# Anesthetic Management and Hemodynamic Management

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## Introduction

Medical management of patients with heart failure is certainly challenging. Perioperative anesthetic management of these oftentimes extremely sick individuals is even more challenging for a wide variety of reasons (essentially all anesthetic techniques compromise the cardiovascular system, patients are undergoing major invasive surgery, detrimental physiologic effects associated with cardiopulmonary bypass, etc.). In order to ensure acceptable postoperative outcome, a true team approach is required by the surgeon, anesthesiologist, perfusionist, and nursing staff. Adequate communication is required by all to identify and attain perioperative goals. The anesthesiologist's job is to choose and safely administer an appropriate anesthetic technique for each particular patient undergoing their specific surgery. Most times, no specific drug or technique is truly indicated. As we will see, identified goals (analgesia, amnesia, muscle relaxation) can be safely attained in many ways. One of the most challenging tasks confronting the anesthesiologist when managing these patients is that of maintaining perioperative hemodynamic stability. The key to successfully managing this problem is correctly identifying the cause of hemodynamic instability (preload, myocardial contractility, afterload) via a wide variety of monitoring techniques (electrocardiography, pulmonary artery catheter, transesophageal echocardiography, etc.). Once again, as we will see, identified goals (optimize preload, optimize myocardial contractility, optimize afterload) can be safely attained in many ways.

The successful perioperative anesthetic management of patients with heart failure is complex and challenging. Anesthesiologists managing these patients need to have extensive knowledge regarding cardiovascular physiology and pharmacology, physiologic effects of anesthetic drugs and techniques on the cardiovascular system, and rational assessment/pharmacologic treatment of hemodynamic instability. In the current era, all such anesthesiologists managing these extremely sick individuals should possess appropriate skills regarding use of transesophageal echocardiography. Identified perioperative goals may be attained safely in many ways. Thus, there is much "art" (which requires extensive clinical experience) to the successful perioperative anesthetic management of patients with heart failure.

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## Anesthetic Management

### Preoperative Assessment

The goals of preoperative assessment include reducing surgical morbidity, increasing quality and decreasing cost of perioperative care, and allowing the patient to return to desirable functioning as quickly as possible. Traditionally, the anesthesiologist will meet with the patient to review medical and surgical history, order appropriate laboratory rests, obtain informed consent, educate the patient regarding all aspects of perioperative care, and answer questions the patient may have. A thorough history and physical exam are performed, and the airway is assessed for ease in intubation.

Table 17.1 lists items reviewed by the anesthesiologist during preoperative assessment. Numerous factors profoundly influence perioperative anesthetic management. For instance, the presence of renal failure and/or hepatic failure dictates which specific anesthetic medications may or may not be administered. Specifically regarding patients with heart failure, knowledge of current cardiac medications (beta-adrenergic blockers, diuretics, digitalis, etc.) is required prior to planning technique of anesthesia. Additionally, certain preoperative tests (echocardiography, cardiac catheterization, etc.) give the anesthesiologists valuable information regarding left ventricular function and valvular function; again, knowledge required to adequately plan anesthetic technique.

Patients with heart failure undergo a wide variety of surgical procedures. Thus, it is important for all perioperative caregivers (surgeon, anesthesiologist, perfusionist, and nursing staff) to "be on the same page" regarding the planned surgical procedure (coronary artery bypass grafting, valve repair or replacement, ventricular reconstruction, etc.). Additionally, it should be determined whether or not cardiopulmonary bypass will be utilized. Numerous surgical procedures are now being attempted without assist of cardiopulmonary bypass (off-pump). If cardiopulmonary bypass is to be utilized, it should be clear to all what specific technique will be used (normothermic, hypothermic, beating heart, arrested heart, etc.). The planned surgical procedure and use/non-use/technique of cardiopulmonary bypass (decisions arrived at oftentimes only after intraoperative transesophageal echocardiographic evaluation) profoundly influence technique of anesthesia.

### Goals of Anesthetic Management

The major goals of anesthesia include analgesia (pain relief), amnesia (lack of recall), hemodynamic stability, and perhaps muscle relaxation (paralysis). Table 17.2 presents the variety of most common ways the anesthesiologist may safely attain these goals (methods of attaining hemodynamic stability will be addressed later). Most commonly, a combination of intravenous opioid (analgesia), intravenous benzodiazepine (amnesia), and inhalational anesthetic (analgesia and amnesia) is used for induction and maintenance of anesthesia. In the current era of "fast-tracking", specific drugs and amounts are

**Table 17.1** Preoperative assessment

| |
|---|
| Age/gender/race/height/weight |
| Proposed surgery |
| Past medical history |
| Past surgical history |
| Allergies |
| Current medications |
| Vital signs |
| Physical exam |
| Laboratory tests |
| Additional tests |

