Acta Neurochirurgica Supplement 130

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Complications in Neurosurgery

MOREMEDIA

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ISSN 0065-1419 ISSN 2197-8395 (electronic)
Acta Neurochirurgica Supplement 130
ISBN 978-3-030-12886-9 ISBN 978-3-030-12887-6 (eBook)
https://doi.org/10.1007/978-3-030-12887-6

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

I owe a debt of gratitude to all of my teachers, not only those during my residency but also those during my undergraduate days, and not only to neurosurgeons but even to those in allied surgical fields, as well as neurology and allied neurosciences.
However, the man who changed my life, not only as a neurosurgeon but also as a person, was Professor Dr. Madjid Samii—my true mentor of basic, as well as specialized, neurosurgery—who taught me the right and simple ways to do even the most difficult and complex surgeries and tasks of different sorts.
Nevertheless, the greatest teachers in my life were my patients, who trusted me with their lives and function, and never or seldom complained when things went wrong. True neurosurgery was learned through the complications they suffered, caused by our own decisions and actions. I acknowledge today the blessings of those who benefited, and I seek forgiveness from those who suffered or even perished.
Lastly, I must acknowledge all of my colleagues who believed in my belief of not shying away from discussing complications. Yes, they do occur, and they do need serious introspection and discussion. So, I thank all of those who agreed to come and frankly discuss them on an open platform in the true spirit of learning.
Keki E. Turel

To my colleagues worldwide, who, hopefully, will find this book practical and helpful in their daily neurosurgical work. And to my embattled Motherland—the Victory will be ours, as usual.
Mikhail F. Chernov

To our patients, who deserve the highest standards of safety and quality assurance, and who, having gone through some real unfortunate and sad events themselves, teach and inspire us to further advance the art and science of neurosurgery and make it safer. Let this work be a beacon for neurosurgeons all across the globe as they navigate some tough situations in the operating room and strive hard to keep their patients safe.
Hrishikesh Sarkar

Preface

Neurosurgery is an intricate field of medicine, demanding not only exemplary surgical skills but also pre-, intra-, and postoperative decision-making, all of which can have great impacts on the patient's life.

Complications are an unfortunate part of surgery, making the consequences of treatment worse than the original disease, bringing great suffering to the patient and his or her family, and also tarnishing the reputation of the surgeon and the specialty at large. Complications may arise because of numerous factors, such as inadequate preoperative clinical and radiological assessment or an error of execution; they may be related to the technology or tools employed, or simply to an insurmountable disease. It is often said that "It is better to stay out of complication than get out of complication"—a reflection of the old adage that "Prevention is better than cure." Simply speaking, the two sides of the coin of complications are anticipation or prevention, and management.

When dealing with the issue of complications, while on one hand there is valuable and unmatched scientific learning, on the other hand there are ethical considerations and issues, philosophical aspects, moral obligations or probity, and legal implications, which ruin many a promising or successful career. Neurosurgery is a vast specialty with myriad subspecialties and rapidly evolving technology. Though the fundamentals of anatomy, physiology, pathology, and surgery remain nearly the same, the modes of imaging and surgical treatment are ever-changing and have been becoming progressively sophisticated and minimalistic. Modern technology lures new adventurers, along with the inevitable "learning curve" with its accompanying problems (which, ideally, should be restricted to cadavers, models, or animal labs and not imposed on already suffering patients). In the USA alone, there are an estimated 200,000 preventable medical deaths every year, which amount to the equivalent of almost three fatal airline crashes per day. As the renowned airline pilot Chesley Sullenberger noted, "if such a level of fatalities was to happen in aviation, airlines would stop flying, airports would close, there would be congressional hearings and there would be a presidential commission. No one would be allowed to fly until the problem had been solved." The field of aviation has strict and elaborate safety guidelines, protocols, and checklists. Even in aviation, complications occur more often because of human error than because of technical snags or "accidents," such as bird strikes or abrupt and adverse changes in weather. Medicine, too, is an "uncertain" field, and complications may occur because of a variety of avoidable and unavoidable factors. Surgery is risky and dangerous, and it carries 6–12% overall complication rates. As surgeons, we too would have better outcomes if we promulgated and assiduously followed such rigorous guidelines. Dr. Atul Gawande, the author of "The Checklist Manifesto", emphasized that "checklists, when followed have helped reduce complications by 36%, deaths by 47% and infection by 50%."

All of this makes the subject of complications very encompassing. While most medical conferences deal with rather staid and conventional discussion of diseases, both common and uncommon, with speakers extolling their superb management and results, and with a slide on complications occasionally rushed in toward the end, very few have shown the fortitude to highlight only pitfalls of management or confessions of errors and mistakes. As was said earlier, medicine is an uncertain field, and mistakes of judgment (besides ability and skill) are

inevitable. Having committed a "mistake," it is our moral obligation to not forget it and to pass the lessons learned on to the next generation, lest they should have to go through them again at great and repetitive cost to humanity. Hence, it is about time we shifted our focus from "How I do it" rhetoric to "How I would not do it" or "How I wish I had done it differently." Indeed, our focus should be on complications, their avoidance, and their management!

With this approach of having an open forum of unabashed declaration of one's failures and what one has learned and is willing to share with others on level ground, the first International Conference on Complications in Neurosurgery (ICCN) was held on March 3–5, 2017, in Mumbai, India. It was made amply clear that the speakers would present complications experienced at their own hands or in their own division. One had to refrain from presenting complications encountered by a surgeon at another service that one eventually happened to correct or salvage. That would be putting our colleagues down and appear in bad taste. In fact, no one needed to talk about their own success, except for how they were able to surmount it, having encountered an unexpected disaster in their own patient. Such deliberations on complications proved to be far more humbling and enriching than those indulging in boastful one-upmanship.

It was essential to hold the entire conference in one single banquet hall, as running parallel sessions would mean denying the delegates the opportunity to witness the entire proceedings in all subspecialties of neurosurgery. Because there was an unprecedented number of incredible presentations, most of them restricted to 5–10 min of allocated time, it was very important to maintain time discipline. This would not have been possible without the cooperation of moderators, panelists, presenters, and delegates alike. The session ran continuously from 8:30 a.m. to 6:30 p.m., with only a 45-min lunch break, on all 3 days of the conference. Such was the passion among the attendees that apart from a quick visit to the washroom or to grab a cup of tea (kept available round-the-clock outside the hall), all of them were glued to their seats for the full 3 days. In all, 216 talks were delivered, of which 183 described individual complications and 33 were didactic lectures, including overviews, guidelines, protocols, and discourses on ethics, philosophy, moral probity, legal implications, etc. The first ICCN Oration was delivered by Professor Dr. Madjid Samii. The conference was inaugurated by the internationally celebrated space scientist Dr. Koppillil Radhakrishnan, a former chairman of the Indian Space Research Organization (ISRO). There are many parallels between conducting space exploration and performing neurosurgical operations, both requiring intensive research and preparation, coordinated teamwork, and huge risks and accountability.

On record, the first ICCN was attended by 383 delegates from across the globe, with presentations done by speakers from 24 countries: Canada, Chile, China, the Czech Republic, Egypt, France, Germany, India, Indonesia, Ireland, Israel, Italy, Japan, Jordan, Kazakhstan, Nepal, Oman, Russia, Saudi Arabia, Serbia, South Africa, Turkey, the UK, and the USA. Excellent feedback was received from the attendees, who promised to return for the second ICCN. At the end, the organizers felt vindicated for having experimented with this idea, which proved to be of immense value to all. Indeed, we have inadvertently sown the seeds of a new concept—of a new era in neurosurgery.

Following close on the heels of the first ICCN was the much-awaited 16th Congress of the World Federation of Neurosurgical Societies (WFNS), organized by Dr. Uğur Türe and his team in Istanbul, Turkey, on August 20–25, 2017. The program on August 21 included a 2-hour dedicated symposium on complications in neurosurgery, held in the largest of the parallel halls. Once again, there was an overwhelming response from the speakers (22 presenters from 16 countries on five continents), thus cutting down the presentation time from 7 min to 5 min, including 2 min for discussion following each talk. Even more overwhelming was the response of the participants, some of whom congregated outside the hall since the space inside was full. This further endorsed the impact of the subject of complications and the eagerness to share and learn on the part of presenters and attendees alike.

This volume of Acta Neurochirurgica Supplement is a compilation of carefully selected presentations from the two aforementioned conferences. Unlike other contemporary literature,

this book on complications will never be outdated. As the American media magnate Sumner Redstone said, “Success is not built on success. It’s built on failure. It’s built on frustration. Sometimes it’s built on catastrophe.” While we may savor success, we learn only from failures. Failure is a defeat only if you do not learn from it. That is the main take-home message of our work!

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Contents

Surgical Complexity and Complications: The Need for a Common Language

Morgan Broggi, Paolo Ferroli, Silvia Schiavolin, Costanza Zattra, Marco Schiariti, Francesco Acerbi, Dario Caldiroli, Alberto Raggi, Ignazio Vetrano, Jacopo Falco, Camilla de Laurentis, and Giovanni Broggi

Abstract

Background: Quality measurement and outcome assessment have recently caught an attention of the neurosurgical community, but lack of standardized definitions and methodology significantly complicates these tasks.

Objective: To identify a uniform definition of neurosurgical complications, to classify them according to etiology, and to evaluate them comprehensively in cases of intracranial tumor removal in order to establish a new, easy, and practical grading system capable of predicting the risk of postoperative clinical worsening of the patient condition.

Methods: A retrospective analysis was conducted on all elective surgeries directed at removal of intracranial tumor in the authors' institution during 2-year study period. All sociodemographic, clinical, and surgical factors were extracted from prospectively compiled comprehensive patient registry. Data on all complications, defined as any deviation from the ideal postoperative course occurring within 30 days of the procedure, were collected with consideration of the required treatment and etiology. A logistic regression model was created for identification of independent factors associated with worsening of the Karnofsky Performance Scale (KPS) score at discharge after surgery in comparison with preoperative period. For each identified statistically significant independent predictor of the postoperative worsening, corresponding score was defined, and grading system, subsequently named Milan Complexity Scale (MCS), was formed.

Results: Overall, 746 cases of surgeries for removal of intracranial tumor were analyzed. Postoperative complications of any kind were observed in 311 patients (41.7%). In 223 cases (29.9%), worsening of the KPS score at the time of discharge in comparison with preoperative period was noted. It was independently associated with 5 predictive factors—major brain vessel manipulation, surgery in the posterior fossa, cranial nerve manipulation, surgery in the eloquent area, tumor size >4 cm—which comprised MCS with a range of the total score from 0 to 8 (higher score indicates more complex clinical situations). Patients who demonstrated KPS worsening after surgery had significantly higher total MCS scores in comparison with individuals whose clinical status at discharge was improved or unchanged (3.24 ± 1.55 versus 1.47 ± 1.58; $P < 0.001$).

Conclusion: It is reasonable to define neurosurgical complication as any deviation from the ideal postoperative course occurring within 30 days of the procedure. Suggested MCS allows for standardized assessment of surgical complexity before intervention and for estimating the risk of clinical worsening after removal of intracranial tumor. Collection of data on surgical complexity, occurrence of complications, and postoperative outcomes, using standardized prospectively maintained comprehensive patient registries seems very important for quality measurement and should be attained in all neurosurgical centers.

Keywords

Brain tumor surgery · Complication · Craniotomy · Grading system · Karnofsky Performance Scale · Milan Complexity Scale · Neurosurgery · Outcome · Quality measurement · Risk stratification · Surgical complexity

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_1

Introduction

Quality measurement and outcome assessment have gained great importance in neurosurgery in recent years, not only because they reflect the value of surgical treatment itself, but also because they can be used to evaluate the efficiency of the health care sector in general and to allocate resources accordingly [1]. It is certainly not an easy task, and even the definition of "treatment quality" may differ widely between patients, surgeons, society, administrators, and health care policy-makers [2]. Therefore, several factors should be considered to make sure that all of these different perspectives are taken into account [3].

The first milestone that should be clarified when quality issues are being addressed in neurosurgery is the definition, classification, and registration of postoperative complications. Indeed, in order for us to "speak the same language," an internationally shared definition of neurosurgical complications is truly needed [4] because, despite the many propositions made in past years [5–12], there is still no consensus on this matter. In general surgery, on the other hand, there is a long tradition of attempts to designate what a complication is. In particular, starting from 1992, Drs. P. A. Clavien and D. Dindo published several works on this topic [2, 13–16], in which they defined and classified surgical complications on the basis of a treatment-oriented grading system. In the neurosurgical field, their classification has been adopted by Sarnthein et al. [17] and further revised and expanded by Landriel Ibañez et al. [18].

To gather all materials related to complications, a prospectively collected patient registry is essential not only for making quality measurement more objective but also to control the completeness of clinical and surgical records and to review the data available for research projects [17]. Therefore, besides details of perioperative complications, a patient registry should include various information that are mandatory for outcome assessment and monitoring. In particular, patients' preoperative conditions and surgical case complexity deeply influence results of treatment, and, in our opinion, these factors also represent important milestones of appropriate treatment quality measurement.

