more

difficult. Being cognizant of the risk of dental injury with every laryngoscopy is the best means of prevention.

Eye Injury

Post-operative visual loss (POVL) is a rare but alarming complication of anesthesia that can occur with any non-ocular surgery, although it has mostly been described in spine and cardiac surgeries. One series investigating the prevalence of POVL in over five million patients spanning a 10-year period revealed an estimated rate in cardiac surgery of 8.64/10,000 and 3.09/10,000 in spinal fusion. By contrast, POVL after appendectomy was 0.12/10,000. The frequency of this complication has decreased over time [14]. The pathophysiology of POVL is varied and includes anterior ischemic optic neuropathy (AION), posterior ischemic optic neuropathy (PION), and ischemic optic neuropathy (ION). ION is the most common cause of permanent POVL and accounts for 89% of POVL following prone spine surgeries [15]. The mechanism for perioperative visual loss is presumed to be ischemia, and risk factors include long duration in the prone position, obesity, excessive blood loss, hypotension, anemia, hypoxia, excessive fluid replacement, use of vasopressors, elevated venous pressure, head positioning, and a preexisting vascular susceptibility such as occurs in smokers and patients with diabetes mellitus. Awareness of these risk factors and interventions to minimize them can help limit the frequency of this dreadful complication [15, 16]. It may be prudent to advise patients, particularly for those undergoing cardiac or spine cases where you anticipate a prolonged procedure or substantial blood loss, that POVL can occur.

Corneal abrasions are another minor but bothersome complication of anesthesia as they are extremely painful. Prevalence rates vary in the literature, with one recent series describing a rate of 3% at an institution reviewing 132,000 PACU admissions [17]. These may be due to direct trauma to the eye, as can occur with carelessness during mask ventilation. More frequently, they occur due as exposure keratitis due to failure of the eyelids to close fully, resulting in drying of the cornea. Risk factors identified

include longer operations, non-supine patient positioning, and patient sedation or agitation when arrival to PACU [17]. Corneal abrasions can be prevented by taping the eyelids closed, or the use of paraffin-based ointments.

Peripheral Nerve Injuries

Peripheral nerve injuries (PNI) can occur during regional or general anesthesia. These conditions can have profound consequences for the patient from the resulting disability. The cause of PNI is much more than simply patient positioning. Oftentimes, PNI is multifactorial, caused by both local (stretching, compression, ischemia, and transection) and systemic (systemic hypotension, inflammation) factors. Furthermore, the extent of PNI depends on the severity and duration of insult as well as the underlying nerve condition (for example, presence of pre-existing neuropathy) [18]. Injuries may be due to external pressure or non-anatomical positioning, and may occur more frequently with old patients, thin patients, and patients with vasculopathies such as smokers and diabetics. Brachial plexus injuries recently replaced ulnar nerve injuries as the most common PNI reported in the ASA closed claim database. Notably, for nearly one half of these cases, no mechanism of injury could be identified [18]. When positioning, the head and neck should be kept in neutral position and the arms should not be extended more then 90°. Shoulder abduction and lateral rotation should be minimized to prevent brachial plexus injury. Padding should also be used on pressure points.

Intraoperative Recall

The problem of awareness during general anesthesia has received much public attention recently and is a prime concern with patients. Awareness has been shown to have a frequency of less than 1 in 1000 general anesthetics, but the consequences in terms of patient distress are profound. The ASA advises specific interventions to help reduce the risk and impact of intraoperative

awareness, beginning with the preoperative identification of risk factors. These include a prior episode of intraoperative awareness, a history of anticipated difficult intubation, receiving high doses of opioids for chronic pain, substance use/abuse, ASA status 4–5, and limited hemodynamic reserve. In addition, there are certain surgical procedures with an increased risk of intraoperative awareness, such as cardiac, trauma, emergency, and cesarean sections. Some anesthetic techniques can also increase the risk of intraoperative recall, such as using a low MAC of anesthetic or total intravenous anesthesia in the presence of paralysis. The use of brain function monitors for the assessment of the depth of anesthesia has enjoyed increasing popularity, but studies about the actual effectiveness in reducing incidence of awareness remain ongoing [19, 20].

The Future

The growing burden of healthcare costs has resulted in increased pressure on anesthesiologists to improve the quality and safety of healthcare in a cost-effective manner. It is recognized that adherence to evidence-based practices may improve outcomes, decrease complications, and decrease costs. For example, widespread use of Enhanced recovery after surgery (ERAS) protocols, multimodal evidence-based strategies applied to perioperative techniques, have been shown to reduce postoperative complications and to achieve early recovery [21]. The "pay-for-performance" concept uses a variety of incentives to encourage delivery of evidence-based practices. In 2006, the Institute of Medicine (IOM) put forward a statement on pay-for-performance, defining which practices should be rewarded, and how they should be implemented. The IOM recommended that rewards be given for high quality clinical care and to those providers who communicate well with patients and coordinate care effectively. For anesthesia providers, some specific metrics might include on-time

antibiotic administration and maintenance of intraoperative normothermia. By the same token, "never events," defined by CMS as "serious, preventable and costly" complications, lead to penalties for hospital systems where services necessary after such occurrences are not reimbursed. Examples relevant to the Anesthesiologist include wrong site surgery, intraoperative or immediate post-operative death in an ASA 1 patient, or death or disability due to a medication error [3].

With these measures in place, quality assurance and patient safety have become mandated areas of focus for anesthesia providers. It is important to remember, however, that the ultimate responsibility to ensure that our patients receive the best care lies with each of us.

Case Study

An anxious 48-year-old patient is in the preoperative holding area awaiting outpatient surgery under general anesthesia. With her is her husband, an expert on risk assessment in nonmedical industries, and her father, a retired surgeon in his late 1970s. She is anxious because her father has told her stories of surgery in the 1950s and 1960s, when he remembers significant numbers of patients dying or suffering significant morbidity. Her husband has worked in aviation, industrial process design, and is an industry safety expert. All three acknowledge your assurance that the practice of anesthesia is remarkably safer now but ask you to explain some of the safety advances that characterize anesthesiology today and explain the improvements.

You have just finished setting up the operating room for this case. What safety features of the modern anesthesia machine can you point to in reassuring the patient and her family?

There are quite a few features of a modern anesthesia machine, even those that do not have the most recent electronic controls built in. These include:

- Safety indexed gas lines
- Pin indexed cylinder connectors
- Failsafe valve
- Minimum oxygen flow whenever machine is on
- Knurled flowmeter knobs with standardized textures and positions on the machine
- Oxygen always rightmost in sequence of gas flowmeters to guard against upstream leaks
- Built-in inspired oxygen monitors and alarms
- Low pressure (disconnect) alarm
- All vaporizers standardized to clockwise-off
- Safety fillers for vaporizers
- Vaporizer interlock to prevent multiple agent administration
- Standardized machine checkout, either manual or automatic, before each case*What are some of the monitoring developments since the 1950s that have improved safety?*

Numerous monitors have been added to the manual blood pressure cuff and finger on the pulse of the mid-twentieth century. Electrocardiography, automatic blood pressure monitoring with alarms, pulse oximetry, capnography, agent and inspired gas monitoring, neuromuscular blockade monitoring, and consciousness monitoring are all routinely found in the modern OR. Interestingly, although without a doubt the introduction of these monitors paralleled the decline in anesthesia-related mortality and morbidity, it has been difficult to prove a causal relationship. For example, a large meta-analysis of randomized trials of pulse oximetry showed that it reliably detected episodes of hypoxemia but did not affect postoperative outcomes! One explanation for this paradox is the concept of "learning contamination bias," which means that anesthesiologists have learned so much from the use of the monitor that even when it is absent, they employ tactics that prevent episodes of hypoxia.

Examples include preoxygenation, use of oxygen during transport to the PACU, and use of high-flow oxygen when discontinuing nitrous oxide administration.

What drug-related advances and procedures have you employed that have enhanced safety?

The use of standardized color-coded drug labels and the use of standardized concentrations of drugs are two practices that help reduce drug errors. Anesthesiologists also have learned from human performance studies to use safe practices such as "3 looks" when drawing up medications (before drawing, during drawing, after complete before setting down the vial) or positioning drugs in a standardized way on the anesthesia cart. Development of shorter acting drugs (fentanyl and derivatives, low solubility and minimally bio-transformed inhalation agents) and drugs with a greater margin of safety between therapeutic and toxic doses have also helped. Other practices include checking blood with two people, pharmacy-mixed drug infusions, computerized infusions pumps with safety programs to limit errors in setting, and in some settings bar codes to verify drug identity.

What communication procedures will you employ that enhance safety?

In nearly every US operating room, The Joint Commission "safety pause" or "time-out" is performed prior to incision, in which the anesthesiologist, surgeon, and circulating nurse (and sometimes the patient) verbally state and agree on the planned procedure. An advancement of this idea is the WHO surgical safety checklist, which adds such practices as "once around the room" checks with all personnel regarding potential concerns. We also have standardized record keeping in the OR, whether manual or electronic and automated, and practice provider-to-provider anesthesia handoff procedures and standardized handoffs in PACU or ICU.

What other safety procedures are routine for all anesthetics in modern practice?

Anesthesiologists note and ensure pressure point and eye protection, assessment of the airway and teeth prior to and following induction, and in some settings temperature, radiation, or laser protection. A key development in the last half-century has been the simple presence of qualified anesthesia personnel in the OR at all times.