**Table 17.2** Agents commonly used during anesthesia

| |
|---|
| Intravenous opioids |
| Morphine, fentanyl, sufentanil |
| Intravenous benzodiazepines |
| Diazepam, midazolam |
| Inhaled anesthetics |
| Isoflurane, desflurane, sevoflurane |
| Intravenous alpha-2 receptor agonists |
| Dexmedetomidine |
| Intravenous muscle relaxants |
| Pancuronium, vecuronium, rocuronium |

chosen for specific anesthetic goals in each individual patient in order to allow the patient to awaken from anesthesia in the immediate postoperative period. Thus, short-acting drugs (fentanyl, midazolam) and/or inhalational anesthetics are favored.

## Monitored Anesthesia Care

The term monitored anesthesia care (MAC) generally implies intravenous sedation without laryngeal intubation. Most commonly, a combination of intravenous opioid and benzodiazepine is administered to a spontaneously breathing patient and titrated to facilitate surgery while keeping the patient comfortable. Because amounts of opioid and benzodiazepine must be carefully kept to an appropriate minimum (both drug classes promote respiratory depression), only certain minimally invasive surgeries may be performed in patients with heart failure under monitored anesthesia care. Procedures that may be amenable to MAC include pacemaker insertion/replacement, transcatheter aortic valve implantation, transesophageal echocardiography, and cardioversion.

## Regional Anesthesia

The term regional anesthesia generally implies the use of a wide variety of peripheral nerve blocks (parasternal block, intercostal nerve block, etc.), intrathecal techniques, and/or epidural techniques [1]. While general anesthesia may be supplemented with regional anesthetic techniques, the traditional use of the term regional anesthesia usually implies the use of regional anesthetic techniques and intravenous sedation in a spontaneously breathing patient. Thus, amounts of intravenous opioid and benzodiazepine must be carefully kept to an appropriate minimum, limiting the scope of surgeries that may be performed in patients with heart failure under regional anesthesia.

Use of regional anesthetic techniques in patients undergoing cardiac surgery, while seemingly increasing in popularity, remains extremely controversial, prompting numerous Editorials by recognized experts in the field of cardiac anesthesia. One of the main reasons such controversy exists (and likely will continue for some time) is that the numerous clinical investigations regarding this topic are suboptimally designed and utilize a wide array of disparate techniques preventing clinically useful conclusions all can agree on [2–5].

## General Anesthesia

The term general anesthesia usually implies the use of moderate to large doses of intravenous agents and/or inhalational agents (with or without intravenous muscle relaxants) along with endotracheal intubation and mechanical ventilation. The vast majority of cardiac surgeries performed in patients (with or without heart failure) are performed under general endotracheal anesthesia. The total control over the respiratory system via mechanical ventilation allows the anesthesiologist to administer large amounts of intravenous anesthetics and/or inhalational anesthetics to the patient, permitting invasive cardiac surgery to occur. General anesthesia is sometimes supplemented with regional anesthetic techniques.

## Premedication

The goals of premedication include decreased patient anxiety, production of amnesia, and minimization of pain associated with vascular cannulation in the preanesthetic period without producing ventilation or cardiac depression. These goals are most commonly met by administering small and appropriate amounts of intravenous opioids for analgesia and intravenous benzodiapines for amnesia. Additionally, most anesthesiologists have patients take their routine cardiovascular medications (beta-adrenergic blockers, etc.) the morning of surgery (with small sips of water) in hopes of promoting perioperative hemodynamic stability.

## Monitoring

Numerous physiologic parameters are monitored in patients undergoing cardiac surgery (Table 17.3). Arterial blood pressure may be monitored noninvasively or invasively. Cardiac rate and rhythm is assessed via electrocardiography. Cardiac function (preload, myocardial contractility, etc.) is most commonly monitored via the pulmonary artery catheter and/or transesophageal echocardiography, and will be discussed in greater detail later in this chapter. Pulmonary function is assessed in a wide variety of ways, including assessment of pulmonary compliance and interpretation of arterial blood gas tensions (oxygen, carbon dioxide). Urine output is closely monitored in all patients undergoing cardiac surgery, especially so in patients with preoperative renal dysfunction. Maintenance of normothermia in patients is extremely important (and sometimes difficult), especially in cardiac surgeries without assist of cardiopulmonary bypass. Numerous arterial blood samples are obtained perioperatively in order to monitor pulmonary function, a wide variety of serum electrolytes (potassium, magnesium, etc.), glucose levels, and hemoglobin levels. Frequent assessment of coagulation is important as well, because essentially all patients undergoing cardiac surgery will be subjected to at least some degree of anticoagulation (and possibly reversal of anticoagulation). Cerebral function monitoring is somewhat controversial. Neurologic insult (via microemboli and/or macroemboli) continues to haunt cardiac surgery. Although numerous investigators have valiantly tried, we are still without a monitor that reliably and effectively predicts intraoperative recall or the development of postoperative neurologic insult (stroke or diffuse neuropsychological dysfunction).