The issue of assessing surgical complexity in advance of intervention is extremely difficult. Neurosurgery is, in fact, such a wide discipline that its entire patient population would be too heterogeneous for a specific and effective risk scale to be built up. Consequently, what would be ideal is preoperative definition of the complexity of surgery for each type of neurosurgical procedures—for example, as Spetzler and Martin did in 1986 for resection of brain arteriovenous malformations (AVM) [19].

Not only could a standardized and shared means of collection and interpretation of preoperative information (patients' clinical characteristics, surgical complexity, etc.) and postoperative outcome data help to optimize results of treatment, health care organization, and hospital costs, but also it would be useful in driving the policy-making process toward efficacy and efficiency. With this objective in mind, our aims were, first of all, to identify a uniform shared definition of neurosurgical complications and, second, to propose their new etiological classification and integrate it with already existing treatment-oriented one. In the present study, in particular, we thought that focusing on surgeries for removal of intracranial tumors would result in a wide enough, representative, and fairly homogeneous sampling of cases. More specifically, we tried to define some important preoperative factors with which to build a new, easy, and practical grading system capable of predicting the risk of postoperative clinical worsening of the patient's condition.

Methods

A retrospective analysis was conducted on all elective neuro-oncological surgeries performed at the Fondazione IRCCS Istituto Neurologico Carlo Besta (FINCB) in Milan, Italy, during a 2-year study period. The research protocol was approved by the ethical committee of the FINCB, and all patients signed an informed consent form.

Study Design and Inclusion Criteria

The records used in this study pertained to patients of all ages who had a diagnosis of a possible intracranial tumor of any type and underwent surgery aimed at maximal safe lesion resection. Craniotomies for open biopsies, stereotactic biopsies (either frame-based or frameless), or endoscopic endonasal biopsies were excluded from this analysis. The maximal safe resection principle [20–24], which is generally employed at our institution, allowed for tailored extent of resection (EOR) on the basis of the tumor features (such as its location and size) and the patient's characteristics (such as his or her age and comorbidities) in order to remove as much of the mass as possible without impairing general health status of the treated individual. For tumors located in eloquent areas, comprehensive neurophysiological monitoring and, in selected cases, use of awake craniotomies were considered in order to perform cortical and subcortical brain mapping and reduce the incidence of irreversible postoperative neurological deficits [15].

Sociodemographic, clinical, and surgical data were prospectively collected and retrospectively assessed by both the first and the second authors (MB, PF) through the Neurosurgical Complications Protocol and Database Besta-NSC [25], which includes information on all cases of neurosurgical procedures performed in our institution. The

Karnofsky Performance Scale (KPS) was used to evaluate the patients' general health status before surgery and at discharge. It was chosen because KPS has the strongest support in the literature for estimating surgery-related outcomes, and it has been also effective in predicting early (≤30-day) morbidity in patients with intracranial tumors [26].

On the basis of previous studies [17, 18], a complication was defined as any deviation from the ideal postoperative course occurring within 30 days of the procedure, and was characterized as a condition, which is usually inherent in the intervention (but not necessarily); which is usually impairs the patient's functional status (but not necessarily); and, finally, which is considered transient if it is totally or partially (but significantly) resolved within 30 days of the surgery, and permanent if it is still present thereafter.

Besides determination of corresponding KPS scores before surgery and at discharge, complications were designated as major and minor, and were classified on the basis of the treatment they required (according to the Landriel Ibañez classification [18]) and their etiology. Major complications were characterized as follows: new or aggravated neurological deficit (e.g., hemiparesis, hemianopia, cranial nerve palsies), stroke, sepsis, "major" reoperation (e.g., removal of intracerebral, subdural, or extradural hematoma; decompressive craniectomy for brain swelling; surgical repair of the cerebrospinal fluid [CSF] leak), and life-threatening medical morbidity (e.g., cardiac arrhythmias, pulmonary embolism). Minor complications were characterized as follows: local wound infections, postoperative meningitis, subgaleal fluid collections, seizures, subjective neurological deficits (visual disturbances, confusion, etc.), postoperative fever or minor infections (e.g., urinary tract infections), and "minor" surgical interventions (e.g., wound revision; external ventricular drainage; ventriculoperitoneal shunt; external spinal drainage for CSF leak management). The etiological categories of complications were defined as follows: traumatic (i.e., directly related to the surgical trauma/manipulation of a specific neurovascular structure), CSF-related (i.e., CSF leaks, hydrocephalus), infectious (septic), ischemic, hemorrhagic, epilepsy-related, and general medical complications.

Data Analysis

The following statistical analyses were performed sequentially to build the grading system (subsequently named Milan Complexity Scale [MCS]) for predicting postoperative worsening of the patient's general health status after removal of intracranial tumor.

First, all evaluated demographic, clinical, and surgical factors were characterized by means of descriptive statistics, with highlight of the mean values (± standard deviation) and ranges for continuous variables, and frequencies (percentages) for categorical variables. Thereafter, proposed predictive factors of postoperative worsening were defined. They included: age (0–44 years, 45–64 years, ≥65 years), tumor size (largest diameter ≤4 cm, >4 cm), surgery in an eloquent area (yes, no), major brain vessel manipulation (yes, no), cranial nerve manipulation (yes, no), surgery within the brain stem (yes, no), and surgery in the posterior fossa (yes, no). Related factors were evaluated on preoperative radiological images, including magnetic resonance imaging (MRI), computed tomography (CT), digital subtraction angiography (DSA), CT angiography (CTA), and magnetic resonance angiography (MRA). Specifically, surgery in an eloquent area was considered if it was performed within motor, sensory, language or visual cortex; hypothalamus; thalamus; internal capsule; brain stem; or pineal region. Major brain arteries were considered as follows: internal carotid artery (ICA), anterior cerebral artery (ACA), middle cerebral artery (MCA), anterior communicating artery (AComA), posterior communicating artery (PComA), anterior choroidal artery (AChA), ophthalmic artery (OA), vertebral artery (VA), basilar artery (BA), posterior inferior cerebellar artery (PICA), anterior inferior cerebellar artery (AICA), superior cerebellar artery (SCA), and posterior cerebral artery (PCA). Major venous structures were considered as follows: the superior sagittal sinus (SSS), transverse and sigmoid sinuses, internal cerebral veins, the vein of Galen, the vein of Labbé, and the vein of Trolard.

Second, a logistic regression model was built to investigate the strength of the relationship between the change in the patient's general health status after removal of intracranial tumor and diverse demographic and surgical predictive factors. The outcome was defined as the difference between the KPS score before surgery and that at discharge, and all cases were categorized as improved/unchanged or worsened ones. Odds ratios (OR) and Nagelkerke pseudo-R^2 were used to evaluate the performance of the logistic regression model. The goodness of fit of the final and baseline models was compared by computing the difference in their −2 log likelihoods with χ^2 test.

Third, for each identified statistically significant independent predictor of the postoperative worsening, its OR was rounded to the closest even number, and corresponding predictive scores were assigned. Thus, MCS was formed. Based on the sum of each predictor scores, the total MCS score was calculated for every individual patient included in the study. An analysis of variance (ANOVA) was used for comparison of the mean MCS scores between improved/unchanged and worsened subgroups. Initially, it was done in all evaluated cases. Thereafter, to test the performance of MCS in detail, two different sets of subsample analyses were accomplished. First, mean MCS scores were compared between improved/

unchanged and worsened subgroups separately in those patients who underwent gross total tumor resection (GTR), and those ones with either subtotal tumor resection (STR; >90% tumor removal) or partial tumor resection (PR; <90% tumor removal). Second, the same comparison was done separately in patients with intra-axial tumors (gliomas), and in those with extra-axial tumors (meningiomas).

To test the performance of our scale, we ran two different subsample analyses. First, we took into account the cases with gross total tumor resection (GTR) and those with either subtotal tumor resection (STR; >90% tumor removal) or partial tumor resection (PR; <90% tumor removal): in the GTR and STR/PR samples, we compared the mean MCS scores between the impaired and improved/unchanged groups, using ANOVA. Second, we used the same procedure by defining subsamples on the basis of histological findings and divided cases with extra-axial tumors from those with intra-axial tumors. To have the most homogeneous samples possible, we limited this second analysis to cases with meningiomas and gliomas.

Finally, the relative risk (RR) of clinical worsening after surgery for each subgroup of the total MCS score was calculated and their OR were compared; for this purpose subgroups comprising fewer than ten patients were combined.

All calculations were conducted using SPSS version 18.0 software (IBM Corp.; Armonk, NY, USA).

Results

A total of 746 neurosurgical interventions directed at removal of intracranial tumor were performed during the period under study. The series comprised 397 female (53.2%) and 349 male (46.8%) patients, with a mean age of 51.3 ± 17.1 years (range 1–87 years). The procedures performed included 661 craniotomies for tumor removal (88.6%) and 85 endoscopic endonasal tumor resections (11.4%). The most frequent tumors were meningiomas (28.6%) and glioblastomas (24.1%), followed by pituitary adenomas (8.4%), anaplastic astrocytomas (8.0%), low-grade gliomas (7.2%), and metastases (6.2%). Demographic, histological, and surgical data are summarized in Table 1.

The mortality rate in this series was 0.94% (7 patients died). Overall, 523 patients (70.1%) had improved or unchanged KPS scores at discharge after surgery in comparison to preoperative period. As shown in Table 2, complications of any kind were recorded in 311 patients (41.7%): of these, 68 were major (9.1% of all procedures) and 243 were minor (32.6% of all procedures). When classified on the basis of the treatment they required (according to the Landriel Ibañez classification [18]), these 311 complications were distributed as follows (Table 3): 216 grade I complications not requiring invasive treatment (69.5% of all complications); 69 grade II complications requiring invasive treatment (22.2%); 19 grade III complications requiring management in an intensive care unit (6.1%); and 7 grade IV complications resulting in the patient's death (2.3%). Bearing in mind that a single complication may have more than one etiology, the most frequent ones were traumatic (53.4%), CSF-related (13.8%), and infectious (11.6%).

Proposed surgical predictors of postoperative worsening of the KPS score are presented in Table 4, and results of their logistic regression analysis in Table 5. The variable "surgery in the brain stem" was excluded from the multivariate analysis, as it was collinear with the variable "surgery in an eloquent area." The contribution of all defined surgical predictors to the model was high, and all of them were associated with increased odds of clinical worsening,

Table 1 Demographic, histological, and surgical data in our series of patients with intracranial tumors (*N* = 746)

Characteristic	Value
Sex (*N*)	
Male	349 (46.8%)
Female	397 (53.2%)
Age (years)	
Mean ± SD	51.3 ± 17.1
Range	1–87
Tumor histology (*N*)	
Meningioma	213 (28.6%)
Glioblastoma	180 (24.1%)
Pituitary adenoma	63 (8.4%)
Anaplastic astrocytoma	60 (8.0%)
Low-grade glioma	54 (7.2%)
Metastasis	46 (6.2%)
Schwannoma	35 (4.7%)
Dermoid and epidermoid cysts	21 (2.8%)
Chordoma	11 (1.5%)
Craniopharyngioma	10 (1.3%)
Other	53 (7.1%)
Type of surgery (*N*)	
Craniotomy for tumor removal	661 (88.6%)
Endoscopic endonasal tumor resection	85 (11.4%)

SD Standard deviation

Table 2 Outcomes and complications in our series of patients with intracranial tumors (*N* = 746)

Characteristic	Number of cases
Change in KPS score after surgery	
Worsened	223 (29.9%)
Improved/unchanged	523 (70.1%)
Mortality	7 (0.94%)
Neurosurgical complications	
No complications	435 (58.3%)
Complications	311 (41.7%)
Major complications	68
Minor complications	243

KPS Karnofsky Performance Scale

Table 3 Complications in our series of patients with intracranial tumors classified on the basis of the treatment they required (according to the Landriel Ibañez classification [18]) and their etiology

Characteristic	Number of cases
Total number of complications	311 (100%)
Treatment required[a]	
Grade I	216 (69.5%)
Grade Ia	120
Grade Ib	96
Grade II	69 (22.2%)
Grade IIa	19
Grade IIb	50
Grade III	19 (6.1%)
Grade IIIa	16
Grade IIIb	3
Grade IV	7 (2.3%)
Etiological categories[b]	
Traumatic	166 (53.4%)
CSF related	43 (13.8%)
Infectious (septic)	36 (11.6%)
Ischemic	26 (8.4%)
Hemorrhagic	20 (6.4%)
General (extra-CNS) medical complications	19 (6.1%)
Epilepsy	12 (3.9%)
Other	7 (2.3%)

CNS Central nervous system, *CSF* Cerebrospinal fluid

[a]Treatment required according to the Landriel Ibañez classification [18]: *grade I*: any non-life-threatening deviation from the normal postoperative course but not requiring invasive treatment (*grade Ia*: complication requiring no drug treatment; *grade Ib*: complication requiring drug treatment); *grade II*: complication requiring invasive treatment such as surgical, endoscopic, or endovascular intervention (*grade IIa*: complication requiring intervention without general anesthesia; *grade IIb*: complication requiring intervention with general anesthesia); *grade III*: life-threatening complication requiring management in an intensive care unit (*grade IIIa*: complication involving single organ failure; *grade IIIb*: complication involving multiple organ failure); and *grade IV*: complication resulting in death

[b]When assessed on the basis of their etiological categories, the numbers of complications were higher than those based on the Landriel Ibañez classification [18] because a complication may have multiple etiologies

whereas "patient age" did not reach the level of statistical significance. The −2 log likelihood difference of the goodness of fit between the final and baseline models was large and significant (χ^2 = 167.8; degrees of freedom = 7; $P < 0.001$). The final model demonstrated a moderate goodness of fit (Nagelkerke pseudo-R^2 = 0.286).