References

1. Anesthesia patient safety foundation. www.apsf.org
2. Donabedian A (2002) An introduction to quality assurance in health care. Oxford University Press, New York. 4 p
3. Centers for Medicare and Medicaid Services. www.cms.gov
4. National Research Council (US), Institute of Medicine (US) (2013) In: Woolf SH, Aron L (eds) U.S. Health in International Perspective: Shorter Lives, Poorer Health. National Academies Press (US), Washington DC
5. Kohn LT, Corrigan J, Donaldson MS (1999) To err is human: building a safer health system. Washington National Academy Press, Washington DC
6. Metzner J, Posner K, Lam M, Domino KB (2011) Closed claims analysis. Best Pract Res Clin Anaesthesiol 25(2):263–276
7. American Society of Anesthesiologists. www.asahq.org
8. Peterson GN, Domino KB, Caplan RA, Posner KL, Lee LA, Cheney FW (2005) Management of the difficult airway: a closed claims analysis. Anesthesiology 103(1):33–39
9. O'Reilly M, Talsma A, VanRiper S, Kheterpal S, Burney R (2006) An anesthesia information system designed to provide physician-specific feedback improves timely administration of prophylactic antibiotics. Anesth Analg 103(4):908–912
10. Röhrig R, Junger A, Hartmann B et al (2004) The incidence and prediction of automatically detected intraoperative cardiovascular events in noncardiac surgery. Anesth Analg 98(3)
11. Schroeder RA, Pollard R, Dhakal I et al (2018) Temporal trends in difficult and failed tracheal intubation in a regional community anesthetic practice. Anesthesiology 128(3):502–510
12. Joffe AM, Aziz MF, Posner KL, Duggan LV, Mincer SL, Domino KB (2019) Management of difficult tracheal intubation: a closed claims analysis. Anesthesiology 131(4):818–829

13. Yasny J (2009) Perioperative dental considerations for the anesthesiologist. Anesth Analg 108(5):1564–1573
14. Shen Y, Drum M, Roth S (2009) The prevalence of perioperative visual loss in the United States: a 10-year study from 1996 to 2005 of spinal, orthopedic, cardiac, and general surgery. Anesth Analg 109(5):1534–1545
15. Berg S, Braehler M (2019) The postanesthesia care unit. In: Gropper MA, Eriksson LI, Fleisher LE, Wiener-Kronish JP, Cohen NH, Leslie K (eds) Miller's anesthesia, 9th edn. Elsevier, pp 2586–2613
16. Practice advisory for perioperative visual loss associated with spine surgery 2019: an updated report by the American Society of Anesthesiologists task force on perioperative visual loss, the North American Neuro-Ophthalmology Society, and the Society for Neuroscience in Anesthesiology and Critical Care. Anesthesiology. 2019;130(1):12–30
17. Deljou A, Weingarten TN, Mahr MA, Sprung J, Martin DP (2019) Postoperative corneal injuries: incidence and risk factors. Anesth Analg 129(3):737–742
18. Chui J, Murkin JM, Posner KL, Domino KB (2018) Perioperative peripheral nerve injury after general anesthesia: a qualitative systematic review. Anesth Analg 127(1):134–143
19. Kent CD, Posner KL, Mashour GA et al (2015) Patient perspectives on intraoperative awareness with explicit recall: report from a North American anaesthesia awareness registry. Br J Anaesth 115 Suppl 1:i114–I121
20. Domino KB, Cole DJ (2018) Awareness under anesthesia. In: Pardo MC, Miller RA (eds) Basics of anesthesia, 7th edn. Elsevier, pp 812–820
21. Moningi S, Patki A, Padhy N, Ramachandran G (2019) Enhanced recovery after surgery: an anesthesiologist's perspective. J Anaesthesiol Clin Pharmacol 35(Suppl 1):S5–S13

Ethical and Legal Issues in Anesthesia

36

Jesse M. Ehrenfeld

For maximum impact, it is recommended that the case study and questions found on page xxxiv are reviewed before reading this chapter.

Key Learning Objectives

- Understand the principle and process of obtaining informed consent
- Learn the definition of medical malpractice and how to avoid frivolous claims
- Know the procedure for addressing DNR/DNI status in the operating room

Informed Consent

Informed consent is a process in which a patient makes decisions and gives consent for procedures and treatments *after* having achieved a clear understanding of the facts and implications of

J. M. Ehrenfeld (✉)
Department of Anesthesiology, Medical College of Wisconsin, Milwaukee, WI, USA
e-mail: jehrenfeld@mcw.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_36

taking a particular course of action. Contrary to popular belief, informed consent is a process – not just a signed legal document.

Informed consent is only possible when a patient is both (1) able to make rational decisions and (2) has received all of the relevant facts. Typical discussion points should include diagnosis, purpose of the therapy, possible risks and benefits, potential alternative therapies, and risks associated with not receiving the therapy. The process is summarized below.

Guide to Obtaining Informed Consent

- Informed consent is a process – not simply a signed document
- Informed consent should be obtained prior to administering sedatives
- The patient may accept/refuse any treatment (principle of patient autonomy)
- The patient should receive a description of procedure, potential risks and benefits
- Incapacitated patients (altered consciousness, incompetent, disabled)
  - do not have the ability to provide consent
  - next of kin or a healthcare proxy should provide consent instead
- If obtaining consent via telephone, make sure to obtain a witness
- Under emergency, life threatening situations, consent is implied and may be waived
- Use an official hospital interpreter for non-English speakers whenever possible
- Pediatric patients and minors (<18 years of age) cannot give consent for themselves (except pregnant patients or emancipated minors in some states)

Malpractice

Medical malpractice is a legal definition for a specific type of negligence, where a professional (e.g. a physician) fails to follow professional standards and causes harm to a patient. In order for medical malpractice to have occurred, these items must be established:

- The physician had a duty to care for the patient (i.e. the patient was under the care of a physician and a relationship had been established)
- The duty of care was breached
- The physician deviated from the standard of care ("What a prudent physician would do")
- The breach caused harm to the patient

Keep in mind that even when physicians act appropriately, patients still may have adverse outcomes. It is therefore important to set appropriate expectations and inform patients about the potential risks of therapy before initiation of treatment. This will prevent confusion, ill-will, and unnecessary malpractice lawsuits.

Advanced Directives

Advance directives are specific instructions given by a patient to direct providers on how to proceed if he/she can no longer make decisions because of illness or other incapacitation. There are a number of different types of advance directives including living wills and health care proxies. A **living will** provides specific instructions regarding particular treatment courses. For example, a living will may specify that the patient is not to receive specific interventions such as intubation or CPR. A **Health Care Power of Attorney** differs in that it appoints another individual to make decisions on behalf of the patient should he/she become incapacitated. It does not provide specific guidance as to what those decisions should be.

Do Not Resuscitate (DNR)/Do Not Intubate (DNI)

Some patients will choose to forgo life saving treatments, such as intubation or CPR. Typically this decision is made near the end of a patient's life or by a patient with a terminal illness. Keep in mind that patients have the right to choose whether or not resuscitative measures should be instituted in case of cardiac arrest.

These choices (DNR/DNI) are *not* automatically placed on hold should a patient present for surgery or anesthesia care. It is therefore imperative that a discussion regarding a patient's specific preferences be initiated prior to coming into the operating room. In this discussion, the patient should be asked to outline which therapies are acceptable and which are not during the operative period. Treatments typically discussed include intubation, CPR, defibrillation, and vasopressors. The outcome of the discussion and the patient's choices should be (1) clearly documented in the chart, and (2) communicated to the entire operative team. In a growing number of facilities, a physicians order may be placed to indicate the patients status and preference in the electronic medical record.

Case Study

An 80-year-old man has terminal colon cancer. He has metastatic disease with liver and brain metastases. As his condition worsened over the preceding year, he had several conversations with his family and physicians about his end of life care. He has a signed and witnessed advanced directive indicating his desire to be treated as "DNR/DNI" (do not resuscitate, do not intubate). He has now developed bowel obstruction and was admitted with severe abdominal pain. His surgeons have recommended a diverting colostomy for palliative care. They obtained consent for the operation from the patient last night, but anesthesia consent has not yet been obtained. The patient was medicated with hydromorphone and is now somnolent and falls asleep immediately upon waking. The surgeons are eager to operate before the bowel ruptures.

Can you obtain informed consent from the patient? Is surgical consent sufficient? What options do you have?

A somnolent, barely arousable patient can probably not give informed consent. Just waking up the patient long enough to obtain his signature on the consent form is not sufficient. Informed consent is a process of discussing risks and benefits with the patient and allowing him to make an informed decision that the latter outweighs the former. The signature on the form merely documents the successful completion of the informed consent process. In emergency situations, many anesthesiologists will consider surgical consent to represent implied anesthesia consent, but this case is not such an emergency. There are separate risks and benefits associated with anesthesia and surgery, and there are some unique risks in this patient who has a DNR/DNI order. Separate consent is necessary, therefore. Your options hinge on whether or not the patient has designated a health care proxy to consent on his behalf. If he has, you should approach this person and have a complete discussion regarding the anesthetic risks and options. If the patient has left a detailed advanced directive, you may be able to follow this document and consider proceeding. If not, your options include waiting until the patient is more awake, partially reversing the effect of hydromorphone, or proceeding without consent. The latter option is problematic and should not be contemplated without consulting hospital lawyers or risk management first.

How should you interpret the patient's DNR/DNI order for the operation, assuming you have obtained consent? You are planning general endotracheal anesthesia for the operation.