**Table 17.3** Monitored physiologic parameters

| |
|---|
| Arterial blood pressure |
| Cardiac rate and rhythm |
| Cardiac function |
| Pulmonary function |
| Renal function |
| Body temperature |
| Blood gas analysis |
| Coagulation analysis |
| Cerebral function |

## Anesthesia and Transesophageal Echocardiography

Intraoperative transesophageal echocardiography (TEE) was introduced in 1980s, and there has been significant development in training and technology since that time. The most common applications intraoperatively include assessment of left and right ventricular function, valvular anatomy and function, intracardiac air, clot, or masses, detection of pericardial fluid, and evaluation of the aortic root and ascending aorta. Minhaj et al. found that the routine use of TEE during cardiac surgery revealed new findings in 30 % of patients and of these 20 % had a change in surgical plan [6]. Many cardiothoracic anesthesiologists undergo extensive training and/or certification in perioperative TEE. Newer three dimensional technology is available that allows very accurate reconstruction of anatomy and assessment of function. It is particularly useful in mitral valve repair because of the ability to accurately identify the lesion (P2, ruptured cordae, etc.) and target the surgical approach.

## Induction of General Anesthesia

Prior to induction of general anesthesia in patients scheduled for cardiac surgery, a wide variety of items need to be prepared and checked out. The anesthesia machine needs to be checked out and airway materials (laryngoscope) prepared. Appropriate medications (anesthetic drugs, potent cardiovascular drugs) need to be prepared as well. Preoperatively, peripheral venous access is obtained and intravenous premedication administered. Most anesthesiologists insert invasive arterial catheters (usually radial artery) prior to induction of general anesthesia. Induction of anesthesia (depending on the choice and dose of drugs and the patients' cardiac reserve) can result

in significant hemodynamic changes. Safe induction of general anesthesia in patients with heart failure can be accomplished in a wide variety of ways. A variety of anesthetic drugs can be selected on the basis of both their anesthetic properties and their hemodynamic effects. However, one must realize that essentially all intravenous and inhalational anesthetics can initiate profound (dose-related) cardiorespiratory depression. Additionally, the anesthesiologist should thoroughly understand the patient's underlying cardiac status (left ventricular function, extent of valvular disease, etc.) prior to induction of general anesthesia because specific choices of anesthetic drugs may be determined by specific physiologic goals in individual patients (for example; avoidance of arterial vasodilation in a patient with aortic stenosis). Most commonly, a combination of intravenous opioid (analgesia), intravenous benzodiazepine (amnesia), and inhalational anesthetic (analgesia and amnesia) is used. Following induction of general anesthesia, the trachea is intubated with a cuffed endotracheal tube (following administration of an intravenous muscle relaxant). The choice of a particular muscle relaxant is based upon pharmacokinetics (speed of onset, half-life, etc.) and autonomic and hemodynamic side effects. In most patients, tracheal intubation is accomplished via direct laryngoscopy. However, in patients with altered airway anatomy, tracheal intubation must be accomplished in another manner (awake fiberoptic, asleep fiberoptic, etc.). Once the airway is secured, mechanical ventilation is appropriately initiated.

### Maintenance of General Anesthesia

Maintenance of general anesthesia involves continued administration of intravenous anesthetics and/or inhalational anesthetics to achieve the goals of analgesia and amnesia (and possibly muscle relaxation). While muscle relaxation during cardiac surgery is not required, it is often achieved for a wide variety of reasons (facilitate endotracheal intubation, limit oxygen consumption, prevent shivering, and prevent unexpected movement during critical periods of the operation). The drawback of continuous muscular paralysis is its interference with somatic signs (movement) of light anesthesia. If cardiopulmonary bypass is used, maintenance of general anesthesia is attained via continued administration of intravenous anesthetics and/or inhalational anesthetics.

### Emergence from General Anesthesia

With the focus on reducing costs by shortening the length of stay in the intensive care unit, the anesthesiologist in encouraged to design an anesthetic plan that not only fulfills the requirements of general anesthesia (analgesia, amnesia, muscle relaxation, hemodynamic stability, etc.) during intense noxious stimulation intraoperatively, but also allows an appropriately rapid recovery of consciousness and spontaneous ventilation postoperatively. In the uncomplicated case, the goal is to allow tracheal extubation very soon after the patient's condition is stabilized in the intensive care unit, usually within two to fours hours postoperatively. Hence, there is continuing effort to develop rapid-onset, short-acting anesthetics, opioids, benzodiazepines, and muscle relaxants that allow efficient titration of dose (or infusion rate) according to the individual patient's needs both intraoperatively and postoperatively.