Thereby, the MCS was built out by rating each statistically significant independent predictive factor on the basis of its OR. Initially, a grading scale was obtained, with scores ranging between 0 and 16, but for simplification we decided to reduce it to a 0–8 range, while maintaining the same ratio between predictive scores (Table 6). Higher scores indicated more complex clinical situations in cases of intracranial tumor resection. Evaluation with ANOVA showed that the worsened subgroup had a significantly higher mean total MCS score than the improved/unchanged subgroup (3.24 ± 1.55 versus 1.47 ± 1.58; $P < 0.001$).

Table 4 Descriptive data on surgical predictors of postoperative outcome in our series of patients with intracranial tumors (N = 746)

Characteristic	Number of cases
Tumor size	
0–4 cm	521 (69.8%)
>4 cm	225 (30.2%)
Surgery in an eloquent area	
No	490 (65.7%)
Yes, in an eloquent area	216 (29.0%)
Yes, in the brain stem	40 (5.4%)
Surgery in the posterior fossa	
Yes	137 (18.4%)
No	609 (81.6%)
Major brain vessel manipulation	
Yes	92 (12.3%)
No	654 (87.7%)
Cranial nerve manipulation	
Yes	135 (18.1%)
No	611 (81.9%)

In this series, GTR, STR, and PR of the tumor were carried out in 569 (76.3%), 127 (17.0%), and 50 (6.7%) cases, respectively; therefore, 93.3% of the patients had more than 90% of their mass lesion removed. The mean MCS scores were 1.80 ± 1.67 for GTR, 2.63 ± 1.91 for STR, and 2.72 ± 1.98 for PR, and according to ANOVA these differences were statistically significant ($P < 0.001$). In addition, *post hoc* analysis with applied Bonferroni correction showed that patients with GTR had lower total MCS scores than those with STR/PR, whereas the scores of patients with STR or PR did not differ significantly from each other (data not shown). When subsamples of patients with GTR and STR/PR were analyzed separately, the results also showed good performance of the MCS. Among patients with GTR, the worsened subgroup had a significantly higher mean total MCS score than the improved/unchanged subgroup (2.99 ± 1.42 versus 1.38 ± 1.54; $P < 0.001$). In concordance, among patients with STR/PR, the worsened subgroup had a significantly higher mean total MCS score than the improved/unchanged subgroup (3.72 ± 1.70 versus 1.85 ± 1.68; $P < 0.001$).

When subsamples of patients with gliomas (n = 294) and meningiomas (n = 213) were analyzed separately, the results also showed good performance of the MCS. Among glioma cases, the worsened subgroup had a significantly higher mean total MCS score than the improved/unchanged subgroup (3.17 ± 1.54 versus 1.67 ± 1.60; $P < 0.001$). Similarly, among meningioma cases, the worsened subgroup had a significantly higher mean total MCS score than the improved/unchanged subgroup (3.39 ± 1.77 versus 1.30 ± 1.60; $P < 0.001$).

Table 5 Results of logistic regression analysis for worsening of the Karnofsky Performance Scale score after intracranial tumor removal

Predictive factors	B (SE)	OR (95% CI)	*P* value
Constant	−2.88 (0.40)	–	<0.001
Surgery in an eloquent area (including the brain stem)			
No (reference)	–	–	–
Yes	1.93 (0.20)	6.71 (4.65–10.28)	<0.001
Major brain vessel manipulation			
No (reference)	–	–	–
Yes	0.53 (0.26)	1.69 (1.02–2.83)	0.042
Cranial nerve manipulation			
No (reference)	–	–	–
Yes	1.47 (0.25)	4.34 (2.62–7.17)	<0.001
Tumor size			
0–4 cm (reference)	–	–	–
>4 cm	0.67 (0.20)	1.95 (1.33–2.86)	0.001
Age			
0–44 years (reference)	–	–	–
45–64 years	−0.15 (0.22)	0.86 (0.56–1.32)	0.490
≥65 years	0.11 (0.23)	1.12 (0.71–1.76)	0.626
Surgery in the posterior fossa			
No (reference)	–	–	–
Yes	0.70 (0.24)	2.02 (1.26–3.24)	0.007

Model based on intercept only: −2 log likelihood = 358.7; final model: −2 log likelihood = 190.9; $\chi^2 = 167.8$, degrees of freedom = 7; $P < 0.001$; Nagelkerke pseudo-$R^2 = 0.286$

B Logistic regression coefficient, *CI* Confidence interval, *OR* Odds ratio, *SE* Standard error

Table 6 The Milan Complexity Scale for intracranial tumor surgery

Variable	Score
Major brain vessel manipulation[a]	
No	0
Yes	1
Surgery in the posterior fossa	
No	0
Yes	1
Cranial nerve manipulation	
No	0
Yes	2
Surgery in an eloquent area[b]	
No	0
Yes	3
Tumor size	
0–4 cm	0
>4 cm	1
Total score	0–8

[a]*Major arteries*: internal carotid artery, anterior cerebral artery, middle cerebral artery, anterior communicating artery, posterior communicating artery, anterior choroidal artery, ophthalmic artery, vertebral artery, basilar artery, posterior inferior cerebellar artery, anterior inferior cerebellar artery, superior cerebellar artery, and posterior cerebral artery; *major veins*: superior sagittal sinus, transverse sinus, sigmoid sinus, internal cerebral veins, the vein of Galen, the vein of Labbé, and the vein of Trolard

[b]Motor, sensory, language, or visual cortical areas; hypothalamus; thalamus; internal capsule; brain stem; and pineal region

Finally, a grid showing RR of clinical worsening after surgery for each total MCS score value was developed. Scores higher than 6 were merged because of small number of cases (< 10) in each corresponding subgroup. As shown in Table 7, scores of 0 and 1 were indicative of a significantly lower risk of postoperative worsening: therefore, such patients were likely to improve or at least be stable after surgery. Conversely, scores of 3 and higher were suggestive of an increased risk of postoperative worsening.

Table 7 Relative risk analysis in our series of patients with intracranial tumors ($N = 746$)

MCS score	Number of cases	Incidence of the postoperative worsening of the KPS score	OR (95% CI)
0	224	7.6%	0.13 (0.08–0.21)
1	129	13.9%	0.33 (0.19–0.55)
2	59	20.3%	0.58 (0.30–1.24)
3	169	44.4%	2.31 (1.62–3.30)
4	116	58.6%	4.31 (2.88–6.55)
5	29	72.4%	6.69 (2.92–15.35)
6–8	20	60%	3.66 (1.47–9.08)

CI Confidence interval, *KPS* Karnofsky Performance Scale, *MCS* Milan Complexity Scale for intracranial tumor surgery, *OR* Odds ratio

Illustrative Cases

Case 1—Clival Chordoma, MCS Score 6

A 37-year-old woman came to our attention because she had the trochlear nerve palsy, dysphagia, a gait imbal-

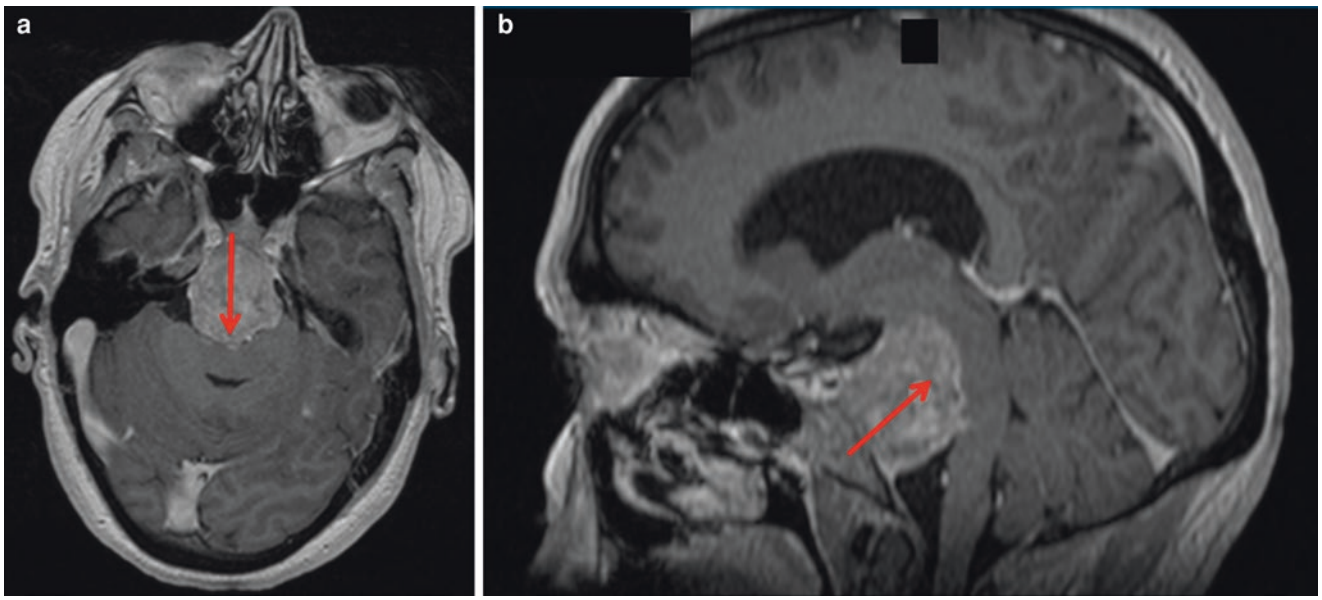

Fig. 1 Preoperative axial (**a**) and sagittal (**b**) postcontrast volumetric T1-weighted magnetic resonance imaging in a 37-year-old woman with a clival chordoma. Prominent brain stem compression was evident (*arrowed*). The Milan Complexity Scale score was 6, comprising 3 points for surgery in an eloquent area (the brain stem), 2 points for manipulation of multiple cranial nerves (III, IV, V, and VII–VIII), and 1 point for surgery in the posterior fossa

ance, and left inferior limb weakness. Her KPS score was 70. Preoperative brain MRI showed a 3 × 3 × 3.5-cm mass lesion arising from the clivus and extending posteriorly and superiorly, causing brain stem compression and secondary hydrocephalus (Fig. 1). Her MCS score was 6, comprising 3 points for surgery in an eloquent area, 2 points for cranial nerve manipulation, 1 point for surgery in the posterior fossa, 0 points for no major brain vessel manipulation, and 0 points for a tumor size ≤4 cm. She underwent GTR (histopathological examination confirmed clinical diagnosis of chordoma) followed by proton beam therapy. All of her symptoms improved except for dysphagia, which worsened slightly, requiring a temporary tracheostomy. At discharge, her KPS score was 60.

Case 2— Hypothalamic Pilocytic Astrocytoma, MCS Score 7

A 6-year-old boy was referred to our institution because of a 2-month history of headache, vomiting, poor appetite, weight loss (of at least 4 kg), global weakness, and decreased left visual acuity. Funduscopic examination revealed bilateral papilledema. His KPS score was 80. CT and MRI showed a 4.5 × 3-cm tumor in the chiasmatic–hypothalamic region, which completely occupied the third ventricle and extended into the left carotid cistern (Fig. 2). The MCS score was 7, comprising 3 points for surgery in an eloquent area, 1 point for a tumor size >4 cm, 2 points for cranial nerve manipulation, 1 point for major brain vessel manipulation, and 0 points for no surgery in the posterior fossa. STR was then performed via a subfrontal interhemispheric approach (histopathological examination revealed a pilocytic astrocytoma). The postoperative course was uneventful, and the patient's KPS score at discharge was 80.

Case 3—Left Rolandic Glioblastoma, MCS Score 3

A 77-year-old man was referred to our center because he had a left Rolandic mass causing slight speech impairment and right upper limb weakness. His KPS score was 80. Preoperative brain MRI with intravenous contrast administration showed a 3 × 3.5 × 2.5-cm lesion (Fig. 3). His MCS score was 3, comprising 3 points for surgery in an eloquent area, 0 points for no major brain vessel or cranial nerve manipulation, 0 points for no surgery in the posterior fossa, and 0 points for a tumor size ≤4 cm. He successfully underwent GTR (histopathological examination revealed glioblastoma multiforme) with intraoperative motor function monitoring and was discharged home with improvement of his preoperative neurological deficits and a KPS score of 90.