DNR/DNI orders usually indicate a patient's wish in the setting of cardiac arrest or other extreme emergency, which may indicate death at the end of a fatal illness. These orders may not indicate the patient's wishes in situations such as general anesthesia, when there is a reasonable expectation

that the condition requiring intubation or resuscitative efforts is brief and reversible. For example, many patients with a DNR order may choose to undergo surgery with intubation and accept use of pressor agents to correct hypotension. However, they may not wish to be shocked or have CPR in the event of an intraoperative arrest. The main point is that like consent, the interpretation of a DNR/DNI order during surgery follows from a conversation with the patient or his proxy, not a set protocol. Part of the process you should employ to obtain consent is having this discussion. Conversely, some anesthesiologists and surgeons believe that consenting to operation necessarily means suspension of any DNR/DNI order. Many surgeons and anesthesiologists will only take patients to surgery if the DNR/DNI order is suspended. If this is done, then a specific timeframe for the suspension, and plan for resumption of the order, should be defined preoperatively.

If you proceed with surgery with general endotracheal anesthesia, and you are unable to extubate the patient at the end of the case, what will you do? Are you liable for a malpractice claim?

Assuming you have done the consent process properly, you will already know the answer to this question for this patient! In a critically ill patient undergoing abdominal surgery, there is a chance that postoperative intubation and ventilation may be required; your consent procedure should acknowledge this fact and a plan for what to do in this event should be made in advance. Some authorities believe that the operating room is a particularly difficult place for death to occur because surgeons and anesthesiologists routinely intervene aggressively. “Resuscitation” is what we do for a living! Therefore, some have argued, a decision to extubate or discontinue ventilation might be better made in the ICU than the OR, if for no other reason that the patient’s family can be present and participate in the decision-making.

Malpractice claims arise when a physician breaches a duty to a patient and causes harm. Although there is no guarantee that any given situation will not lead to a lawsuit, the mere fact that you are unable to extubate should not constitute malpractice unless you have not adequately counseled the patient and obtained informed consent.

Suggested Further Reading

1. Beauchamp TL, Childress JF (2001) Principles of biomedical ethics. Oxford University Press, New York
2. Studdert DM et al (2006) Claims, errors, and compensation payments in medical malpractice litigation. N Engl J Med 354:2024–2033
3. Drane JF (1984) Competency to give an informed consent. A model for making clinical assessments. JAMA 252:925–927

Clinical Simulation in Anesthesia Education

37

Justin R. Traunero and Emily M. Hayden

For maximum learning impact, it is recommended that the case study located at the end of this chapter be reviewed before reading this chapter.

Key Learning Objectives

- Understand the different types of simulation
- Learn how crisis resource management can be used to manage a critical scenario
- Appreciate the ways medical simulation can improve your training
- Gain an understanding of what to expect when participating in a medical simulation

J. R. Traunero (✉)
Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA

Center for Experiential and Applied Learning, Wake Forest University School of Medicine, Winston-Salem, NC, USA
e-mail: jtrauner@wakehealth.edu

E. M. Hayden
Division of Medical Simulation, Department of Emergency Medicine, Massachusetts General Hospital, Boston, MA, USA
e-mail: emhayden@mgh.harvard.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_37

Introduction

Medical simulation is increasingly being utilized in undergraduate medical education, graduate medical education, and in maintenance of board certification for practicing physicians. Simulation based education is an attractive addition to both formal and informal curricula because simulation laboratories provide a "safe" environment for trainees to practice clinical reasoning and procedural skills. The simulation laboratory is a place where mistakes can be made and where key lessons can be learned from these mistakes without placing patients in potentially injurious situations. Furthermore, structured teaching, skills training/practice, and various forms of assessment can occur in these laboratories in order to assist educators with identifying students' educational gaps and focus further instruction on demonstrated areas of weakness [1] (Fig. 37.1).

Fig. 37.1 A "Mock OR" simulation laboratory

What Is Simulation?

The term "simulation" is a generic term for any technique that allows duplication or imitation of a portion of a real-world clinical encounter. As a medical student, it is likely that various forms of simulation have already been an important component of your medical training. You have used simulation if you have participated in any form of problem-based learning using case-based discussion, have practiced suturing on a pig's foot, have performed ultrasound techniques on models or fellow classmates, have taken part in a simulated patient care scenario using a high-fidelity full-body mannequin in a mock OR/ICU, have taken an Advanced Cardiac Life Support (ACLS) course, or have been assessed through standardized patient encounters.

In order to understand simulation better, it is helpful to categorize the types of simulation. One set of classifications focuses on the objective of the simulation, such as cognitive, procedural, or teamwork practice. Another category focuses on the fidelity, or level of realism, of each simulation. Table 37.1 is a matrix with examples of different types of simulation.

All modalities of simulation can be used for either instruction (teaching) or various levels of assessment (testing). Many medical educators are excited about the possibilities of testing using higher-fidelity simulations. In fact, several medical specialty

Table 37.1 Matrix of categories of simulation

Fidelity	Cognitive	Procedural	Teamwork
Low	Case-based discussion	Pig foot suturing	Table-top exercise
Medium	Computer case	Ultrasound models (i.e., Blue Phantom training block models)	Role-playing
High	Full-body mannequin/ patient actors	Single or part task trainers	Full-body mannequin/ patient actors
Highest	Virtual reality	Single or part task trainers with haptics (tactile sensation)	Virtual reality

boards are incorporating various forms of simulation in the board-certification process. In 2018, The American Board of Anesthesiology began administering an Objective Structured Clinical Examination (OSCE) that incorporates various modalities of simulation noted in (Table 37.1) as a portion of their primary board certification examination process.

What Is the History Behind Medical Simulation?

The first medical simulator mannequin was created in the 1960s for anesthesiologists. It was not until the 1980s with the advent of smaller and more affordable personal computers that mannequins were developed for use in mainstream medical training. Around this time, simulation was being used in other sectors, such as aviation, nuclear power, and the military. Until the start of the twenty-first century, medical simulation was being used mainly in anesthesia and some surgical fields. Since the early 2000s, medical simulation has spread to all levels of medical training (undergraduate medical school to continuing medical education) and into many different specialties [2]. A survey by the Association of American Medical Colleges demonstrated that a majority of medical schools (52%) utilize medical simulation during the 4-year medical school curriculum with 95% using standardized patients or full-scale mannequins. Simulation is commonly used as a training and a tool for assessing core competencies in clerkship training within internal medicine, pediatric emergency medicine, and anesthesiology rotations [3]. Additionally, the residency review committees for several specialties, including anesthesiology, have added a medical simulation component to the residency training requirements, ensuring that trainees in these fields are all exposed to a certain degree of simulation as part of their educational curriculum.

What Are the Benefits of Participating in Medical Simulation?

There are numerous benefits to participation in medical simulation that cannot be achieved either through other teaching methodologies or in direct participation in the clinical environment. Key benefits to medical simulation include:

- ***Scheduled*** – Unlike clinical events, specific simulation experiences can be scheduled to occur at prescribed times during wakeful hours for better attention and learning
- ***Targeted*** – The simulation experience can be altered to correspond to the various professional and skill levels of the specific learners and participants
- ***Rare events*** – Medical simulation can expose participants to uncommon critical incidents on demand
- ***Active Environment*** – The simulation environment provides learners with the opportunity to receive immediate feedback directed at each participant's performance
- ***Intense*** – Medical simulation can create a stressful environment that may help facilitate recall in a similar clinical environment
- ***Systems Issues*** – A high-fidelity simulation environment provides the opportunity for multi-disciplinary team practice that may unmask potential system-level or team communication problems

What Is the Evidence Behind Medical Simulation?

Over the past decade, there has been steadily increasing interest in leveraging medical simulation to further learners' educational experiences in both undergraduate and graduate medical education. Additionally, medical simulation is becoming instrumental

in helping board-certified physicians meet Practice Performance Assessment and Improvement (PPAI) requirements of American Board of Medical Specialties Maintenance of Certification (MOC) programs.

Medical simulation has been successfully used to improve medical students' self-confidence, knowledge, and skills in performing procedural skills such as intubation, arterial line placement, lumbar puncture, and central line insertion [4]. Simulation-based learning has also been shown to be superior to a problem-based learning format when teaching medical students about critical care concepts [5] and tracheal intubation when compared to textbook reading and random hands-on training in the operating room [6].

Beyond the applicability of simulation to undergraduate medical education curricula, some studies have examined the positive effect of medical simulation training on patient safety. Simulation training has resulted in improvement of the quality of care provided by residents during actual ACLS events [7] as well as increased demonstrated competence in bronchoscopy when residents were taught these procedural skills using medical simulation [8].

However, simply practicing procedures and skills in the simulation setting alone does not result in permanent retention of competence. Medical students who have participated in simulation based education to acquire clinical skills have been shown to become deficient in these same skills without continued, deliberate practice under the supervision of engaged instructors [9]. Ensuring that diplomates of the American Board of Anesthesiology (ABA) maintain ongoing competence with clinical skills, decision making, and communication skills led to the development of a simulation-based course for practicing anesthesiologists. These courses emphasize a multimodality simulation-based approach to emphasize team training, communication skills, and crisis management with attendance and reflection on the course becoming part of the 10-year recertification requirements for ABA diplomates [10].

How Is High-Fidelity Simulation Used in Medical Training?