## Hemodynamic Management

Potential therapeutic interventions in managing patients with hypotension and/or decreased cardiac output include manipulation of heart rate or rhythm, optimizing preload, optimizing myocardial contractility, and/or optimizing systemic vascular resistance [7, 8]. When managing patients with hypotension and/or decreased cardiac output, the initial important task for the clinician is to appropriately assess the hemodynamic instability to determine the etiologic roles that heart rate/rhythm, preload, myocardial contractility, and/or systemic vascular resistance contribute to the hemodynamic instability. Once the cause

(or causes) of hemodynamic instability are identified, the physiologic goal (or goals) are identified and appropriate specific therapy is initiated. Such decisions are clinically important. Appropriate clinical interventions can prove lifesaving. Conversely, inappropriate clinical interventions can prove deadly. For example, administering a vasoconstrictor to a patient who has hypotension/decreased cardiac output from left ventricular failure will most certainly precipitate clinical deterioration. This patient requires agents that increase myocardial contractility and/or initiate afterload reduction (not vasoconstrictors). This section will focus on how clinicians should appropriately assess hemodynamic instability, choose the physiologic goal (or goals), initiate appropriate specific therapy, and assess the outcome of the chosen therapy [9, 10].

## Hemodynamic Instability Assessment

Numerous clinical variables must be contemplated during assessment of hemodynamic instability (Table 17.4). Determination of blood pressure and evaluation of heart rate and rhythm obviously play an important role in initial early assessment of hemodynamic instability. Level of hypotension (mild, moderate, severe) determines the time frame in which the clinician must operate. In certain patients, manipulation of heart rate and/or heart rhythm may restore hemodynamic stability. While the physical examination may be of great value in diagnosing gross or acute pathology (pneumothorax, hemothorax, acute valvular insufficiency), it is of limited value in diagnosing and managing ventricular failure. While level of mental status and amount of urine output may be beneficial in certain patients, classic clinical indicators of decreased cardiac output (oliguria, metabolic acidosis) may not always be reliable. Thus, in essentially all patients with clinically significant hemodynamic instability that requires more than routine therapy, more information will be required then is routinely obtained in order to appropriately assess the hemodynamic instability. Such information is most commonly obtained via assessment of central venous pressure, insertion of a pulmonary artery catheter, and/or some form of echocardiography. Each of these three methods has unique advantages and disadvantages.

**Table 17.4** Hemodynamic instability assessment

| |
|---|
| Blood pressure/heart rate |
| Electrocardiogram |
| Mental status/urine output |
| Arterial/venous blood analysis |
| Central venous pressure |
| Pulmonary artery catheter |
| Echocardiography |

The routine use of a pulmonary artery catheter in all patients with hemodynamic instability has progressively been replaced by a more selective approach. In general, a central venous pressure catheter alone may be used for monitoring in patients with preserved left ventricular function (ejection fraction greater than 40 %) and no severe valvular pathology. If the patient continues to clinically deteriorate (progressive hypotension, unexplained oliguria, and/or acidosis), then a pulmonary artery catheter may then be inserted to gather additional information, such as right ventricular pressure, pulmonary artery pressure, and pulmonary artery occlusive pressure. Derived variables, such as cardiac output/cardiac index, pulmonary vascular resistance, and systemic vascular resistance may also then be obtained. Special purpose pulmonary artery catheters for continuous cardiac output measurements, continuous mixed venous oximetry measurements, pacing ability, and/or right ventricular ejection fraction are also available.

The introduction of the flow-directed pulmonary artery catheter in the 1970s represented, at the time, a major advance in the monitoring of hemodynamically unstable patients. A very large amount of information (intracardiac pressures, derived hemodynamic and pulmonary parameters) can be gathered. However, one must keep in mind that clinical data obtained from a pulmonary artery catheter may be erroneous and/or misleading [11, 12]. Some recent clinical investigations have indicated that information obtained from pulmonary artery

catheters may in fact lead clinicians to initiate inappropriate therapy, which may increase morbidity and mortality. Such clinical investigations have stirred controversy regarding proper clinical utilization of (and interpretation of data from) the pulmonary artery catheter. Some Investigators/Editors have even suggested that use of the pulmonary artery catheter should be abandoned.