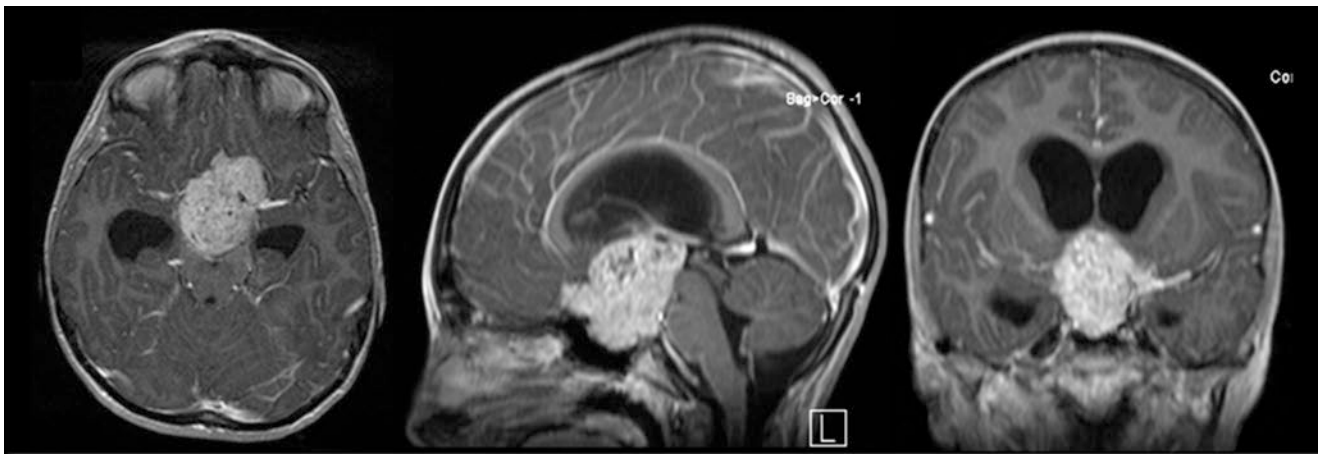

Fig. 2 Preoperative axial (*left*), sagittal (*middle*), and coronal (*right*) postcontrast volumetric T1-weighted magnetic resonance imaging in a 6-year-old boy with a hypothalamic pilocytic astrocytoma. The tumor arose from the optic chiasm and extended into the third ventricle; secondary hydrocephalus and mild midbrain compression were present. The Milan Complexity Scale score was 7, comprising 3 points for surgery in an eloquent area (the hypothalamus), 1 point for a tumor size >4 cm, 2 points for cranial (optic) nerve manipulation, and 1 point for major brain vessel (internal carotid, middle cerebral, and anterior communicating arteries) manipulation

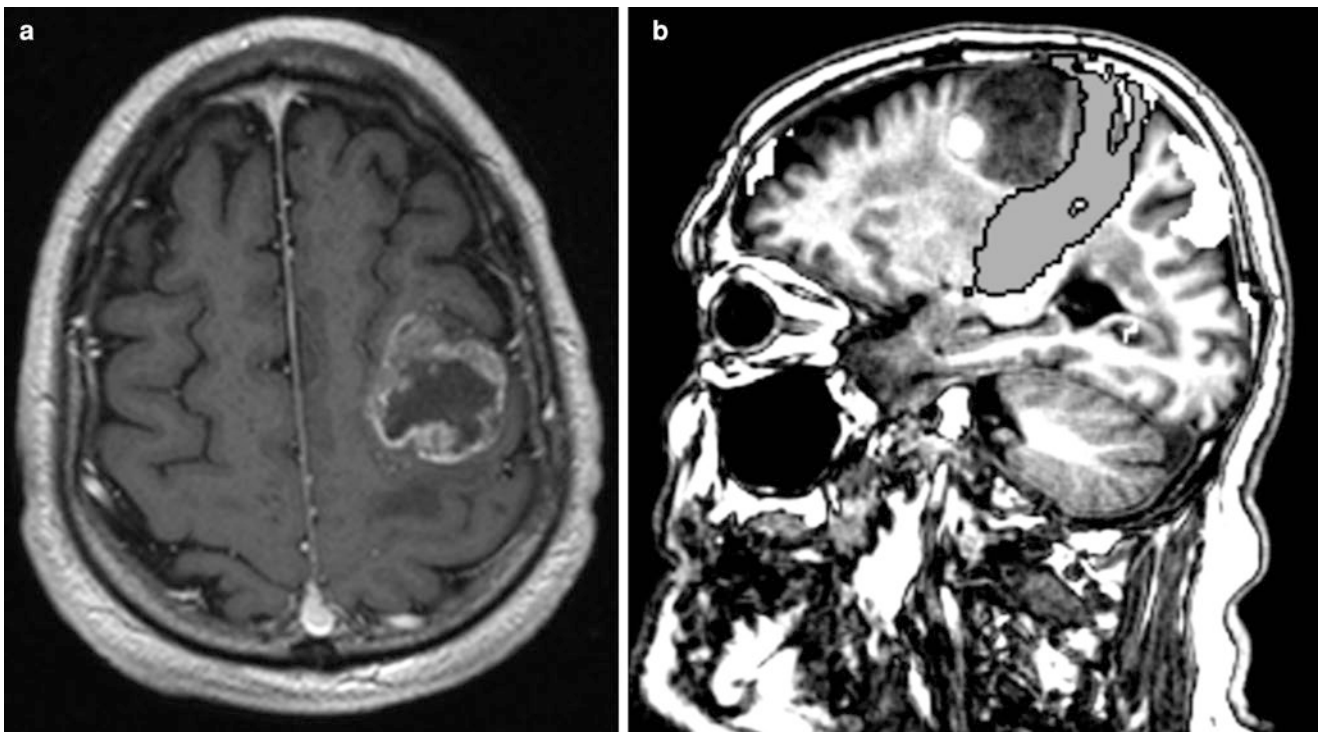

Fig. 3 Preoperative axial postcontrast T1-weighted magnetic resonance imaging (**a**) and sagittal tractography imaging (**b**) in a 77-year-old man with a left Rolandic glioblastoma. There was a close contact between the corticospinal tract (*in gray*) and the tumor. The Milan Complexity Scale score was 3, comprising 3 points for surgery in an eloquent area (the motor cortex and adjacent corticospinal tract)

Discussion

The issue of how to characterize negative results of surgical interventions has been a matter of debate for years in general surgery and more recently also in the neurosurgical field [4, 18, 27, 28]. More than 30 years ago, general surgeons defined a complication as any morbid event occurring "as a result of the procedure, during the performance or recovery from the procedure, which causes deviations from the ideal course and tends to impair or delay complete recovery and induces changes in the management of the patient" [13]. In neurosur-

gery, the issue of what a complication is and how it should be classified is being discussed as well [5, 7, 18, 29, 30], but, to date, no uniform definition of such an unfavorable event has been accepted by the entire professional community.

In this study, following the valuable work of other groups [17, 18], we proposed a simple and clear definition of a neurosurgical complication—that is, any deviation from the ideal postoperative course occurring within 30 days of the procedure. Usually, it is inherent in the intervention (but not necessarily) and impairs the patient's functional status (but not necessarily). Finally, a complication is considered transient if it is totally or partially (but significantly) resolved within 30 days of the surgery, and permanent if it is still present thereafter.

Review of postoperative complications on the basis of the treatment they require and their etiology are important for data analysis. Herein, we took advantage of two different classification systems: the Landriel Ibañez classification [18] (derived from the Clavien–Dindo general surgery grading [14]) and our own etiological classification [1]. The former, a treatment-oriented score system, is easy to apply and correlates well with outcomes; however, it does not predict the long-term prognosis of neurosurgical patients precisely [25], since does not account for new or aggravated neurological deficits, that may be disabling, while not immediately life-threatening, and cannot be treated [17]. The etiological classification, on the other hand, allows identification of weak points of neurosurgical procedures that require maximal consideration to improve outcomes [25].

After an accepted definition is adopted, postoperative complications should be rigorously collected and classified at each neurosurgical center, which is critically important for quality measurement and outcome assessment. However, these tasks are quite challenging and require consideration of several factors. It has been demonstrated, for example, that both a hospital's case volume and a surgeon's case volume have impacts on outcomes across a variety of subspecialties, including neurosurgery. The relationships of these parameters to mortality and neurological deficits after biopsy or resection of primary brain tumors have been shown [1], but mere complication rates and case volumes can, nonetheless, be misleading. There are clinical situations in which a neurological deficit (at least, temporary) caused by surgical trauma is, in fact, somehow unavoidable (as it is often seen in surgery of the spinal cord, the brain stem, deep brain regions, the skull base, motor and language cortex, etc.), and only if the procedure is executed perfectly might the related morbidity be merely slight and resolve within a short time. For this reason, high-volume centers, where various kinds of highly challenging surgeries are usually performed, are exposed to the paradox of having the highest complication rates overall [4]. Therefore, although diagnosis-related group (DRG) records and case volume data are certainly important, they cannot be the only characteristics considered.

The idea that multiple factors contribute to the treatment quality and outcomes is not new; actually, those same general surgeons who first focused on surgical complications brought up another pivotal concept—surgical complexity, an integrated clinical parameter mainly predetermined by a number of preoperative conditions which plays a big role in the risk of incurring postoperative complications and unfavorable results. Indeed, to assess preoperative risk factors in individual cases, a scale taking into account the patient's age and concomitant morbidities has been proposed by Clavien et al. [13] long time ago, and several variations of this classification have since been suggested by different authors [16, 31–33].

We strongly believe that standardized definition of objective criteria for quality measurement and outcome assessment, including preoperative conditions, the postoperative worsening rate, the complication rate, and the surgical case complexity, should be among the top priorities of today's neurosurgeons. With this notion in mind, the presented study has proposed a new scale designed for preoperative assessment of the complexity in intracranial tumor surgery. The MCS is aimed at providing a score that addresses the comparative complexity of neurosurgical procedures and is able to translate that feeling of complexity that surgeons experience while evaluating the relationships between the tumor and surrounding structures on radiological images, which is somewhat comparable to the feeling of complexity that a climber experiences when looking at a mountainside and wants to transmit his or her considerations to other climbers. However, although experienced neurosurgeons are able to feel the complexity of a resection while looking at a patient's tumor on imaging, a common objective language to share this feeling with other colleagues is still lacking. If one could rely on a universally accepted predictive score, this could have implications for training and the resourcing required for both safe climbing and highly effective neurosurgery.

Sagberg et al. [34] clearly demonstrated how assessments of operability, risks, and complications are highly subjective, and surgeons seem to be overly optimistic about their expected results. The MCS is able to objectively estimate the risk of an unfavorable clinical course after intracranial tumor surgery, defined as a worsening of the general health status assessed by means of KPS at discharge. The MCS is composed of five items (the "Big Five" [1]): major brain vessel manipulation, surgery in the posterior fossa, cranial nerve manipulation, surgery in an eloquent area, and a tumor size >4 cm. The total score can range between 0 and 8, and it values of 3 and higher are indicative of an increased risk of postoperative worsening. The MCS offers several specific advantages: it is easy to use, practical, intuitive, and quick. Therefore, its application may be quite effective in predicting the safety and outcome of neurosurgical procedures,

thereby enabling appropriate adjustment of anticipating risk in quality measurement programs for intracranial tumor management. Moreover, it allows the neurosurgeon to better inform patients on the basis of their preoperative clinical conditions about the likelihood that their general health status will improve, worsen, or be stable after surgery.

If the prognostic value of MCS and related "Big Five" is also confirmed by other researchers, the implications for education and training, resource allocation, and ethical and legal issues will become evident. As far as neurosurgical education and training are concerned, it is obvious that the tumor case complexity should be graded in order to plan the learning curve of a surgical trainee in a progressive "crescendo" in which sudden jumps from treating simple lesions to treating highly difficult cases should be avoided [35]. In terms of resource allocation, it should be clear to administrators that by measuring case complexity in terms of the likelihood of postoperative deterioration, they will be able to grade surgical centers on the basis of both case complexity and patient outcomes. This new integrative indicator might contribute to creation of a meritocratic system in which the best centers receive more attention and resources. Regarding ethical and legal issues, it is well recognized that intracranial tumors are a variety of different diseases with an extremely wide range of treatment complexity and possible outcomes. The MCS could allow the patient to understand, in advance of intervention, which clinical factors could influence the postoperative outcome in his or her specific case and therefore to make more conscious and informed decisions with the surgeon. Certainly, grading systems with the ability to predict postoperative clinical outcomes have been proposed previously as well. For example, Chelazzi et al. [36] created a score to predict the occurrence of postoperative complications in general surgery, and similar to us they aimed to identify high-risk surgical candidates through a simple, economical, and objective system. Lawton et al. [37] suggested grading to predict neurological outcomes after surgery for brain AVM, with the goals of improving and refining patient selection. To our knowledge, however, similar works are lacking in neuro-oncological surgery, and the MCS is the first system created *ad hoc*.