The term "High-Fidelity Simulation" has become ubiquitous throughout medical training and is often considered synonymous with full-featured breathing and blinking mannequins with peripheral pulses. However, it is important to remember that high-fidelity simulation is truly multidimensional. High-fidelity simulation is not limited to the type of equipment used in the simulation, but also the environment and the degree to which the trainee perceives the simulation task to approximate the correlating real-world scenario [11]. As such, a high-fidelity medical simulation does not necessarily require the use of a full-featured mannequin and may instead involve the use of limited-scope task trainers or standardized patients.

High-fidelity simulation is frequently employed for team training, or **crisis resource management**. These scenarios bring people with various roles together in a simulation to practice management of a crisis or a chaotic situation. This is similar to the crew resource management philosophy from military aviation and nuclear power plants. In the 1970s, studies by the aviation industry determined the causes of several airline accidents. From these findings, a program of "crew resource management" was developed. The same ideas from crew resource management were translated into the operating room environment and dubbed "crisis resource management." As a student, you may participate in some crisis resource management scenarios in the simulation laboratory.

Medical training institutions are also using high-fidelity simulation in remediation or in root-cause analysis of medical mistakes. Some institutions are bringing actual cases from morbidity and mortality reports or risk management departments to the simulation laboratory for resimulation or analysis and reflection.

The specialty of anesthesiology was the first to embrace simulation as a part of the training process. Simulation has been used in anesthesiology to teach cognitive aspects of the field, including

knowledge content and clinical decision making, as well as **crisis resource management**.

What Is Crisis Resource Management?

Crisis resource management training is intended to improve patient safety by emphasizing teamwork and communication. The specific focuses within crisis resource management address communication, resource management, situational awareness, and role clarity. Key behaviors in crisis resource management include:

- Planning and anticipation of possible problems
- Clear and effective communication
- Clearly defined roles and assertive leadership
- Distribution of the workload
- Utilization of the resources available
- Summoning additional resources/personnel early enough to make a difference
- Wise allocation of attention
- Situation reassessment
- Utilizing cognitive aids when applicable

The concept of crisis resource management translates well to the field of anesthesiology since most anesthesia-related care occurs in environments that are not in isolation: other members of the patient's healthcare team (surgeon/proceduralist, nursing staff, anesthesia technician staff, etc.) are available to help respond in a coordinated fashion when unexpected clinical events occur. The concept of crisis resource management and associated key behaviors noted above emphasize dynamic decision-making and account for human performance issues. Cognitive aids such as emergency manuals and checklists have been shown to be associated with improvement in the management of these dynamic situations when applied as part of a crisis resource management framework [12]. The Stanford Perioperative Emergency Manual is one of the more well-known such cognitive aids [13].

What Is in a Simulation Laboratory?

Each simulation laboratory is unique. Some have only full-body mannequins, while others have only task trainers for endoscopies or laparoscopies. Some have very realistic features that are a complete "mock" copy of an intensive care unit or operating room space, while others may be a mannequin set up in a classroom or closet. Either way, the simulation team works to make the simulation feel realistic to the participants in order to maximize the overall fidelity.

Most of the simulation centers you will encounter during your anesthesia rotations will involve a combination of task trainers and full-body mannequin simulation. Typically, the physical layout of one of these simulation centers will include several rooms: one room with the mannequin and its associated environment, a control room, and a debriefing room. The room with the mannequin usually looks similar to a clinical room such as an operating room, an ICU room, or a floor room in the hospital. Sometimes the room is not "decorated" as a clinical room but is just an available space with the mannequin and monitor. In this case, one room may hold all three sections: the mannequin, the control area, and the debriefing area.

The simulation room with the mannequin may have other equipment available. Some of this equipment may be for intubation, defibrillation (most mannequins are able to receive real defibrillation or external pacing shocks), and medication administration. If a piece of equipment is not available in the room, you should be able to ask for it. Sometimes this requested equipment will be given to you, and other times it will be "simulated" (Fig. 37.2).

For all simulations, there is a control area where someone controls the voice/responses of the mannequin. This control area may be in direct view of you, in the same room but behind a curtain, or in a separate room separated by one-way mirror or viewed through cameras. Usually, you will not spend time in the control room if you are a learner in the sessions (Fig. 37.3).

Fig. 37.2 A typical set-up of a full-body mannequin on an operating bed, with the patient vitals monitor and anesthesia machine

Fig. 37.3 A view of a typical simulation lab control room with one-way glass, camera controls, and simulator controls

Before the simulation encounter, you should receive a pre-briefing from the simulation staff. The pre-briefing will set the stage for the clinical scenario about to be simulated, provide you with any needed background information about your "patient", provide you with information about the clinical environment in which you are practicing, outline the goals of the simulation, and what resources are available to you. The pre-briefing is also an opportunity for you to ask any questions you may have about the scenario or simulation environment prior to the start of the simulation.

There are several people with whom you may have contact while in the simulation laboratory. Around the mannequin, there may be other people working on the same case as you. These could be other students learning through the simulation, or they could be actors. The actors in the scenarios are there to help orient you to the environment and improve the fidelity of the simulation scenario.

At least one instructor will be present during the simulation encounter. This instructor may be a physician, nurse, paramedic, or an educator. During the scenario, the instructor is either in the simulation room or in the control room. While the instructor may be able to help you manage the case, try to use your own knowledge and skills in the scenario rather than depending on the instructor for answers.

A debriefing session will occur *after* the simulation experience and will typically be led by the instructor involved in the simulation encounter. Some simulation centers have a separate room in which this will occur with audio-visual capabilities to playback the scenario during the debriefing. The simulation leader should disclose if the session is being recorded (Fig. 37.4).

In the debriefing session, the faculty member will discuss the case with the participants. The debriefing is a *critical* component to an effective medical simulation and is where participants will be directed to reflect on the scenario and their performance. The discussion will be driven by the objectives of the scenario that were presented during the pre-briefing. For example, if the purpose of the simulation is teamwork or crisis resource management, then discussion points will likely revolve around the principles of cultivating teamwork and communication. If the purpose of the scenario is to understand a specific pathophysiologic concept, then the conversa-

Fig. 37.4 A typical debriefing room with whiteboard and video screens

tion will instead focus on the presentation, recognition, and management of that particular concept. Take advantage of these discussions to ask questions about your performance and fund of knowledge. One of the powerful benefits of simulation is that it allows the participant to actively obtain knowledge through hands-on involvement in the case, learning directly from successes, failures and the debriefing discussion rather than passively hearing the information in a lecture-style environment.

What Can a Mannequin Do?

Several simulation equipment companies exist, each with a mannequin that has slightly different characteristics. The more expensive mannequins typically are able to portray more complex responses or exam findings, often with surprising accuracy and realism. The mannequins range in price from $20,000 to $250,000 each.

Full-body mannequins used in medical simulations typically have chest rise, breath sounds, heart sounds, and pulses. Mannequins can often talk and may blink or have reactive pupils.

An important note about the physical exam findings on mannequins is the variability of the realism of the findings. If you have a question about a specific exam finding, then you should ask either an actor in the room or the instructor to clarify a specific physical exam finding. Do be aware that while the physical characteristics are often very realistic, they are not perfect, and sometimes you may need guidance with interpretation of your findings (Fig. 37.5).

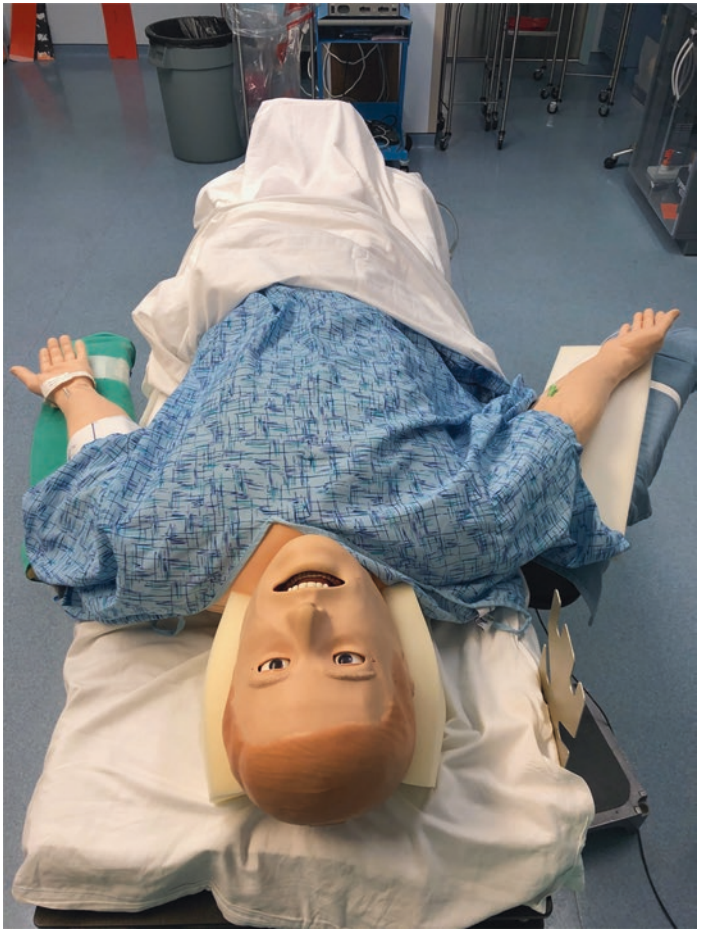


Fig. 37.5 A full body high-fidelity simulation mannequin

The mannequins can usually be intubated, defibrillated, cardioverted, and paced. Be aware that the equipment used to deliver defibrillations or external pacing may be live – as most mannequins can receive actual electricity. In some scenarios involving a medical procedure, you will be required to perform the actual procedure on the mannequin or on a separate task trainer such as an intubation head model or central line model. In other scenarios, you may instead be asked to verbalize what you would do for a procedure. You should be notified before the scenario on how you will "perform" a particular procedure in the simulation lab.