Probably the major reason for the "demise" of the pulmonary artery catheter has been the emergence of echocardiography (specifically transesophageal echocardiography) over the past two decades. It is now clear that information obtained from echocardiography is far superior (in quality and quantity) to that obtained from the pulmonary artery catheter. Furthermore, information from echocardiography has helped prove that much of the information obtained from the pulmonary artery catheter may be erroneous and/or misleading. Specifically, echocardiography provides definitive clinical data regarding preload, myocardial contractility, and systemic vascular resistance whereas the pulmonary artery catheter can only provide surrogates of these important variables. Furthermore, echocardiography can provide additional useful clinical data that the pulmonary artery catheter cannot, such as information regarding diastolic function, myocardial ischemia, valvular function, potential aneurysm/dissection, potential effusion/tamponade, and the presence/position of intracardiac catheters (Table 17.5). The American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists Task Force on Transesophageal Echocardiography deemed that unexplained hemodynamic disturbances not responsive to conventional therapy is a Class I indication for use of transesophageal echocardiography ("frequently useful in improving clinical outcome") [13].

## Physiologic Goals of Therapy

By utilizing a clinically appropriate physical examination, invasive monitoring (central venous pressure, pulmonary artery catheter), and/or echocardiography, one can determine the physiologic goal(s) of therapy. Once assured that heart rate and rhythm are optimized, the clinician must then choose the appropriate mixture of optimizing intravascular volume, optimizing myocardial contractility, and/or optimizing systemic vascular resistance (Table 17.6). The relative importance of each (preload, myocardial contractility, afterload) will vary in each individual patient and clinical scenario and is determined by the clinician during assessment of hemodynamic instability. Once specific physiologic goal(s) of therapy are determined, choice of specific therapy may then be contemplated.

**Table 17.6** Physiologic goals of therapy

| |
|---|
| Intravascular volume? |
| Colloid/crystalloid |
| Myocardial contractility? |
| Inotropic agents |
| Systemic vascular resistance? |
| Vasopressor agents |

**Table 17.5** Comparison of pulmonary artery catheter data and echocardiography data

| Determinant | PA CATH | ECHO |
|---|---|---|
| Preload | CVP, PAOP | Direct |
| Afterload | SVR | Wall stress |
| Systolic function | SV, CO | FAC, EF, SV, CO, ESPVR |
| Diastolic function | CVP, PAOP | Filling profiles |
| Ischemia | Insensitive | Sensitive |
| Valvular function | Indirect | Direct |
| Aneurysm/dissection | Not useful | Extremely useful |
| Effusion/tamponade | Indirect | Direct |
| Intracardiac catheters | Not useful | Extremely useful |

## Choice of Specific Therapy

Optimization of intravascular volume (preload) requires administration of intravenous crystalloid and/or colloid, enhancing myocardial contractility involves administration of intravenous inotropic agents, and increasing systemic vascular resistance (afterload) requires use of intravenous vasopressor agents. The most commonly utilized inotropic agents and vasopressor agents are listed in Table 17.7.

Dopamine is an endogenous catecholamine and is an immediate precursor of norepinephrine and epinephrine. Its actions are mediated via stimulation of alpha, beta, and dopaminergic receptors. In low doses (1–3 mcg/kg/min), dopamine predominantly stimulates dopaminergic receptors. Increasing the dose to 6–14 mcg/kg/min predominantly stimulates beta receptors and further increases in dosing (>14 mcg/kg/min) leads to exclusive stimulation of alpha receptors. Such dose-dependent effects of dopamine are not very specific and can be influenced by many factors. Dopamine is unique in comparison with other endogenous catecholomines owing to its effects on the kidneys. It may increase renal artery blood flow by causing direct vasodilation of the afferent arteries and indirect vasoconstriction of the efferent arteries. This results in an increase in glomerular filtration pressure and in glomerular filtration rate.

**Table 17.7** Choice of specific therapy

| |
|---|
| Inotropic agents |
| Beta-receptor agonists |
| Dopamine |
| Dobutamine |
| Dopexamine |
| Epinephrine |
| Isoproterenol |
| Phosphodiesterase inhibitors |
| Amrinone |
| Milrinone |
| Enoximone |
| Miscellaneous |
| Digitalis preparations |
| Thyroid hormone |
| Calcium |
| Magnesium |
| Vasopressor agents |
| Alpha-receptor agonists |
| Norepinephrine |
| Phenylephrine |
| Arginine vasopressin |
| Methylene blue |

Dobutamine is a synthetic catecholamine that generally produces dose-dependent increases in cardiac output and reductions in diastolic filling pressures. Its primary physiologic effects are mediated via stimulation of beta receptors (does possess minimal alpha receptor activity). Venous return, augmented by adrenergic reduction of venous capacitance, likely contributes to the increase in cardiac output. In addition to increasing contractility, dobutamine may have favorable metabolic effects on ischemic myocardium.