The overall complication rate in the present series was fairly high (41.7%) and roughly 30% of patients demonstrated decrease in KPS scores at discharge after surgery in comparison to preoperative period. It should be emphasized, however, that most of the postoperative KPS score decreases in our patients were transient, with the majority of complications being minor and requiring no invasive treatment (i.e., of grade I according the Landriel Ibañez classification [18]). Indeed, high postoperative morbidity was somewhat expected, as 34.3% of tumors were located in eloquent areas and the aim at our institution is to pursue complete mass lesion removal whenever possible, following the maximal safe resection concept [20, 38, 39]. The fact that surgical manipulation of eloquent neuronal structures was by far the biggest cause of complications was no surprise. All our patients were operated on with the aid of advanced diagnostic and surgical technologies, including functional MRI, tractography, intraoperative neurophysiological monitoring, and brain mapping during awake craniotomy [15], which allowed us to push the resection very close to the boundaries of the eloquent tissue, but which often entailed temporary worsening of neurological functions.

The present study had some major limitations. First, the MCS was built using retrospective data; therefore, it needs to be validated in a new cohort of patients with intracranial tumors in order to prospectively assess its efficacy. It also has to be acknowledged that the approach to treatment was maximal safe resection of the lesion, and whether more aggressive surgical strategies might yield a similar predictive value of the MCS should be investigated as well. Second, caution is needed when generalizing our results, since presented clinical series was based on patients attending a tertiary referral center, where it is highly likely that the surgical cases are representative of more severe clinical situations. We definitely recognize that our methodology, grading scale, and patient registry may still be imperfect and are somewhat rudimentary, but hope that suggested MCS can serve as preliminary tool for quality measurement and outcome assessment in neurosurgery [3].

Further research should be conducted, incorporating more institutions and taking into account other factors that could influence postoperative outcomes—e.g., surgical techniques and neurosurgeons' experience, as well as nonneurological comorbidities that might affect clinical decisions regarding operability and impact the overall results of treatment. Moreover, future studies should also consider permanent functional impairment—i.e., the patients' general health status on the long-term follow-up after surgery.

Finally, all significant data—demographics, preoperative conditions and comorbidities, objectively assessed surgical complexity, complication occurrence rates and types, and outcome parameters—should be collected together into a precise and standardized patient registry. In fact, we recommend creation of such a dedicated comprehensive patient registry at every neurosurgical center. Our dream is the establishment of a national or even an international archive to develop a common network focused on quality measurement and outcome assessment in neurosurgery.

Conclusion

A clear and simple definition of a neurosurgical complication is proposed, which is "any deviation from the ideal postoperative course occurring within 30 days of the procedure." Through evaluation of five parameters (major brain

vessel manipulation, surgery in the posterior fossa, cranial nerve manipulation, surgery in an eloquent area, tumor size >4 cm), the MCS allows preoperative assessment of the surgical complexity and estimation of the risk of clinical worsening after resection of intracranial tumor. All neurosurgical centers should collect their data on surgical complexity, complication occurrence, and outcomes using prospectively compiled standardized patient registries. We expect that in the future, such registries will prove useful in various different ways: for clinical purposes (to predict the quality of surgery in terms of safety and outcome), for research purposes (to compare the quality of treatment provided by different centers), for educational purposes (to direct residents and fellows to high-quality centers), and, finally, for better health system organization (i.e., for use in quality measurement programs for intracranial tumor management and corresponding resource allocation).

Acknowledgments The authors thank the IEN Foundation for its support of this study.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Ferroli P, Broggi M, Schiavolin S, Acerbi F, Bettamio V, Caldiroli D, Cusin A, La Corte E, Leonardi M, Raggi A, Schiariti M, Visintini S, Franzini A, Broggi G. Predicting functional impairment in brain tumor surgery: the Big Five and the Milan Complexity Scale. Neurosurg Focus. 2015;39(6):E14.
2. Dindo D, Clavien PA. Quality assessment in surgery: mission impossible? Patient Saf Surg. 2010;4:18.
3. Broggi M, Zattra C, Ferroli P. How to compare outcomes and complications in neurosurgery: we must make the mission possible! Surg Neurol Int. 2018;9:65.
4. Ferroli P, Caldiroli D, Leonardi M, Broggi M. Complications in neurosurgery: the need for a common language [letter]. J Neurosurg. 2015;122:983–4.
5. Bonsanto MM, Hamer J, Tronnier V, Kunze S. A complication conference for internal quality control at the Neurosurgical Department of the University of Heidelberg. Acta Neurochir Suppl. 2001;78:139–45.
6. Brennum J, Gjerris F. Morbidity & mortality conferences—how can we do it? Acta Neurochir Suppl. 2004;90:67–71.
7. Houkin K, Baba T, Minamida Y, Nonaka T, Koyanagi I, Iiboshi S. Quantitative analysis of adverse events in neurosurgery. Neurosurgery. 2009;65:587–94.
8. Lebude B, Yadla S, Albert T, Anderson DG, Harrop JS, Hilibrand A, Maltenfort M, Sharan A, Vaccaro AR, Ratliff JK. Defining "complications" in spine surgery: neurosurgery and orthopedic spine surgeons' survey. J Spinal Disord Tech. 2010;23:493–500.
9. Pollock JR, Hayward RD. Adverse operative events in neurosurgical training: incidence, trends and proposals for prevention. Br J Neurosurg. 2001;15:312–8.
10. Rampersaud YR, Moro ER, Neary MA, White K, Lewis SJ, Massicotte EM, Fehlings MG. Intraoperative adverse events and related postoperative complications in spine surgery: implications for enhancing patient safety founded on evidence-based protocols. Spine (Phila Pa 1976). 2006;31:1503–10.
11. Veen MR, Lardenoye JWHP, Kastelein GW, Breslau PJ. Recording and classification of complications in a surgical practice. Eur J Surg. 1999;165:421–5.
12. Apuzzo MLJ. Brain surgery: complication avoidance and management. New York: Churchill-Livingstone; 1992.
13. Clavien PA, Sanabria JR, Strasberg SM. Proposed classification of complications of surgery with examples of utility in cholecystectomy. Surgery. 1992;111:518–26.
14. Clavien PA, Barkun J, de Oliveira ML, Vauthey JN, Dindo D, Schulick RD, de Santibañes E, Pekolj J, Slankamenac K, Bassi C, Graf R, Vonlanthen R, Padbury R, Cameron JL, Makuuchi M. The Clavien–Dindo classification of surgical complications: five-year experience. Ann Surg. 2009;250:187–96.
15. Cordella R, Acerbi F, Broggi M, Vailati D, Nazzi V, Schiariti M, Tringali G, Ferroli P, Franzini A, Broggi G. Intraoperative neurophysiological monitoring of the cortico-spinal tract in image-guided mini-invasive neurosurgery. Clin Neurophysiol. 2013;124:1244–54.
16. Dindo D, Demartines N, Clavien PA. Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. Ann Surg. 2004;240:205–13.
17. Sarnthein J, Stieglitz L, Clavien PA, Regli L. A patient registry to improve patient safety: recording general neurosurgery complications. PLoS One. 2016;11(9):e0163154.
18. Landriel Ibañez FA, Hem S, Ajler P, Vecchi E, Ciraolo C, Baccanelli M, Tramontano R, Knezevich F, Carrizo A. A new classification of complications in neurosurgery. World Neurosurg. 2011;75:709–15.
19. Spetzler RF, Martin NA. A proposed grading system for arteriovenous malformations. J Neurosurg. 1986;65:476–83.
20. Almeida JP, Chaichana KL, Rincon-Torroella J, Quinones-Hinojosa A. The value of extent of resection of glioblastomas: clinical evidence and current approach. Curr Neurol Neurosci Rep. 2015;15(2):517.
21. Duffau H. Resecting diffuse low-grade gliomas to the boundaries of brain functions: a new concept in surgical neuro-oncology. J Neurosurg Sci. 2015;59:361–71.
22. Lee MH, Kim SH, Seoul HJ, Nam DH, Lee JI, Park K, Kim JH, Kong DS. Impact of maximal safe resection on the clinical outcome of adults with craniopharyngiomas. J Clin Neurosci. 2012;19:1005–8.
23. Martino J, Gomez E, Bilbao JL, Dueñas JC, Vázquez-Barquero A. Cost-utility of maximal safe resection of WHO grade II gliomas within eloquent areas. Acta Neurochir (Wien). 2013;155:41–50.
24. Uzuka T, Aoki H, Natsumeda M, Takahashi H, Fujii Y. Effectiveness of maximal safe resection for glioblastoma including elderly and low Karnofsky performance status patients: retrospective review at a single institute. Neurol Med Chir (Tokyo). 2012;52:570–6.
25. Ferroli P, Brock S, Leonardi M, Schiavolin S, Acerbi F, Broggi M. Complications in neurosurgery: application of Landriel Ibañez classification and preliminary considerations on 1000 cases. World Neurosurg. 2014;82:e576–7.
26. Reponen E, Tuominen H, Korja M. Evidence for the use of preoperative risk assessment scores in elective cranial neurosurgery: a systematic review of the literature. Anesth Analg. 2014;119:420–32.
27. Ferroli P, Broggi M. Outcome prediction in brain tumor surgery [letter]. J Neurosurg. 2018;128:953–6.
28. Rolston JD, Han SJ, Lau CY, Berger MS, Parsa AT. Frequency and predictors of complications in neurological surgery: national trends from 2006 to 2011. J Neurosurg. 2014;120:736–45.
29. Behrens E, Schramm J, Zentner J, König R. Surgical and neurological complications in a series of 708 epilepsy surgery procedures. Neurosurgery. 1997;41:1–10.
30. Latimer K, Pendleton C, Olivi A, Cohen-Gadol AA, Brem H, Quiñones-Hinojosa A. Harvey Cushing's open and thorough docu-

mentation of surgical mishaps at the dawn of neurologic surgery. Arch Surg. 2011;146:226–32.
31. Goslings JC, Gouma DJ. What is a surgical complication? World J Surg. 2008;32(6):952.
32. Gough I. What is a surgical complication? World J Surg. 2008;32(6):950–1.
33. Woolhandler S, Ariely D, Himmelstein DU. Why pay for performance may be incompatible with quality improvement. BMJ. 2012;345:e5015.
34. Sagberg LM, Drewes C, Jakola AS, Solheim O. Accuracy of operating neurosurgeons' prediction of functional levels after intracranial tumor surgery. J Neurosurg. 2017;126:1173–80.
35. Snyderman C, Kassam A, Carrau R, Mintz A, Gardner P, Prevedello DM. Acquisition of surgical skills for endonasal skull base surgery: a training program. Laryngoscope. 2007;117:699–705.
36. Chelazzi C, Villa G, Vignale I, Falsini S, Boni L, De Gaudio AR. Implementation and preliminary validation of a new score that predicts post-operative complications. Acta Anaesthesiol Scand. 2015;59:609–18.
37. Lawton MT, Kim H, McCulloch CE, Mikhak B, Young WL. A supplementary grading scale for selecting patients with brain arterio venous malformations for surgery. Neurosurgery. 2010;66:702–13.
38. Marko NF, Weil RJ, Schroeder JL, Lang FF, Suki D, Sawaya RE. Extent of resection of glioblastoma revisited: personalized survival modeling facilitates more accurate survival prediction and supports a maximum-safe-resection approach to surgery. J Clin Oncol. 2014;32:774–82.
39. Sanai N, Polley MY, McDermott MW, Parsa AT, Berger MS. An extent of resection threshold for newly diagnosed glioblastomas. J Neurosurg. 2011;115:3–8.

Different Approaches in Skull Base Surgery Carry Risks for Different Types of Complications

Joao Paulo Almeida, Miguel Marigil-Sanchez, Claire Karekezi, Ian Witterick, and Fred Gentili

Abstract

Complications are not uncommon in the complex field of skull base surgery. The intrinsic relationship of lesions in this region to important neurovascular structures, dura mater, and bone may lead to significant morbidity and mortality. The evolution of endoscopic endonasal surgery has had a significant impact on this field as a less invasive option for treatment of selected lesions, but major morbidity may still occur; moreover, endoscopic approaches have been associated with higher rates of some specific complications, such as cerebrospinal fluid leaks. Based on a presented case report, the authors discuss the management of various complications associated with different approaches for resection of skull base malignancies, including epidural and intradural pneumocephalus, subdural hematoma, and subdural empyema. Important lessons learned by the senior author throughout more than 30 years of his skull base surgery practice are highlighted. The inherent risk of complications in skull base surgery emphasizes the importance of their avoidance, prevention, and learning from one's unfavorable experience so as not to repeat them.

Keywords

Complication · Endoscopic approaches · Neurosurgery · Pneumocephalus · Skull base surgery · Subdural empyema · Subdural hematoma

Introduction

Skull base surgery is one of the most complex fields in neurosurgery. The intrinsic relationships of pathological lesions (mostly, tumors) to the bone of the skull base, dura mater, major arteries and their perforating branches, dural sinuses, cranial nerves, and brain stem require deep knowledge of microsurgical anatomy and the surgical techniques available to achieve treatment success. The size of the tumor, encasement of major vessels, brain invasion, the age of the patient, and previous radiation therapy are all factors classically associated with higher chances of major morbidity, which may be present in 30–40% of cases [1–5].