The mannequin will have a patient vital sign monitor similar to the monitors available in the ICU or operating room. Depending on the specific mannequin being used, the mannequin's vital signs may be either simulated or actually produced by the mannequin. In order to view the vital signs, they may need to be "activated" by either asking for the patient monitor and requesting the specific vital signs you desire to monitor in the simulation, or by placing a blood pressure cuff, oxygen saturation probe, and EKG leads to measure the respective vital signs. The simulation lab staff will instruct you on the specific details for the equipment being used for your scenario.

What Should You Expect in the Simulation Laboratory?

As part of your participation in any medical simulation, you will receive verbal feedback on your performance as part of the debriefing following the simulation. You may not have a formal assessment of your performance during a medical simulation, but in some programs, your simulation performance may be included as a component of your rotation evaluation. Prior to the start of the simulation, you should ask if there will be a formal assessment of your performance during the encounter. If you are being formally assessed, it is important to ascertain the rater's expectations of your performance. It is equally as important to have a chance to experience the simulation equipment before the examination so

that any unfamiliarity with the environment or equipment does not unnecessarily compromise your grade.

One great advantage of the simulation encounter is for you to practice, reflect upon your actions and thoughts, and have the chance to practice again. Learning from mistakes is a key part of effective use of medical simulation in your education. Studies of experts in many fields have shown that to become an expert, one needs to have opportunities for deliberate practice with coaching and feedback [14]. Simulations allow you to challenge yourself and make mistakes, with the opportunity for practice and this real-time feedback.

Some centers will have you work as an individual in the case: a situation where you are in the "hot seat." Sometimes you will have more students allowed into the scenario throughout the case, or you may be able to ask for a consultant to help. Other scenarios will have a group of trainees working together to manage the case. If you have multiple cases, you may experience a combination of the above approaches during multiple encounters.

What Are the Expectations of You, the Learner, in Simulation Scenarios?

In general, you will be expected to manage the patient in the scenario to the best of your abilities. Some encounters will have required pre-scenario reading or other preparation; however, most encounters will give you no advance information regarding the case content. Scenarios may be simulating rare events that you may not have seen or managed in the past. The faculty member observing the case will be able to directly observe your actions and may ask for you to verbalize your thoughts in the simulation scenario. Not only is your participation in the simulation scenario important to your learning, but your active participation in the debriefing discussion is critical. Once you have been a trainee in the simulation laboratory, you may wish that all of your clinical encounters in the "real" world were observed and debriefed in a similar manner!

The final expectation of you is feedback on the process and content of the simulation and debriefing. Just as you will receive feedback on your performance, the staff at the simulation laboratory desire feedback on the scenario and the debriefing experience.

How Do You Make the Best of the Simulation Experience?

The best way to take advantage of the simulation experience is to be open-minded. One of the biggest challenges for most learners is the concept of "suspending disbelief" – that is, learning to disregard the fact that you are working with a task trainer or mannequin in an artificial environment and instead behave and react as you would in an equivalent real-life situation. "Suspending disbelief" can be difficult for some learners, but with some intentional effort towards treating the mannequin or task trainer as a real patient, you will find yourself engaging in the scenario and feeling the normal emotions and stresses that accompany real patient care. Additionally, as you perform actions in the simulation, verbalizing your actions and events out loud is an excellent suggestion. Verbalizing your interventions in this manner allows them to be more easily tracked and accounted for in the physiology of the simulator. Voicing your observations and actions is also excellent practice for building effective team communication strategies. Again, participating in a medical simulation scenario is an opportunity to receive feedback on your performance and clinical reasoning by someone who is more expert than you. The simulation laboratory provides a unique opportunity in your training for direct observation and real-time formative feedback.

Case Study

*Note that not all simulation cases may be this complex.

It is the last day of your rotation. You are doing a case completely by yourself in the simulator. You are surprised by how nervous you felt in the beginning, as if the patient you are caring for is not the mannequin in front of you but a real patient. But there is no attending guiding you, and you have heard that sometimes things go very wrong in the simulator. You are not being graded, but you are being videotaped, and you know that your fellow students and the instructors will be reviewing your performance. But so far it has been a quiet case. Your "patient" is undergoing an abdominal operation under general anesthesia. You handled the application of monitors, induction of anesthesia, mask ventilation and endotracheal intubation like a pro. The patient is being mechanically ventilated. You are using standard monitors and have a peripheral 18 G IV in place. You are administering desflurane, nitrous oxide, fentanyl, and rocuronium for anesthesia. Blood loss has been about 100 mL. However, the surgeons anticipate more blood loss later in the case, and you have blood available in the blood bank. You are feeling pretty good about yourself, thinking that you might enjoy anesthesiology as a career. After all, you have learned a ton of the basics on your rotation, and here you are doing a case pretty much by yourself!

Suddenly, all the lights in the room go off and the room falls into an inky blackness and eerie quiet. It does not stay quiet for long. The surgeon shouts that he has just incised a structure and is concerned that the patient may be bleeding. He is screaming for light and asking you and the circulating nurse for information about what is happening. The circulator is screaming back at the surgeon that she has no idea what is going on and is appearing panicked herself.

What are your first steps in assessing the situation?

Stay calm. Find some light. Most anesthesia stations include a flashlight, often kept in one of the drawers in the

anesthesia machine. If you cannot find it, reach for your laryngoscope. If your operating room is above ground, there may be natural light in the hallway, so you can open the OR door. Try to take control of the chaos with a firm but calm voice, explaining what you are doing to everyone. Preferably, call each of the team members by name. Next, quickly survey the patient's condition and that of your anesthesia equipment. If both regular and emergency power are off, nothing electronic without a backup battery will be working. Your anesthesia machine ventilator should have a battery backup, but many patient monitors do not. Additionally, the desflurane vaporizer does not function without main electrical power. Also communicate with the other OR personnel briefly and directly to make sure no one is injured (especially electrocuted!) and to assess the criticality of the current stage of the surgical procedure. Call for assistance and to assess the degree of power failure: is the power failure hospital-wide, or only limited to your operating room?

The surgeon says that the operation is at a critical juncture but that if he can work for 5–10 min, he will be at a stable stage and could safely end the operation with a quick closure. He is still concerned that the patient may be bleeding.

How can you provide the surgeon enough light to continue?

Since you are ventilating the patient, you can offer him your laryngoscope or flashlight. Every anesthesia set-up includes at least two laryngoscopes, so you can use one and the surgeon can use the other. Also consider using the flashlight functions on any cellphones that may be present in the operating room.

You recognize that both the ordinary hospital power supply and the emergency generator backup power seem to have failed. Your ventilator is still functioning on battery backup. All of your patient monitors are NOT functional.

How will you alter your anesthetic?

Without a functioning vital sign monitor, you cannot monitor the patient with the normal degree of fidelity. Therefore, it would be prudent to discontinue nitrous oxide and ventilate the patient with 100% oxygen. Unless the hospital gas supplies fail, you should be able to alter the inspired gases accordingly. Your desflurane vaporizer will be inoperable, because it requires power to heat and administer desflurane vapor; recall that it is an electronic gas blender, not a true vaporizer. Other vaporizers are purely mechanical devices, so you can safely switch to another volatile agent such as isoflurane or sevoflurane. Although low fresh gas flows are tempting, this must be tempered by the need to ensure high flow oxygen and eliminate nitrous oxide until you can monitor oxygenation. Total intravenous anesthesia would eliminate the need for the anesthesia machine altogether, but it is difficult to manage without infusion pumps and is not necessary as long as your anesthesia machine is functioning normally. Longer acting intravenous agents such as ketamine are possible backups if needed. Your patient is paralyzed with rocuronium, and you will have to make a judgment regarding the relative merit of continuing its use vs. allowing the patient to regain the ability to breathe spontaneously should the emergency continue.

How will you monitor the patient?

You will have to rely on your senses and manual monitors! Your twitch monitor (neuromuscular blockade monitor) is battery powered and can still be used, whether you continue rocuronium, allow it to wear off, or actively reverse neuromuscular blockade. This course of action will depend on the surgical plan going forward during this crisis combined with the surgical requirements and your need for spontaneous ventilation. You can attempt to monitor oxygenation grossly by the patient's color, but this will be difficult without a steady and bright light source. You can monitor blood pressure with a manual cuff. You can also use

breath and heart sounds as qualitative monitors of respiration and cardiac output, heart rate, and rhythm. Palpating peripheral pulses is always prudent as a qualitative measure of cardiovascular condition. Don't forget other monitoring options as well: portable anesthetic monitors or defibrillators could be potential other backup monitors that *may* be available.

The battery backup on your ventilator has now run out of power and the ventilator stops. The oxygen flowmeter drops to zero and you realize that the pipeline oxygen supply has failed.

How will you proceed?

You will activate the backup oxygen tank supply on the back of the anesthesia machine by opening the valve on the neck of the green tank. Now, it may be prudent to reduce fresh gas flows to preserve your limited supply. You will manually ventilate the patient through the anesthesia machine using the breathing bag and APL valve to generate appropriate airway pressure/ventilation; the carbon dioxide absorbent, isoflurane/sevoflurane vaporizer, and oxygen flowmeter are all still functional. You should locate the manual self-inflating respirator ("Ambu" bag) in case you need to ventilate the patient for transport or if you run out of oxygen.