Dopexamine is a relatively newly developed synthetic catecholamine, structurally related to dopamine and dobutamine. The drug stimulates both dopaminrergic and beta receptors. An inhibitory action in the neuronal catecholamine uptake mechanism has also been demonstrated and may account for the positive inotropic action of this drug. Continuous infusion of dopexamine results in systemic and preferential renal vasodilation, causing afterload reduction, increases in cardiac output, and improved renal perfusion. Dopexamine reduces afterload through pronounced systemic arterial vasodilation, increased renal perfusion by selective renal vasodilation, and cardiac stimulation through direct and indirect positive inotropic mechanisms. The increase in cardiac output appears to occur predominantly as a result of an increase in heart rate, as stroke volume demonstrates only a minimal change. Dopexamine's physiologic effects are most pronounced when used as a continuous infusion of 1–4 mcg/kg/min.

Epinephrine stimulates both alpha and beta receptors in a dose-dependent fashion. The sympathoadrenal (endogenous) secretion of epinephrine is critical to support cardiac contractility, exert tonic control of vascular beds, and in the modulation of the body's "stress response". Epinephrine increases stroke volume and cardiac

output in a dose-dependent fashion (10–40 ng/kg/min). However, heart rate may also be increased to unacceptable levels.

Isoproterenol is a potent beta receptor agonist devoid of alpha receptor agonist activity. Isoproterenol dilates skeletal, renal, and mesenteric vascular beds and decreases diastolic blood pressure. The drug's potent chronotropic action, combined with the potential to decrease coronary perfusion pressure (via decreased diastolic blood pressure), may limit its usefulness in patients with coronary artery disease. Isoproterenol may be uniquely useful for stimulation of cardiac pacemaker cells in the management of acute bradyarrhythmias or heart block. It reduces refractoriness to conduction and increases automoaticity in myocardial tissues. The tachycardia seen with isoproterenol is a result of both direct effects of the drug on the heart and reflex effects caused by peripheral vasodilation. Additional application of isoprotereonol has included management of right ventricular dysfunction associated with pulmonary hypertension. However, although isoproterenol is an excellent pulmonary vasodilator, decreases in perfusion pressure (particularly diastolic arterial pressure) may lead to right ventricular ischemia.

Phosphodiesterase inhibitors are noncatecholamine and nonadrenergic agents [14]. Therefore, they do not rely upon beta receptor stimulation for their positive inotropic activity. As a result, the clinical effectiveness of the phosphodiesterase inhibitors is not altered by previous beta blockade nor is it reduced in patients who may experience beta receptor down-regulation. Although the precise mechanism of action of the phosphodiesterase inhibitors has yet to be elucidated, the proposed theory of action involves the inhibition of type III phosphodiesterase found predominantly in cardiac muscle. This inhibition results in a secondary increase in cyclic AMP, which leads to an increase in calcium channel entry into the cell, accounting for the positive inotropic action. These agents also produce systemic and pulmonary vasodilation. As a result of this combination of hemodynamic effects (positive inotropic support and vasodilation), the term "inodilator" has been coined to describe this class of drugs. Because these agents exert their hemodynamic effects by a nonadrenergic mechanism of action, when used in combination with traditional beta receptor agonists, phosphodiesterase inhibitors have been shown to result in an additive effect on myocardial performance. Phosphodiesterase inhibitors decrease pulmonary vascular resistance by both a direct action on the pulmonary vasculature (increasing cGMP) and an indirect effect (increasing cardiac output, decreasing pulmonary artery occlusive pressure).

Digitalis binds to a subunit of sodium potassium ATPase, producing complete inhibition of enzymatic and transport processes. Thus, intracellular sodium and calcium increase and intracellular potassium is lost. The elevated intracellular sodium increases the availability of calcium to the contractile proteins, increasing contractility. Increased intracellular calcium is associated with decreased intracellular pH, which increases inward sodium movement and outward hydrogen ion movement, further increasing intracellular sodium concentration and inotropy. Digitalis exerts its positive inotropic effect independent of catecholamine liberation. Digitalis augments both force and velocity of myocardial contraction without raising cardiac output. Ventricular end-diastolic volume and end-diastolic pressure are decreased. The positive inotropic effects of digitalis, however, are weak. The physiologic onset of action of digitalis occurs within 15–30 min following intravenous administration, with peak effects being obtained in 2–5 h. It must be kept in mind that the therapeutic plasma level "window" of digoxin is relatively narrow and substantial toxicity (heart block, enhanced automaticity) may occur.