Although surgical experience is widely accepted as a factor associated with fewer complications, they can and do happen even in the most experienced hands. While advanced imaging techniques and modern intraoperative tools—such as electrophysiological monitoring, neuronavigation, and Doppler ultrasound—have all contributed to safer intervention, skull base surgeons still face complications that may or may not have been expected or preventable. Additionally, it is not uncommon that one complication in a patient may lead to another, potentially resulting in severe morbidity with reduced quality of life (QOL) and even mortality.

In an attempt to reduce complication rates associated with some traditional skull base approaches, new techniques have been introduced into clinical practice in the last 20 years. The development of endoscopic endonasal approaches has had a significant impact in this field [6–11]. Especially useful for midline lesions, endoscopic technique allows for safe and effective resection in selected cases while avoiding manipulation of the brain parenchyma, cranial nerves, and vascular structures, such as the internal carotid artery (ICA) and its branches. Nevertheless, while they are classically considered "minimally invasive," endoscopic skull base approaches carry their own risks for complications. Endoscopic pituitary surgery is relatively straightforward in most cases, with little manipulation of the nasal cavity and skull base, whereas extended endoscopic approaches for resection of skull base

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_2

lesions, either benign or malignant, usually require resection of nasal structures and extensive drilling of the skull base. Independently of how aggressive the approach is, complications may happen, and the surgeon should be aware and have knowledge of their management.

Complications in skull base surgery may occur at any time during the perioperative period, either intra- or postoperatively (early or after some delay). They can be classified as sinonasal, vascular, neurological, endocrinological, infectious, or related to cerebrospinal fluid (CSF) leaks. Complications may also be classified as approach-related, lesion-related, or those caused by failed reconstruction of the skull base defect. It is therefore important to understand specific types of complications that are typically associated with different approaches (although any type of morbidity may certainly occur in both open and endoscopic procedures). For instance, despite the advances in reconstructive techniques in endoscopic skull base surgery, postoperative CSF leaks still remain a problem and they are more common after endoscopic procedures than after open ones; conversely, neurological deficits secondary to brain injury may be observed more often if open approaches are utilized [12].

Herein we discuss different complications associated with skull base surgery and their management. To illustrate this discussion, we present a case treated in our department that had multiple complications associated with different skull base approaches.

Case Report

A 73-year-old woman with a previous history of nasal polyps presented with a complaint of nasal obstruction and loss of smell over the previous 6 months. Computed tomography (CT) and magnetic resonance imaging (MRI) were done and demonstrated the presence of a contrast-enhancing mass lesion occupying the ethmoid cells with extension into the anterior cranial fossa, closely related to the medial wall and the roof of the left orbit (Fig. 1). An endoscopic transnasal biopsy was performed, confirming the diagnosis of an esthesioneuroblastoma. In accordance with the usual practice at our institution, the patient initially underwent neoadjuvant radiation therapy to be followed by surgical resection.

Because of concern about the close relation of the lesion to the left orbital roof and the medial orbital wall, it was felt that a combined open and endoscopic approach was needed to achieve total resection of the tumor with clear margins. A bicoronal craniotomy was done, which allowed removal of the intracranial component of the lesion, as well as resection of the lamina papyracea and dura mater margins. Then, an endoscopic endonasal approach was used to resect the residual intranasal component. At the end of the resection, frozen sections confirmed tumor-free margins. Multilayer reconstruction of the skull base was then performed with use of a pericranial flap, fascia lata graft, and fat tissue. Postoperative MRI demonstrated gross total resection of the lesion and no signs of complications (Fig. 2). The patient had an uneventful postoperative course in the hospital and was discharged one week after surgery.

Eight weeks after the initial surgery, the patient presented to the emergency department with a decreased level of consciousness. According to her husband, the patient had suffered from a cold a few days earlier, experiencing several forceful sneezing spells. The neurological examination revealed that the patient was drowsy (her Glasgow Coma Scale [GCS] score was 13), with no signs of CSF leaks or focal neurological deficits. CT demonstrated the presence of

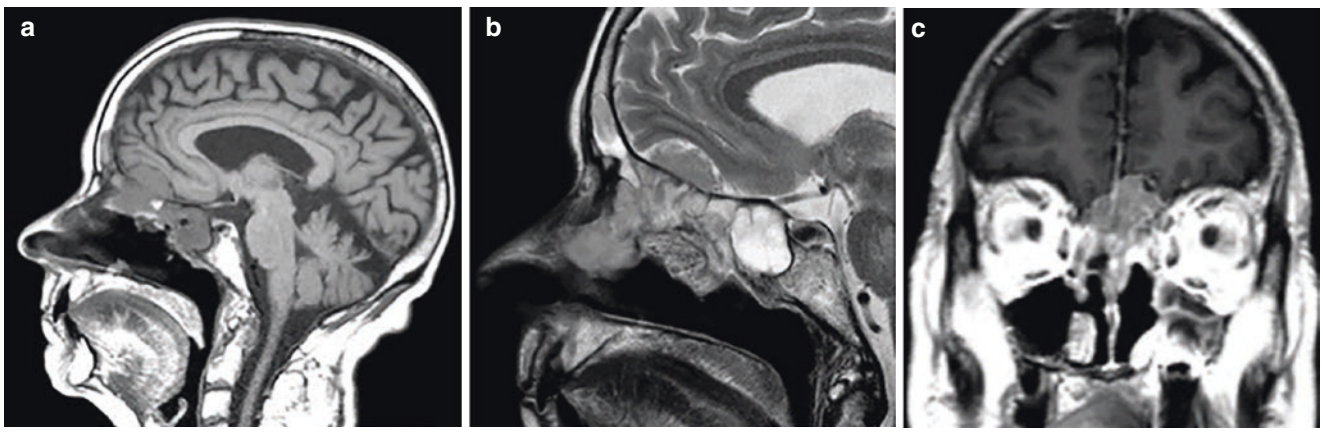

Fig. 1 Preoperative magnetic resonance imaging in sagittal (**a**, **b**) and coronal (**c**) planes shows a sinonasal lesion, which occupies the ethmoid cells with extension into the anterior cranial fossa and is closely related to the medial wall of the orbit and the orbital roof on the left side

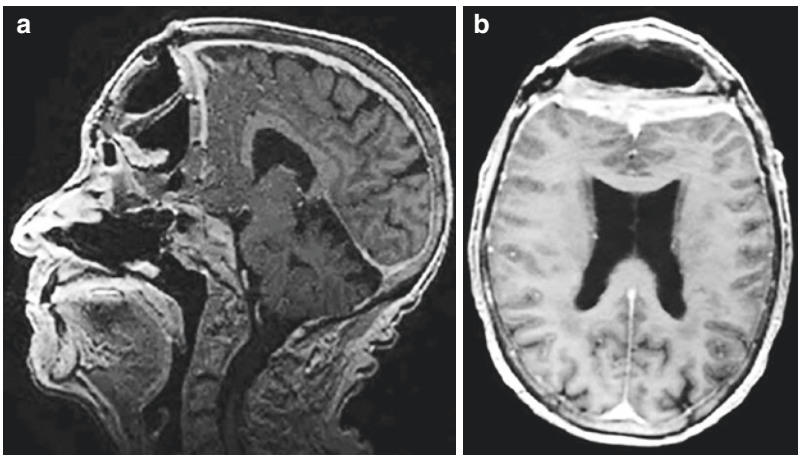

Fig. 2 Postoperative magnetic resonance imaging in sagittal (**a**) and axial (**b**) planes demonstrates gross total resection of the sinonasal tumor with intracranial extension

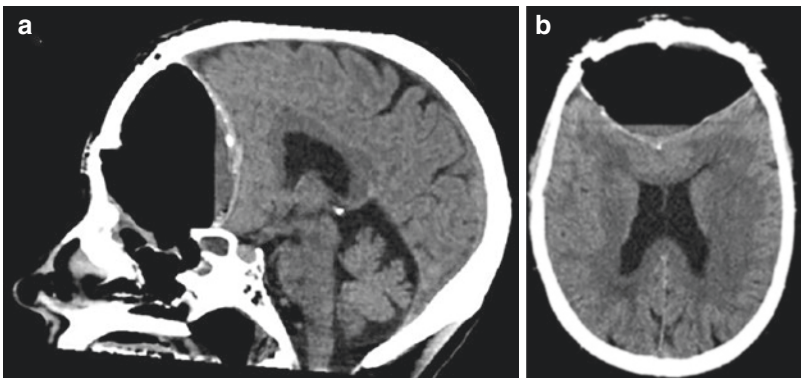

Fig. 3 Computed tomography in sagittal (**a**) and axial (**b**) planes 8 weeks after the resection of esthesioneuroblastoma demonstrates large epidural hypertensive pneumocephalus but no intradural air

a large epidural pneumocephalus but no intradural air. The imaging suggested the air was entrapped between the pericranium and the dura mater (Fig. 3). The dural defect after tumor resection had been repaired with a fascia lata graft to achieve watertight closure, and the extensive skull base defect along the anterior cranial fossa was covered with a pericranial flap. It was suspected there was an entry site (ball valve) that allowed air to get into this space during bursts of increased pressure in the sinonasal tract (e.g., sneezing). The entrapped air was then unable to escape, accumulating under increasing pressure and behaving as a space-occupying lesion, displacing and compressing the adjacent brain.

The patient underwent endonasal endoscopic exploration of the postoperative anterior skull base defect. The pericranial flap used for its reconstruction was bulging inferiorly under tension. The flap was incised, which led to instant deflation, thereby releasing the tension. Further endoscopic inspection beyond the pericranial flap allowed visualization of the previous watertight fascia lata closure of the dural defect, with no evidence of a CSF leak, and further skull base or dural reconstruction was deemed unnecessary. The patient did well postoperatively and demonstrated both clinical and radiological improvement.

The patient was then followed up with routine head MRI every 6 months and remained stable, with no evidence of the tumor recurrence. Two years after surgery, she developed progressive visual deterioration in the right eye, which was initially suspected to be secondary to recurrent disease in the orbit. MRI, however, did not demonstrate any new lesion, and the visual decline was then attributed to optic nerve vasculitis secondary to the previous radiation treatment. No intervention was recommended.

Approximately 6 months later, the patient returned to our emergency department with a headache, confusion, and a decreased level of consciousness. CT demonstrated the presence of marked intracranial tension pneumocephalus (Fig. 4). A burr hole was created and an external ventricular drain (EVD) was inserted urgently to treat the intracranial hypertension. A decision was then made to reopen the bifrontal craniotomy for repair of the presumed dural defect. During the procedure, an arachnoid outpouching with a ball valve effect on the Valsalva maneuver was observed at the base of the pericranial flap at the site of the original dural

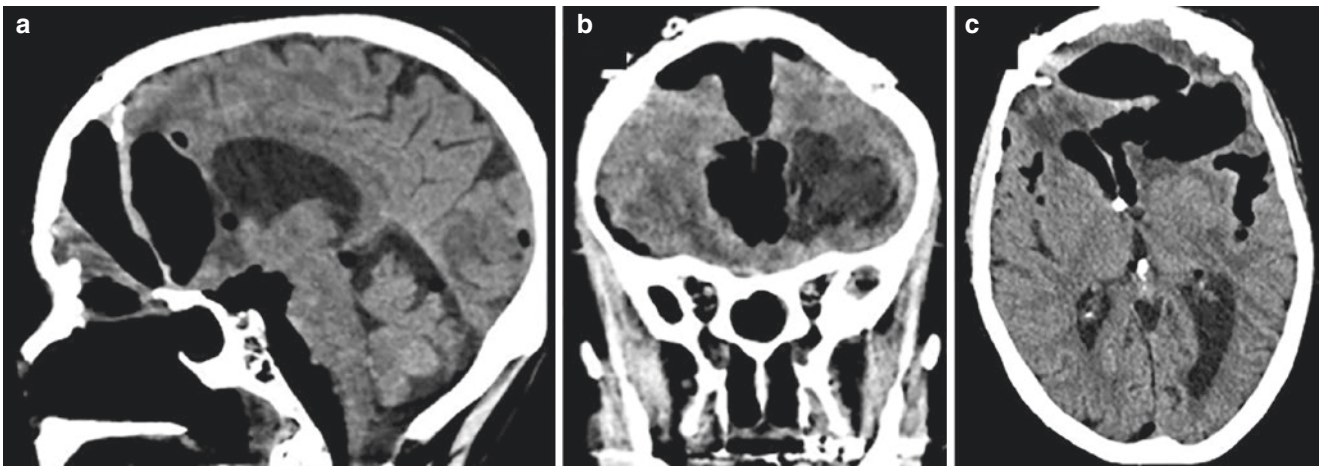

Fig. 4 Computed tomography in sagittal (**a**), coronal (**b**), and axial (**c**) planes at the time of clinical deterioration approximately 2.5 years after surgery depicts intracranial hypertensive pneumocephalus with both epidural and intradural location of air, which necessitated urgent insertion of the external ventricular drain