The lights come back on; your instructor walks into the room and announces, "That's a wrap!" Your colleagues break into applause. You have learned a lot indeed!

References

1. Morgan P, Cleave-Hogg D, DeSousa S, Tarshis J (2003) Identification of gaps in the achievement of undergraduate anesthesia educational objectives using high-fidelity patient simulation. Anesth Analg 97(6):1690–1694
2. Gaba D (2004) A brief history of Mannequin-based simulation & application. In: Dunn W (ed) Simulators in critical care and beyond. Society of Critical Care Medicine, Des Moines, pp 7–14

3. Passiment M, Sacks H, Huang G. Medical simulation in medical education: results of an AAMC Survey 2011[internet]. 2011 [cited 2020 August 19]. Available from: https://www.aamc.org/system/files/c/2/259760-medicalsimulationinmedicaleducationanaamcsurvey.pdf
4. Toy S, McKay RSF, Walker JL, Johnson S, Arnett JL (2017) Using learner-centered, simulation-based training to improve medical students' procedural skills. J Med Educ Curric Dev 4:1–6
5. Steadman RH, Coates WC, Huang YM, Matevosian R, Larmon BR, McCullough L et al (2006) Simulation-based training is superior to problem-based learning for the acquisition of critical assessment and management skills. Crit Care Med 34(1):151–157
6. Minai F, Shafiq R, Ul Haq MI (2014) Value of real life (in situ) simulation training for tracheal intubation skills in medical undergraduates during short duration anesthesia rotation. J Anaesthesiol Clin Pharmacol 30(4):484–487
7. Wayne D, Didwania A, Feinglass J, Fudala M, Barsuk J, McGaghie W (2008) Simulation-based education improves quality of care during cardiac arrest team responses at an academic teaching hospital: a case-control study. Chest 133(1):56–61
8. Blum M, Powers T, Sundaresan S (2004) Bronchoscopy simulator effectively prepares junior residents to competently perform basic clinical bronchoscopy. Ann Thorac Surg 78(1):287–291
9. Offiah G, Ekpotu LP, Murphy S, Kane D, Gordon A, O'Sullivan M et al (2019) Evaluation of medical student retention of clinical skills following simulation training. BMC Med Educ 19(1):263
10. Levine AI, Flynn BC, Bryson EO, Demaria S (2012) Simulation-based maintenance of certification in anesthesiology (MOCA) course optimization: use of multi-modality educational activities. J Clin Anesth 24(1):68–74
11. Beaubein JM, Baker DP (2004) The use of simulation for training teamwork skills in health care: how low can you go? Qual Saf Health Care 13 Suppl 1(Suppl 1):i51–i56
12. Arriaga AF, Bader AM, Wong JM, Lipsitz SR, Berry WR, Ziewacz JE et al (2013) Simulation-based trial of surgical-crisis checklists. N Engl J Med 368(3):246–253
13. Stanford Medicine Emergency Manual. [cited 2020 August 19]. Available from: https://emergencymanual.stanford.edu/
14. Ericsson K, Prietula M, Cokely E (2007) The making of an expert. Harv Bus Rev 85(7–8):115–121

Infection Control and COVID-19

38

B. Scott Segal

Infection control in the operating room and perioperative areas is a significant healthcare challenge. Surgical site infections (SSI) affect over 5% of surgical patients–some 500,000 patients per year in the United States–and are a leading cause of surgical morbidity and mortality, prolonged hospital stay and increased costs, and reoperation [1]. Many newcomers to the surgical arena may consider infection control to be the responsibility of infection control nurses or perhaps surgeons. But anesthesia personnel are intimately involved in a number of aspects of perioperative care that may contribute to SSIs, and best practices in anesthesia care can significantly reduce the risk of this important complication.

Antibiotic Prophylaxis

Several decades ago, antibiotics were not routinely given prior to surgical operations. Only cases considered particularly high risk (for example, colon surgery or contaminated traumatic wounds) routinely received such treatment. Today it is widely considered the standard of care to administer a broad-spectrum antibiotic

B. S. Segal (✉)
Department of Anesthesiology, Wake Forest University School of Medicine, Winston-Salem, NC, USA
e-mail: bsegal@wakehealth.edu

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9_38

prior to skin incision in the vast majority of surgical cases [2]. There is strong evidence from multiple RCTs that such treatment markedly reduces SSIs and perhaps other perioperative infections. Generally, these drugs are administered by the anesthesia team. There is some controversy regarding the timing of antibiotic prophylaxis, however most guidelines suggest the antibiotic be given prior to, but no more than 1 hour before, skin incision. This can pose a problem for certain antibiotics requiring long administration times (e.g., vancomycin). In most cases, a broad-spectrum first-generation cephalosporin (e.g., cefazolin) is given, sometimes supplemented with other drugs for better gram negative or anaerobic coverage. In most patients who claim penicillin allergies, especially vague history of rash, cefazolin can be safely administered, and previous cautions that cross reactivity may be as high as 10% are not correct [3, 4]. Alternative regimens should not be selected casually, as there is evidence that SSI is more common with some such choices [5]. Modern practice includes weight-appropriate dosing of antibiotics and relatively aggressive redosing schedules, with the intent of keeping the tissue level of antibiotic effective throughout the operation.

Other General Prevention Measures

A number of other maneuvers are considered standard practice for reducing SSIs in most ORs. These include avoidance of shaving at the surgical site, skin preparation with alcohol-chlorhexidine mixtures, and frequent, thorough cleaning of surfaces. Some success in decolonizing patients who may asymptomatically harbor resistant bacteria (such as MRSA) has been demonstrated with the use of mupirocin ointment to the nares and chlorhexidine baths in the days preceding surgery. Other practices are somewhat controversial but may be part of "bundles" of recommendations that appear to reduce SSIs, although the contribution of individual items in the bundle is often unclear. Reducing room traffic is commonly requested for certain cases (e.g., total joint replacement). The rationale for this recommendation is that ORs are maintained with a slight positive pressure relative to the less sterile area in the cor-

ridors outside the room, keeping the clean, rapidly turned over air in the OR. But repeated door opening breaks down this gradient, possibly allowing inflow of contaminated air. In addition, additional personnel may be sources of bacteria which can become airborne upon moving into the room. Operating rooms are also connected to ventilation systems that maintain humidity in a fairly narrow range that may reduce growth of bacteria, and the air in an OR turns over multiple times per hour (typically 15–20 times), far more than typical hospital areas. Programs to limit room traffic included in bundles have shown some reduction in SSIs [6]. Some specialized ORs utilize laminar airflow devices or ultraviolet light sources near the surgical field, but these are controversial and in the case of the lights, not without some risk to OR personnel.

One of the most controversial aspects of infection control in the OR concerns attire of non-scrubbed personnel. For years, recommendations by the Association of OR Registered Nurses (AORN) have been followed by most hospitals and regulatory bodies such as the Joint Commission. Recently, the guidelines of this organization have been challenged by new data and they have been softened in the most recent versions. In particular, admonitions not to allow cloth head coverings, requirements for hospital-laundered scrubs, use of shoe covers, prohibiting t-shirts worn under scrubs, and recommendation of scrub jackets have all been dropped or made subject to individual hospital policies. These changes followed careful investigation of the evidence base, and in some cases generation of new data (particularly cloth vs. disposable bouffant caps) [7].

Interventions Specific to Anesthesiology Practice

Hand hygiene (HH) Liberal use of alcohol-based hand sanitizer, or hand washing, has been shown to reduce nosocomial infections in many clinical settings. The World Health Organization (WHO) has identified "5 moments" of HH from clinic and hospital ward settings: before and after touching a patient, before clean or aseptic procedures, after body fluid exposure, and after touching the patient's surroundings. For anesthesia personnel in the OR, such

moments are so prevalent (54–150 times/hour) [8] that they are impractical in clinical practice. However, several studies have documented increasing contamination of the anesthesia workspace and IV stopcocks over the time of a case, and indicate contamination from the anesthetist's hands as a common source. Thus, several studies have documented a decrease in such contamination, and in some cases, in SSIs, when frequent (4–8 times/hour) HH is used [9]. In addition, some practitioners double-glove during airway manipulations and shed the outer gloves immediately after intubation to avoid contamination when HH is difficult to perform.

Glycemic control Hyperglycemia increases the risk of SSIs, even in non-diabetic patients. In general, treatment of blood glucose >180 mg/dL is recommended [10]. Conversely, many anesthesiologists fear causing unrecognized hypoglycemia with insulin treatment, and so they may be reticent to aggressively treat hyperglycemia. A reasonable approach is to target a glucose between 110 and 180 when possible, particularly in higher risk cases, preferably utilizing either an intravenous insulin protocol or rapidly acting subcutaneous insulins (lispro or aspart), accompanied by frequent measurement of glucose by capillary point-of-care testing or via blood gases.

Maintaining patient temperature Hypothermia predisposes to SSI by unclear mechanisms, but lower temperature may adversely affect the function of inflammatory cells, leading to less effective surveillance and clearance of pathogenic bacteria. Hypothermia is a common intraoperative problem and it generally falls to anesthesia personnel to attempt to maintain normothermia. Anesthetics can alter the distribution of blood flow from the core to the periphery, and heat loss through radiation, conduction, and evaporation of body fluids can contribute to heat loss. In addition, tonic muscle activity and other mechanisms of temperature homeostasis are altered in anesthetized individuals. Anesthesia personnel can mitigate these losses by intraoperative and possibly preoperative use of forced warm air blankets (most effective), warmed IV fluids, keeping patients covered as much as possible, advocating for

moderate room temperatures, and use of low fresh gas flows. Maintaining a core temperature of >36 °C is considered best practice by several quality monitoring groups. Several well-conducted RCTs have documented reduction in SSI when near normothermia is maintained [11].