Thyroid hormone's effects on the cardiovascular system are well established in clinical states of hyperthyroidism and hypothyroidism. Clinical studies suggest that a reduction in plasma thyroid hormone concentration may be associated with the decreased myocardial performance that occurs in certain clinical scenarios, such that occurs following exposure to cardiopulmonary bypass and in the setting of organ transplantation. However, the proper role that thyroid hormone

supplementation plays in clinical treatment of hemodynamic instability remains to be determined.

Calcium may antagonize the action of catecholamine activity, but does not alter the cardiotonic actions of phosphodiesterase inhibitors. Calcium influx during ischemia-reperfusion may increase oxygen consumption and contribute to diastolic dysfunction. However, calcium administration usually increases mean arterial pressure via an increase in systemic vascular resistance and may also improve right ventricular function.

Magnesium has a key role in cellular energy transfer and use (involving adenosine triphosphate) and in cell membrane function. It is widely used as an adjunct for the treatment of arrhythmias following myocardial infarction. Magnesium may influence hemodynamic performance through its modulation of vascular tone, intracellular calcium, catecholamine activity, and adenosine triphosphate metabolism. The potential for magnesium deficiency to affect cardiovascular performance may be particularly relevant in the presence of ischemia, and there are reports of a potential role for magnesium in enhancing hemodynamic performance in ventricular dysfunction following cardiac surgery.

Norepinephrine stimulates both alpha and beta receptors in a dose-dependent fashion. Norepinephrine, after a long period of disfavor, is experiencing a renewed popularity for management of hemodynamic instability. When used appropriately, norepinephrine increases blood pressure, increases stroke volume, increases cardiac output, and increases urine output.

Phenylephrine is a potent alpha receptor agonist devoid of beta receptor agonist activity. Thus, the physiologic effect of phenylephrine administration is an increase in systemic vascular resistance, with no effects as myocardial contractility.

Arginine vasopressin is an endogenous peptide synthesized exclusively in the hypothalamus and released from the posterior pituitary. Traditionally, arginine vasopressin release is stimulated by changes in vascular volume and vascular tone. Vasopressin is bound by two distinct types of receptors: renal (V2) and vasomotor (V1). Although under normal conditions, arginine vasopressin contributes little, if any, to blood pressure maintenance, investigations have shown the ability of arginine vasopressin to be helpful in the management of certain refractory vasodilatory states [15, 16]. In a syndrome known as post-conditioning vasodilatory shock (characterized by catecholamine resistance, low systemic vascular resistance despite norepinephrine administration), administration of arginine vasopressin is effective in restoring hemodynamic stability. Numerous investigators have explored the role of arginine vasopressin administration in the management of vasodilatory states in septic shock and following cardiopulmonary bypass. Although the precise mechanisms responsible for this vasodilatory state are unknown, patients experiencing such vasodilatory states are characterized by a significant reduction in circulating vasopressin. In these patients, infusion of arginine vasopressin in the range of 2–8 units/h results in significant hemodynamic improvements. An increase in the infusion above 8 units/h provides little added effect.

Several case reports have been described in the literature in which the guanylate cyclase inhibitor methylene blue was successfully administered intravenously to reverse norepinephrine-resistant vasoplegia after cardiopulmonary bypass [17]. The favorable effect of methylene blue in this scenario suggests refractory vasoplegia may reflect a dysregulation of nitric oxide synthesis and vascular smooth muscle cell guanylate cyclase activation. The available data have been obtained from anecdotal case reports only and the effect of methylene blue has not been examined in larger cohorts. Methylene blue has also been used to effectively treat patients with septic shock and low peripheral vascular resistance. A few adverse effects of methylene blue in the treatment of norepinephrine-refractory vasoplegia have been described, such as cardiac arrhythmias, coronary vasoconstriction, decreases in cardiac output, renal blood flow, and mesenteric blood flow, increases in pulmonary vascular pressure and resistance, and deterioration in gas exchange. However, most of these side effects are dose-dependent and do not occur when the dose of methylene blue is no >2 mg/kg.

Levosimenden is a new inotropic agent and belongs to a class of drugs known as calcium sensitizers. It prolongs the actin-myosin cross bridging time by stabilizing cardiac troponin C. It is a unique drug because it does not increase intracellular calcium unlike traditional inotropic agents, thus it increases cardiac output without increasing myocardial oxygen consumption and causing arrhythmias. It is currently clinically available in Europe and is being investigated in the United States. Studies have demonstrated utility in weaning patients off cardiopulmonary bypass (CPB) and early recovery after CPB in patients with heart failure [18, 19].