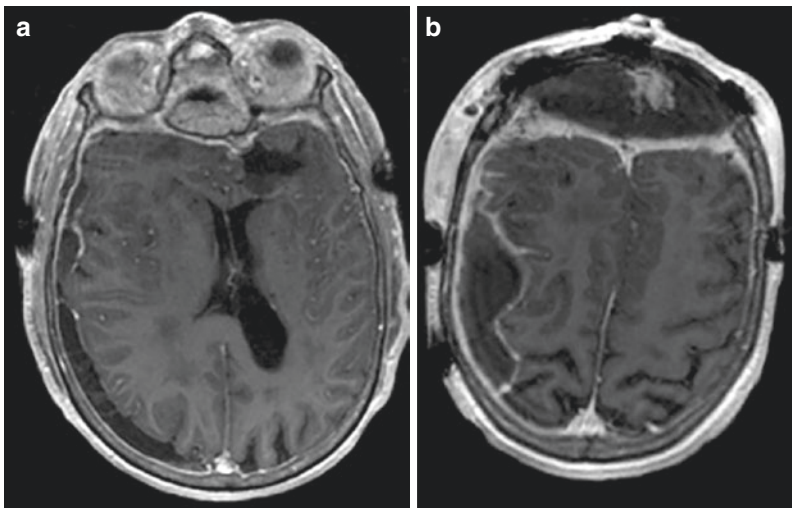

Fig. 5 Postoperative subdural collections. Magnetic resonance imaging one week after revision surgery (**a**) presumably demonstrates a right-side frontoparietal subdural hematoma, but a bit later (**b**) it is suggestive of a subdural empyema

repair. Reconstruction was then performed with use of fascia lata and fat grafting. The patient recovered well after surgery and returned to her baseline status. However, one week after the procedure, she was noted to be drowsy and found to have a new onset of left-side hemiparesis. MRI suggested the presence of a right-side frontoparietal subdural hematoma (Fig. 5a). Its burr-holes drainage was done, but only minimal clinical improvement was achieved, and the patient showed further neurological deterioration. Serial MRI demonstrated an enlargement of the fluid collection, which had now developed signs of a subdural empyema (Fig. 5b). A right-side parietal craniotomy was performed, and the infected fluid collection was successfully drained. Microbiology results confirmed the presence of *Serratia marcescens*, and the patient was then treated with a full intravenous course of an antibiotic (meropenem for 6 weeks). She had a progressive improvement in her symptoms, and, at the end of treatment, achieved a complete return to her baseline status, with no cognitive or focal motor deficit.

At the last follow-up, 3 years after diagnosis, the patient was doing well clinically, with no additional deficits, no signs of new complications, and no evidence of the tumor recurrence on MRI (Fig. 6).

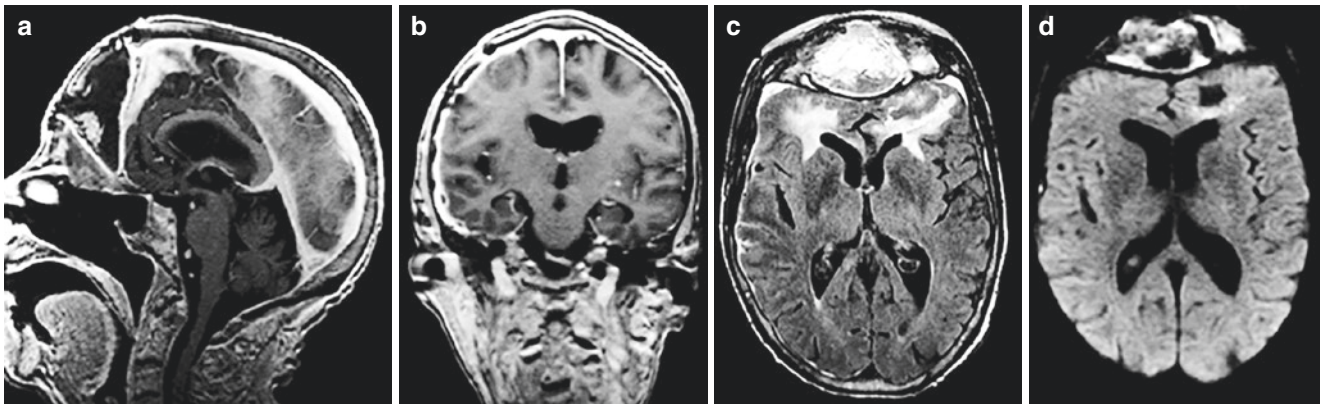

Fig. 6 Magnetic resonance imaging at the last follow-up (approximately 3 years after the diagnosis of esthesioneuroblastoma with intracranial extension) demonstrates no recurrent disease and no signs of further complications, as shown on postcontrast T1-weighted (**a**, **b**), fluid-attenuated inversion recovery (**c**), and diffusion-weighted (**d**) images

Discussion

Complications are inherent in surgical practice, especially in complex skull base procedures. While not all complications are preventable, it is important to learn from one's experience so as not to repeat them. Complications can have significant impacts on both the patient's survival and QOL, and surgical decision-making must take this into account. It is also a well-known fact that avoidance of complications is better and easier than their management.

The major determinants of success and complication avoidance in skull base surgery include selecting the proper surgical approach for the specific case, having clear objectives of the surgery, having a thorough understanding of the surgical anatomy of the approach, and using the least invasive approach that will accomplish the task. Equally important are maintaining the principles of microsurgical technique, the use of intraoperative monitoring and image guidance (where indicated), and interdisciplinary cooperation within a multidisciplinary skull base team, including neurosurgeons; ear, nose, and throat (ENT) specialists; anesthesiologists; and nurses.

The case presented herein demonstrates complications associated with open and endoscopic approaches to the anterior skull base, from which multiple lessons may be learned.

Open Skull Base Surgery

Open microsurgical resection of skull base lesions may be associated with complications secondary to contusions of the brain parenchyma, vascular injuries, and cranial nerve dysfunction. The last part of the procedure—i.e., dura mater repair and skull base reconstruction—is a crucial step to avoid major morbidity. As exemplified by the case reported here, even after careful reconstruction, complications may still occur and lead to several associated problems. At our center, to minimize the chances of complications, we routinely perform multilayer reconstruction for repair of the skull base in cases of both open and endoscopic surgeries. Biological tissues (such as fascia lata, fat, and vascularized flaps) are favored, while artificial materials (dural substitutes) are used as secondary adjuncts in selected cases. The most important tissue for reconstruction is a vascularized pericranial flap. In open bifrontal craniotomies, the dural repair should be watertight, using fascia and fat grafts followed by generous application of fibrin sealant. The harvested pericranial flap is then secured in place, covering the dural repair isolating the intracranial compartment from the aerodigestive tract.

The rate of postoperative complications after an open surgery for resection of anterior cranial fossa malignancies varies from 10% to 59% [4, 12–14]. Multiple risk factors associated with their development have been noted, including the age of the patient, the extent of disease, prior surgery, previous radiation treatment, encasement of neurovascular structures, and invasion of the brain parenchyma. Wound infection and CSF leaks are reported in 6–43% of those cases and are responsible for a significant proportion of the relatively high complication rate after open skull base surgeries [4, 12–14]. Although no CSF leak was present in the case described here, epidural tension pneumocephalus (a rare complication) did occur, as did delayed intradural tension pneumocephalus. The subdural empyema was likely related to the multiple surgical procedures and prior radiation therapy. The delayed nature of some of the complications underscores the importance of following up patients for a long term.

Endoscopic Skull Base Surgery

Endoscopic surgery has been adopted for resection of selected skull base malignancies in recent years [3, 5, 12, 13]. It follows principles similar to those of open surgery—the goal being to achieve tumor-free resection margins and effective reconstruction of the skull base. It requires proper case selection and a combined approach by a neurosurgical skull base and ENT/head and neck surgical team. Morbidity rates after endoscopic skull base surgery range from 9% to 20% [3–5, 12, 13], and complications are mainly secondary to postoperative CSF leaks. Multilayer reconstruction should be performed in order to minimize the chances of such morbidity. We routinely use fascia lata tissue (both inlay and onlay), followed by a vascularized nasoseptal flap (when available), fat, and fibrin sealant. In combined open and endoscopic approaches, a vascularized pericranial graft is also recommended and plays an important role in the skull base reconstruction.

Approach-related complications of endoscopic anterior cranial fossa surgery are not uncommon, but usually minor. These may include anosmia, epistaxis, synechiae, nasal crusting, empty nose syndrome, and chronic sinusitis. Major neurological deterioration may occasionally occur, and it is often related to vascular injury of the ICA or frontopolar and orbitofrontal arteries, which can lead to hemorrhage and ischemic brain injury.

Conclusion

Complications are inherent in neurosurgery, especially in the complex field of skull base surgery. A combination of factors—including (1) an experienced neurosurgical/skull base and ENT/head and neck surgical team; (2) careful application of microsurgical techniques via open or endoscopic approaches; and (3) adequate case selection and choosing the right surgical approach, with awareness of the risk factors for its specific complications—are necessary to minimize the chances of major morbidity associated with these interventions.

All parts of the procedure are equally important, from adequate exposure of the lesion to careful reconstruction of the skull base. While both open and endoscopic techniques are necessary to treat the variety of pathologies encountered at the skull base, with adequate training and experience (reflecting in the learning curve) and proper patient selection, endoscopic approaches have an acceptable safety profile and an important role to play in skull base surgery.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Bentz BG, Bilsky MH, Shah JP, Kraus D. Anterior skull base surgery for malignant tumors: a multivariate analysis of 27 years of experience. Head Neck. 2003;25:515–20.
2. Irish JC, Gullane PJ, Gentili F, Freeman J, Boyd JB, Brown D, Rutka J. Tumors of the skull base: outcome and survival analysis of 77 cases. Head Neck. 1994;16:3–10.
3. Krischek B, Godoy BL, Zadeh G, Gentili F. From craniofacial resection to the endonasal endoscopic approach in skull base surgery. World Neurosurg. 2013;80:56–8.
4. Raza SM, Garzon-Muvdi T, Gallia GL, Tamargo RJ. Craniofacial resection of midline anterior skull base malignancies: a reassessment of outcomes in the modern era. World Neurosurg. 2012;78:128–36.
5. Su SY, Kupferman ME, DeMonte F, Levine NB, Raza SM, Hanna EY. Endoscopic resection of sinonasal cancers. Curr Oncol Rep. 2014;16(2):369.
6. Dehdashti AR, Ganna A, Karabatsou K, Gentili F. Pure endoscopic endonasal approach for pituitary adenomas: early surgical results in 200 patients and comparison with previous microsurgical series. Neurosurgery. 2008;62:1006–17.
7. Dehdashti AR, Ganna A, Witterick I, Gentili F. Expanded endoscopic endonasal approach for anterior cranial base and suprasellar lesions: indications and limitations. Neurosurgery. 2009;64:677–89.
8. Gondim JA, Schops M, de Almeida JP, de Albuquerque LA, Gomes E, Ferraz T, Barroso FA. Endoscopic endonasal transsphenoidal surgery: surgical results of 228 pituitary adenomas treated in a pituitary center. Pituitary. 2010;13:68–77.
9. Hadad G, Bassagasteguy L, Carrau RL, Mataza JC, Kassam A, Snyderman CH, Mintz A. A novel reconstructive technique after endoscopic expanded endonasal approaches: vascular pedicle nasoseptal flap. Laryngoscope. 2006;116:1882–6.
10. Kassam AB, Gardner P, Snyderman C, Mintz A, Carrau R. Expanded endonasal approach: fully endoscopic, completely transnasal approach to the middle third of the clivus, petrous bone, middle cranial fossa, and infratemporal fossa. Neurosurg Focus. 2005;19(1):E6.
11. Kassam AB, Snyderman C, Gardner P, Carrau R, Spiro R. The expanded endonasal approach: a fully endoscopic transnasal approach and resection of the odontoid process: technical case report. Neurosurgery. 2005;57(1 Suppl Operative):E213.
12. Fu TS, Monteiro E, Witterick I, Vescan A, Zadeh G, Gentili F, de Almeida JR. Costs and perioperative outcomes associated with open versus endoscopic resection of sinonasal malignancies with skull base involvement. J Neurol Surg B Skull Base. 2017;78:430–40.
13. Bhayani MK, Yilmaz T, Sweeney A, Calzada G, Roberts DB, Levine NB, DeMonte F, Hanna EY, Kupferman ME. Sinonasal adenocarcinoma: a 16-year experience at a single institution. Head Neck. 2014;36:1490–6.
14. Patel SG, Singh B, Polluri A, Bridger PG, Cantu G, Cheesman AD, deSa GM, Donald P, Fliss D, Gullane P, Janecka I, Kamata SE, Kowalski LP, Kraus DH, Levine PA, dos Santos LR, Pradhan S, Schramm V, Snyderman C, Wei WI, Shah JP. Craniofacial surgery for malignant skull base tumors: report of an international collaborative study. Cancer. 2003;98:1179–87.