High inspired oxygen concentration The use of high (80%) FiO2 vs. lower inspired oxygen (30%) is a controversial intervention to lower SSI, particularly in major abdominal surgery, especially colorectal operations. The maneuver is biologically plausible, as low oxygen tension at the edges of surgical wounds has been observed, and this is associated with growth of pathologic organisms in some models. As a result, use of high FiO2 is commonly included in colorectal surgery bundles [12]. However, the clinical evidence for this practice is questionable, and large, well conducted RCTs have found no support; systematic reviews of high FiO2 in a variety of surgical operations have shown no overall benefit, with some studies showing reduction, no difference, or even increased SSI with high FiO2 [13].

Syringes and stopcocks Stopcocks are commonly used for easy access to intravenous drug administration, but unfortunately, they become increasingly contaminated with ongoing use during an anesthetic, with the number of different drugs used, and with the total number of accesses. Contaminated stopcocks have been associated with SSI [14]. Infection controls include routine recapping of stopcocks after accessing, disinfecting stopcocks and injection ports with alcohol swabs prior to non-emergency use, and consideration of antimicrobial stopcock caps. A regulation known as USP 797 suggests that drugs prepared in the OR should be used within 1 hour whenever possible (though a modification allowing use for the entire case is under consideration). Evidence to support longer use is sparse but mostly supports use for several hours [15]. Anesthesia personnel must weigh using drugs immediately after preparation for infection prevention against being good stewards of the drug supply and patient safety considerations. For example, emergency resuscitation drugs should be immediately available at all times. Premixed syringes prepared in

pharmacy hoods or commercial facilities offer longer shelf lives after opening.

Line placement Bundles of maneuvers for central lines include use of full sterile gown, gloves, cap and mask, and total body draping of the patient prior to placement. Peripheral arterial lines should be placed with use of sterile gloves, cap, mask, and a fenestrated drape [16].

Equipment Current guidelines suggest laryngoscope blades should undergo high level disinfection between uses and regulatory agencies ask for them to remain covered until just before use. Ultrasound probes should be covered with a sleeve and disinfected if they become contaminated by blood or other body fluids [17].

Drugs and fluids Nitrous oxide, perhaps because its use results in a lower FiO2, or perhaps due to immune modulation, was suspected to be a contributor to SSI but an RCT demonstrated no effect [18]. Similarly, low-dose dexamethasone, often given to reduce the risk of postoperative nausea and vomiting, does not increase SSI [19]. Spiking of IV fluid bags far in advance of use has been suspected, but never demonstrated, to increase risk of contamination and therefore SSI. Transfusion of blood products leads to immune suppression and has been associated with increased SSI in some settings [20].

A consensus statement of the Society for Healthcare Epidemiology of America, with representatives from the American Society of Anesthesiologists, the Anesthesia Patient Safety Foundation, and the American Association of Nurse Anesthetists, has been issued for many infection control practices related to anesthesia practice [17].

COVID-19

The worldwide pandemic of coronavirus disease 2019 (COVID-19) has infected many tens of millions of persons worldwide, and close to eighty-eight million in the U.S. as of this writ-

ing. Millions have died worldwide, and over 1,000,000 in the U.S. Anesthesia personnel have been at the forefront of the pandemic in many respects since it first struck the U.S. early in 2020 [21]. Because instrumentation of the airway may be an "aerosolizing" procedure, the threat of becoming infected with SARS-CoV-2 (the virus causing COVID-19) was an important early concern. Appropriate use of personal protective equipment (PPE) was an early priority. Current recommendations for caring for COVID+ patients (or those suspected to be, so-called PUI, or persons under investigation) include use of an N95 or equivalent mask, goggles or face shield, gown, and gloves. In selected cases, or when a tight fitting N95 is unavailable or not able to be worn, a Powered Air Purifying Respirator (PAPR) should be used. At the time of this writing, most elective surgical patients are screened for symptoms of COVID, and if negative, are subsequently tested for the presence of the virus. Only those with negative testing undergo elective surgical procedures. Some practitioners, particularly if fully vaccinated, are comfortable not following full PPE guidelines in this setting, though professional societies continue to recommend their use due to occasional false negatives. Extubation, which sometimes causes vigorous coughing, may be a more aerosolizing procedure than intubation, so consideration for use of appropriate PPE should also be considered in this setting. Some institutions have specialized ORs or recovery areas for COVID+ patients, and airborne precautions should be followed for positive or suspected patients.

As disease prevalence ebbs and vaccine uptake increases, it is uncertain whether there will continue to be periodic resurgences of the disease. It is also unclear if routine preoperative testing will continue. There is evidence, however, that patients who have or have recently recovered from COVID-19 should defer non-emergency surgery. Postoperative pulmonary complications are significantly increased in positive patients and those who have recently recovered. As is the case for bloodborne infectious risks, anesthesia personnel should practice universal precautions and should exercise extra vigilance when community disease prevalence is significant.

Case study

You are planning to provide anesthesia care for a 74-year-old patient undergoing colectomy for colon cancer. She has a history of Type 2 diabetes managed with insulin, hypertension, and prior successful general anesthetics. She recalls being treated in the past for an infection "with a bug that they said is hard to kill with regular antibiotics." The hospital is engaged in a program to reduce surgical site infections in colon surgery. You have been asked to do all that you can to reduce the patient's risk of SSI.

What steps will you recommend preoperatively in the days and minutes before going to the OR?

If part of the hospital work flow, you may recommend mupirocin ointment applied to the nares and chlorhexidine wipes preop to reduce the chance of MRSA colonization, especially given her history of possibly having contracted it in the past. You should try to optimize her glycemic control prior to operation, as hyperglycemia and poor control of diabetes contribute to the risk. She should be instructed on how to modify her insulin regimen prior to surgery. On the day of the case, you might consider prewarming the patient with a forced air or other device before going to the OR. You should follow careful asepsis in placing her IV and any subsequent lines. If you choose a preop central line, you would follow the full CLABSI "bundle" of appropriate scrubbing, gowning, gloving, draping and other infection control maneuvers. You will set up your room paying attention to cleanliness, asepsis when preparing drugs, and keeping your laryngoscope covered until use.

You proceed to the OR with a peripheral IV in place. Induction of anesthesia proceeds uneventfully. What steps will you take prior to incision?

You should administer preoperative antibiotics before incision. While cefazolin is commonly used in many cases, in abdominal operations, sometimes antibiotic coverage for gram negative organisms is added or substituted (e.g.,

cefoxitin). You should take steps to keep the patient warm such as application of a forced air warming device, as hypothermia in the first hour after induction is common. You will administer drugs via stopcocks and should keep them clean and consider sanitizing the injection port or site prior to affixing syringes. If you decide to place an arterial line, you will wear sterile gloves and prep the site for a sterile procedure, and use a fenestrated drape to keep the area sterile.

The case is proceeding according to plan. What will you do intraoperatively to further reduce the risk of SSI?

Wash your hands frequently! You should periodically check the patient's glucose and treat hyperglycemia accordingly. You should redose antibiotics according to the schedule on the protocol. Many centers will request use of high FiO2 (80%) during the case, and given the intra-abdominal surgery and bowel resection, you will likely omit N_2O. If possible, it would be best not to transfuse the patient unless truly needed, as blood product use has been associated with inhibition of immune system function. Some centers will request diminished room traffic. Surgeons will also follow certain practices as part of a "colon bundle" such as changing their gloves prior to closure and using special clean instruments during closing.

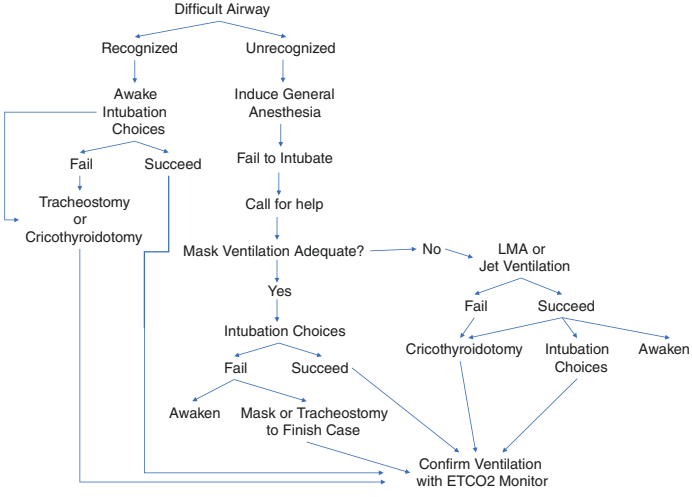
References

1. Gottrup F (2000) Prevention of surgical-wound infections. N Engl J Med 342(3):202–204
2. Liu Z, Dumville JC, Norman G, Westby MJ, Blazeby J, McFarlane E et al (2018) Intraoperative interventions for preventing surgical site infection: an overview of Cochrane Reviews. Cochrane Database Syst Rev 2:CD012653
3. Savic LC, Khan DA, Kopac P, Clarke RC, Cooke PJ, Dewachter P et al (2019) Management of a surgical patient with a label of penicillin allergy: narrative review and consensus recommendations. Br J Anaesth 123(1):e82–e94