## Assessment of Therapy

Assessment of therapy entails contemplation of the same physiologic parameters (heart rate/rhythm, preload, myocardial contractility, and systemic vascular resistance) that were assessed during the initial period of hemodynamic instability. This will involve reassessment of blood pressure, heart rate/rhythm, level of mental status (if applicable), urine output, central venous pressure, information from a pulmonary artery catheter, and/or information from some form of echocardiography.

### Conclusions

The successful perioperative anesthetic management of patients with heart failure is complex and challenging. In order to ensure acceptable postoperative outcome, a true team approach is required by the surgeon, anesthesiologist, perfusionist, and nursing staff. Anesthesiologists managing these patients need to have extensive knowledge regarding cardiovascular physiology and pharmacology, physiologic effects of anesthetic drugs and techniques on the cardiovascular system, and rational assessment/pharmacologic treatment of hemodynamic instability. Most times, no specific drug or technique is truly indicated. Identified goals (analgesia, amnesia, muscle relaxation) can be safely attained in many ways. In the current era, anesthesiologists managing these extremely sick individuals should possess appropriate skills regarding use of transesophageal echocardiography, which simplifies hemodynamic instability assessment and may influence surgical management. Once again, identified goals (optimize preload, optimize myocardial contractility, optimize afterload) can be safely attained in many ways. Thus, there is much "art" (which requires extensive clinical experience) to the successful perioperative anesthetic management of patients with heart failure.

## References


1. Chaney MA. Intrathecal and epidural anesthesia and analgesia for cardiac surgery. Anesth Analg. 2006;102:45–64.
2. Chaney MA. Cardiac surgery and intrathecal/epidural techniques: at the crossroads? (editorial). Can J Anesth. 2005;52:783–8.
3. Chaney MA. How important is postoperative pain after cardiac surgery? (editorial). J Cardiothorac Vasc Anesth. 2005;19:705–7.
4. Schwann NM, Chaney MA. No pain, much gain? (editorial). J Thorac Cardiovasc Surg. 2003;126:1261–4.
5. Mora Mangano C. Risky business (editorial). J Thorac Cardiovasc Surg. 2003;125:1204–7.
6. Minhaj M, Patel K, Muzic D, et al. The effect of routine intraoperative transesophageal echocardiography on surgical management. J Cardiothorac Vasc Anesth. 2007;21:800–4.
7. McMurray J, Pfeffer MA. New therapeutic options in congestive heart failure: part I. Circulation. 2002;105:2099–106.
8. McMurray J, Pfeffer MA. New therapeutic options in congestive heart failure: part II. Circulation. 2002;105:2223–8.
9. Stevenson LW. Clinical use of inotropic therapy for heart failure: looking backward or forward? Part I: inotropic infusions during hospitalization. Circulation. 2003;108:367–72.
10. Stevenson LW. Clinical use of inotropic therapy for heart failure: looking backward or forward? Part II: chronic inotropic therapy. Circulation. 2003;108:492–7.
11. Dalen JE. The pulmonary artery catheter – friend, foe, or accomplice? JAMA. 2001;286:348–50.
12. Hall JB. Use of the pulmonary artery catheter in critically ill patients; was invention the mother of necessity? JAMA. 2000;283:2577–8.
13. American Society of Anesthesiologists, Society of Cardiovascular Anesthesiologists Task Force on Transesophageal Echocardiography. Practice

guidelines for perioperative transesophageal echocardiography. Anesthesiology. 1996;84:986–1006.
14. Levy JH, Bailey JM, Deeb GM. Intravenous milrinone in cardiac surgery. Ann Thorac Surg. 2002;73:325–30.
15. Dünser MW, Mayr AJ, Ulmer H, et al. Arginine vasopressin in advanced vasodilatory shock; a prospective, randomized, controlled study. Circulation. 2003;107:2313–9.
16. Patel BM, Chittock DR, Russell JA, Walley KR. Beneficial effects of short-term vasopressin infusion during severe septic shock. Anesthesiology. 2002;96:576–82.
17. Leyh RG, Kofidis T, Strüber M, et al. Methylene blue: the drug of choice for catecholamine-refractory vasoplegia after cardiopulmonary bypass? J Thorac Cardiovasc Surg. 2003;125:1426–31.
18. Eriksson HL, Jalonen JR, Heikkinen LO, et al. Levosimendan facilitates weaning from cardiopulmonary bypass in patients undergoing coronary artery bypass grafting with impaired left ventricular function. Ann Thorac Surg. 2009;87:448–54.
19. Siirilla-Waris K, Suojaranta-Ylinen R, Harjola VP. Levosimendan in cardiac surgery. J Cardiothorac Vasc Anesth. 2005;19:345–9.