4. Hermanides J, Lemkes BA, Prins JM, Hollmann MW, Terreehorst I (2018) Presumed beta-lactam allergy and cross-reactivity in the operating theater: a practical approach. Anesthesiology 129(2):335–342
5. Blumenthal KG, Ryan EE, Li Y, Lee H, Kuhlen JL, Shenoy ES (2018) The impact of a reported penicillin allergy on surgical site infection risk. Clin Infect Dis 66(3):329–336
6. Crolla RM, van der Laan L, Veen EJ, Hendriks Y, van Schendel C, Kluytmans J (2012) Reduction of surgical site infections after implementation of a bundle of care. PLoS One 7(9):e44599
7. Markel TA, Gormley T, Greeley D, Ostojic J, Wise A, Rajala J et al (2017) Hats off: a study of different operating room headgear assessed by environmental quality indicators. J Am Coll Surg 225(5):573–581
8. Rowlands J, Yeager MP, Beach M, Patel HM, Huysman BC, Loftus RW (2014) Video observation to map hand contact and bacterial transmission in operating rooms. Am J Infect Control 42(7):698–701
9. Koff MD, Loftus RW, Burchman CC, Schwartzman JD, Read ME, Henry ES et al (2009) Reduction in intraoperative bacterial contamination of peripheral intravenous tubing through the use of a novel device. Anesthesiology 110(5):978–985
10. Vogt AP, Bally L (2020) Perioperative glucose management: current status and future directions. Best Pract Res Clin Anaesthesiol 34(2):213–224
11. Kurz A, Sessler DI, Lenhardt R (1996) Perioperative normothermia to reduce the incidence of surgical-wound infection and shorten hospitalization. Study of Wound Infection and Temperature Group. N Engl J Med 334(19):1209–1215
12. Greif R, Akca O, Horn EP, Kurz A, Sessler DI, Outcomes RG (2000) Supplemental perioperative oxygen to reduce the incidence of surgical-wound infection. N Engl J Med 342(3):161–167
13. Wang H, Hong S, Liu Y, Duan Y, Yin H (2017) High inspired oxygen versus low inspired oxygen for reducing surgical site infection: a meta-analysis. Int Wound J 14(1):46–52
14. Loftus RW, Brown JR, Koff MD, Reddy S, Heard SO, Patel HM et al (2012) Multiple reservoirs contribute to intraoperative bacterial transmission. Anesth Analg 114(6):1236–1248
15. Segal S, Gunawan A, McLaughlin DH, Palavecino E (2019) Microbial stability of syringes of anesthetic drugs prepared in the operating room. J Clin Anesth 55:20–23
16. Marschall J, Mermel LA, Fakih M, Hadaway L, Kallen A, O'Grady NP et al (2014) Strategies to prevent central line-associated bloodstream infections in acute care hospitals: 2014 update. Infect Control Hosp Epidemiol 35 Suppl 2:S89–S107
17. Munoz-Price LS, Bowdle A, Johnston BL, Bearman G, Camins BC, Dellinger EP et al (2018) Infection prevention in the operating room anesthesia work area. Infect Control Hosp Epidemiol:1–17

18. Fleischmann E, Lenhardt R, Kurz A, Herbst F, Fulesdi B, Greif R et al (2005) Nitrous oxide and risk of surgical wound infection: a randomised trial. Lancet 366(9491):1101–1107
19. Kurz A, Fleischmann E, Sessler DI, Buggy DJ, Apfel C, Akca O et al (2015) Effects of supplemental oxygen and dexamethasone on surgical site infection: a factorial randomized trialdouble dagger. Br J Anaesth 115(3):434–443
20. Peng XQ, Sun CG, Fei ZG, Zhou QJ (2019) Risk factors for surgical site infection after spinal surgery: a systematic review and meta-analysis based on twenty-seven studies. World Neurosurg 123:e318–ee29
21. Abola RE, Schwartz JA, Forrester JD, Gan TJ (2021) A practical guide for anesthesia providers on the management of coronavirus disease 2019 patients in the acute care hospital. Anesth Analg 132(3):594–604

Appendix A. ASA Difficult Airway Algorithm



Adapted from Practice guidelines for management of the difficult airway: an updated report by the American Society of Anesthesiologists Task Force on Management of the Difficult Airway. Apfelbaum JL, Hagberg CA, Caplan RA, Blitt CD, Connis RT, Nickinovich DG, Hagberg CA, Caplan RA, Benumof JL, Berry FA, Blitt CD, Bode RH, Cheney FW, Connis RT, Guidry OF, Nickinovich DG, Ovassapian A; American Society of Anesthesiologists Task Force on Management of the Difficult Airway. Anesthesiology. 2013;118(2):251–70. https://doi.org/10.1097/ALN.0b013e31827773b2

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9

Appendix B. Malignant Hyperthermia

Definition

Malignant Hyperthermia (MH) is an inherited disorder of skeletal muscle, which is characterized by a hypermetabolic state and can be triggered by *potent volatile anesthetics* (but not nitrous oxide) and *depolarizing muscle relaxants* such as succinylcholine. Patients with some congenital myopathies may also be at increased risk when exposed to triggering anesthetic agents. However, all intravenous hypnotic agents are considered safe. MH is a potentially fatal disorder if it is not promptly recognized and treated, and the overall incidence during general anesthesia is about 1:50,000–1:100,000. For any patient presenting for anesthesia, a preoperative history should include questions about prior MH episodes or family history suggestive of MH.

Mechanism

In a vast majority of cases, MH-susceptible patients have a defective calcium channel (known as *ryanodine* receptor) that is located on the sarcoplasmic reticulum membrane. In normal cells, calcium is released into the cell during muscle contraction. In MH, there is a problem with calcium reuptake, and therefore there is a massive increase in intracellular calcium leading to sustained

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9

muscle contractions. Consequently, there is an increased demand for oxygen and ATP in the muscle cells, leading to glycolysis and lactic acidosis. If left untreated, this uncontrolled hypermetabolism results in cell hypoxia, rhabdomyolysis, organ failure, and death.

Presenting Signs and Diagnosis

The most common presenting features of MH include significant, unexplained elevation in expired CO_2, tachycardia, steady temperature rise, muscle rigidity, rhabdomyolysis, acidosis, and hyperkalemia. MH may occur at any time during anesthesia and in the postoperative period. The earliest signs are usually *tachycardia* and an *increase in expired* CO_2*;* a *rise in temperature* may follow. Diagnosis of MH can be made on the basis of these signs, although the variability in the order and time of the onset of signs often makes clinical diagnosis difficult. These signs may present during or after the administration of the anesthetic. Table B.1 outlines possible presenting signs of MH.

Diagnosis is made based on the presenting signs, and other potential conditions that might cause the same symptoms should be ruled out. Genetic testing is also available, which can be done on an outpatient basis at an MH Testing Center. If MH is suspected, treatment should be initiated as soon as possible.

Table B.1 Main clinical features of malignant hyperthermia

Rising $ETCO_2$ and $PaCO_2$
Tachycardia
Tachypnea
Muscle rigidity and masseter spasm
Hemodynamic instability
Cardiac arrhythmias
Increased body temperature
Metabolic acidosis
Hyperkalemia
Myoglobinuria

Treatment

All triggering agents should be discontinued immediately, the surgical procedure should either be aborted or finished quickly, and patient cooling begun. Dantrolene, a muscle relaxant which abolishes excitation–contraction coupling in muscle cells, is the main drug of choice. Important treatment modalities for MH are outlined in Table B.2.

Over the last several decades, thanks to provider education and increased knowledge about MH, perioperative patient mortality from MH has dropped from 80% to less than 5%. An MH-susceptible patient is still a candidate for any type of anesthetic, including general, regional, or local. If general anesthetic is required, a total intravenous anesthetic (TIVA), with or without nitrous oxide would be a safe option.

Table B.2 Treatment of acute malignant hyperthermia

1. Discontinue volatile agents and succinylcholine
2. Call for help and consider calling the MH hotline (800-MH-HYPER)
3. Hyperventilate with 100% oxygen
4. Inform the surgeon and curtail the surgical procedure
5. Initiate treatment with dantrolene (2.5 mg/kg) DANTRIUM®/REVONTO® – Each 20 mg vial should be reconstituted by adding 60 ml of sterile water and the vial shaken until the solution is clear. RYANODEX®– Each 250 mg vial should be reconstituted with 5 ml of sterile water and shaken to ensure an orange-colored uniform, opaque suspension.
6. Administer bicarbonate for metabolic acidosis
7. Actively cool the patient
8. Treat acidosis and hyperkalemia to avoid arrhythmias
9. Follow ETCO $_2$, electrolytes, blood gasses, CK, temperature, and urine output

Suggested Further Reading

Malignant Hyperthermia Association of the United States. www.mhaus.org
Vicario S (2006) Chapter 139: Heat illness. In: Marx J (ed) Rosenâ's emergency medicine: concepts and clinical practice, 6th edn. Mosby, St, Louis
Dinarello CA, Porat R (2008) Chapter 17: Fever and hyperthermia. In: Fauci A, Kasper D, Longo DL et al (eds) Harrison's principles of internal medicine, 17th edn. McGraw Hill, New York [online version]

Index

J. M. Ehrenfeld et al. (eds.), *Anesthesia Student Survival Guide*,
https://doi.org/10.1007/978-3-030-98675-9

D