Major Internal Carotid Artery Injury During Endoscopic Skull Base Surgery: Case Report

Miguel A. Arraez, Cinta Arraez-Manrique, Bienvenido Ros, and Guillermo Ibañez

Abstract

Major vascular structures are always at risk during complex skull base surgery, particularly with use of the endoscopic endonasal approach, and intraoperative damage of the internal carotid artery (ICA) can be a devastating complication. Herein, we report a case of a young patient who had a major injury of the left ICA during endoscopic resection of a recurrent petrous bone chordoma. Massive bleeding was controlled by a Foley balloon inserted and kept in the resection area. Urgent angiography revealed a persistent leak from the petrous segment of the left ICA, and the vessel was sacrificed with coiling, since a balloon occlusion test showed good collateral blood flow. The patient woke up from anesthesia without a neurological deficit. Salvage resection of recurrent skull base neoplasms deserves specific attention because of the possibility of major vascular damage. In cases of intraoperative ICA injury, its management requires immediate decisions, and the available possibilities for endovascular therapy should always be considered.

Keywords

Carotid artery injury · Complication · Endoscopic surgery · Management · Preventive measures · Skull base surgery

Introduction

Skull base surgery has become one of the most challenging areas in neurosurgery. This constantly evolving field has undergone various changes during recent decades; the most transcendent one has been the transition from microsurgery to endoscopy. Irrespective of the great variety of operative techniques used in skull base surgery, the major vascular structures are always at risk during the procedure. In particular, the internal carotid artery (ICA), a crucial vessel, is very frequently located close to the area of the surgical approach and/or tumor resection; hence, there is an inherent risk of its intraoperative damage. Therefore, the surgeon should be deeply concerned, first, about avoidance of such a worrisome complication and, second, about it appropriate management if this is urgently required. A case of ICA injury during endoscopic skull base surgery is presented herein, along with considerations regarding possible preventive measures and treatment options.

Case Report

A 20-year-old woman underwent partial removal of a clival chordoma through the transmaxillary approach at the age of 14 years (Fig. 1), which was followed by second-stage resection of the tumor remnants via the right-side far lateral approach and a subsequent treatment with stereotactic radiosurgery. She remained asymptomatic for 6 years after the first surgery until recurrence of the neoplasm, affecting the lateral skull base on the left side, was disclosed on magnetic resonance imaging (MRI; Fig. 2). Surgery was done using the endoscopic transpterygoid approach to access the lateral nasopharynx and petrous region. The parapharyngeal component of the lesion was initially removed rather easily, and resection of the tumor in the petrous apex region was then started. The petrous bone was widely infiltrated

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_3

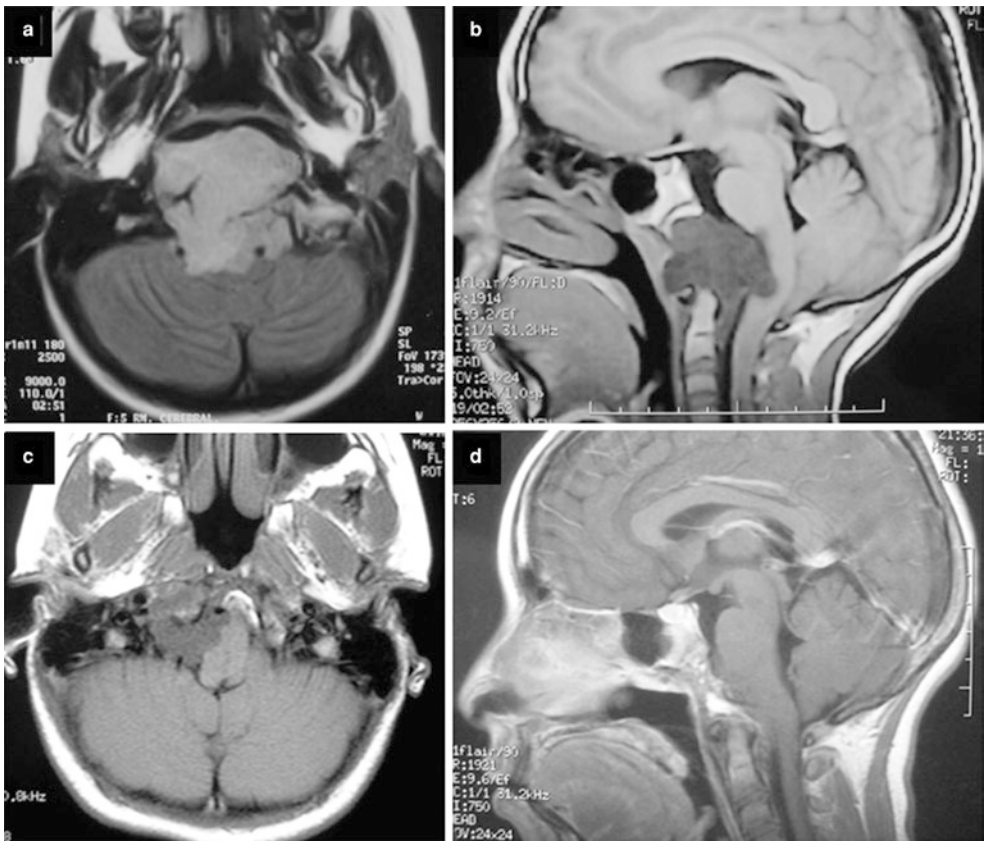

Fig. 1 Magnetic resonance imaging in a patient before (**a**, **b**) and after (**c**, **d**) partial removal of a clival chordoma through the transmaxillary approach at the age of 14 years. Subsequently, second-stage tumor resection using the right-side far lateral approach was achieved, followed by stereotactic radiosurgery

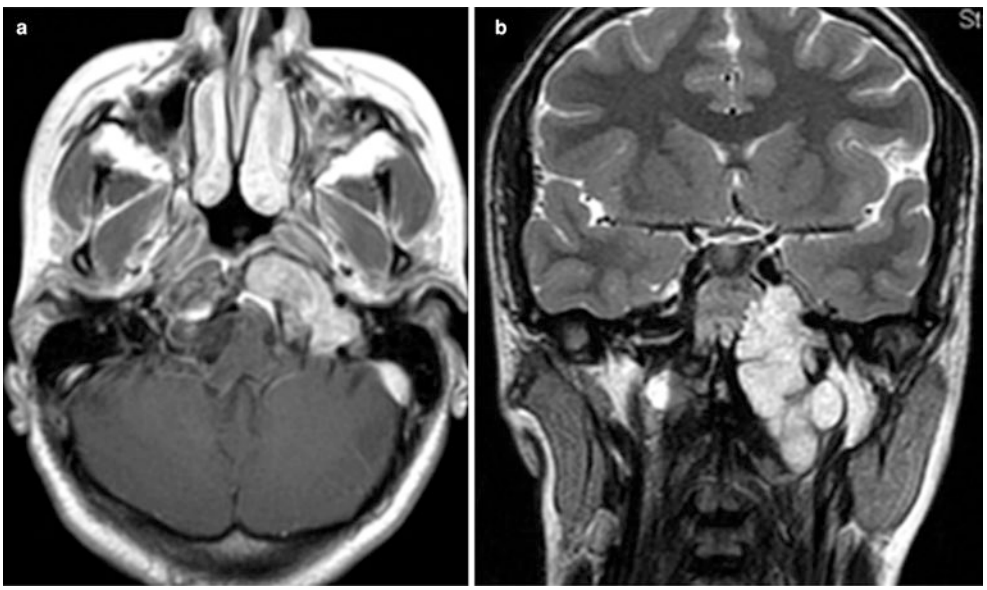

Fig. 2 Axial (**a**) and coronal (**b**) magnetic resonance imaging demonstrate a recurrent chordoma of the left petrous bone, with infratemporal and parapharyngeal extension

by the neoplasm. Despite use of neuronavigation and meticulous dissection, the left ICA was damaged, which was accompanied by massive bleeding. It was controlled by means of a Foley balloon, immediately inserted and kept in the resection area. The patient was urgently transferred to the angiography room, and examination clearly demonstrated a persistent leak from the petrous segment of the left ICA (Fig. 3). A balloon occlusion test showed good collateral blood flow through the posterior communicating artery; therefore, the left ICA was sacrificed with coiling (Fig. 4). The patient woke up from anesthesia without a neurological deficit.

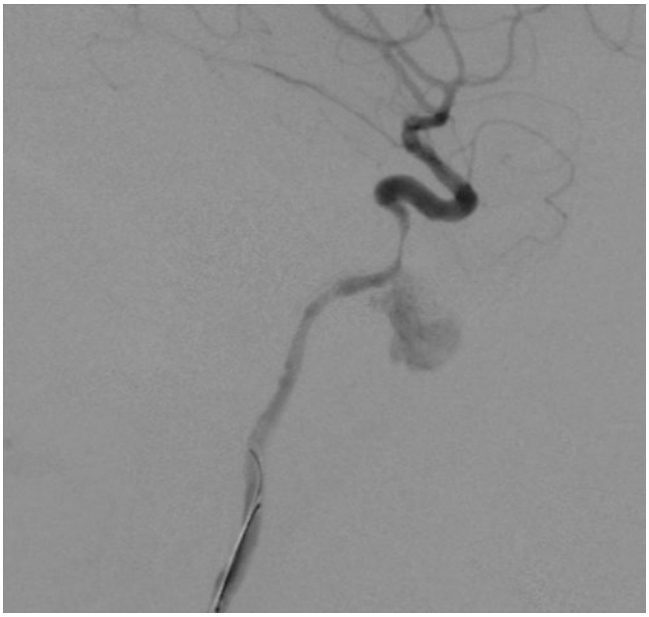

Fig. 3 After intraoperative injury of the left internal carotid artery during endoscopic endonasal resection of a recurrent petrous bone chordoma, emergency angiography demonstrates a persistent leak from the petrous segment (second genu) of the vessel before it enters the cavernous sinus

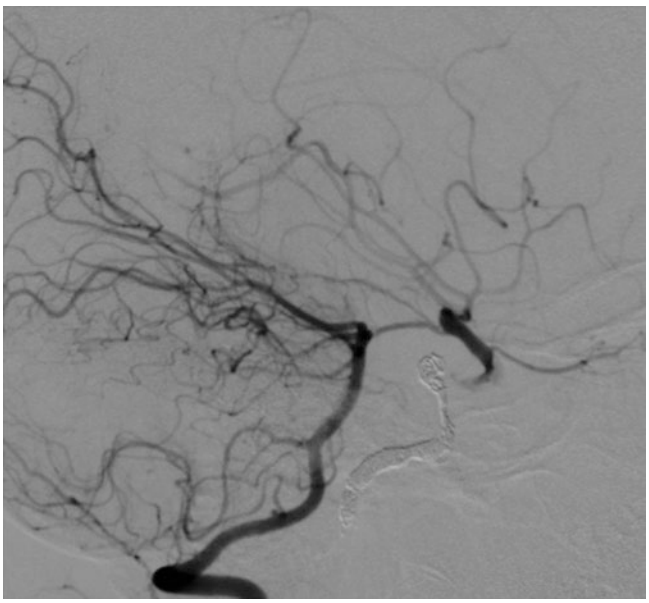

Fig. 4 A balloon occlusion test demonstrated good collateral blood flow through the posterior communicating artery, which allowed sacrifice of the left internal carotid artery by coiling. No neurological deficit was noted after the procedure

Discussion

Skull base surgery, particularly endoscopic surgery, usually deals with really complex anatomical conditions. The difficulty of the surgical techniques, along with the great number of eloquent structures adjacent to the operative area, result in nonnegligible postoperative morbidity. In fact, a PubMed search reveals that one out of four publications on skull base surgery is specifically related to "complications." Among them, injury of the ICA (the reported incidence of which varies from 1.1% in pituitary surgery to 9% in cases with use of an extended endonasal approach [1–3]) and, to a lesser degree, injury of the common carotid artery (CCA) or the external carotid artery (ECA) are of paramount importance [3–7]. Since this devastating complication is clearly life-threatening and may lead to death, the most relevant issue in related discussions is avoidance of such a harmful event.

Preventive Measures for Avoidance of Intraoperative Internal Carotid Artery Injury

Prevention of intraoperative ICA injury requires careful preoperative examination of the tumor extension, the trajectory of the adjacent vessels, and their characteristics (tortuosity, narrowing, encasement, etc.). Nevertheless, the primary issue for avoidance of such a complication is precise knowledge of the normal vascular anatomy and its possible variations [8]. Dal Secchi et al. [9] reviewed the morphology of the sphenoid sinus, its pneumatization, and protrusion of the ICA. They concluded that use of computed tomography (CT) for determination of the sphenoid sinus pneumatization, deviation of the sphenoid septum, and the presence of additional septations facilitate accurate identification of the ICA and reduce the probability of its inadvertent damage. In addition, these authors drew attention to a 3.6% incidence of paraclival ICA dehiscence [9].

The specific histology of the tumor may have an impact on the probability of intraoperative vascular damage. It has been reported that patients with a chondrosarcoma have a higher probability of carotid artery injury during endonasal skull base surgery [10]. On the other hand, juvenile nasal angiofibromas are frequently fed by branches from the cavernous ICA and the Vidian artery but are rarely adherent to the ICA. Finally, nasopharyngeal carcinomas and other paranasal sinus carcinomas can invade soft tissue or bone up to the ICA or can surround it, but in such cases, the artery is damaged only infrequently. Some additional predisposing factors for these complications may be related to the characteristics of the patient or previous treatment, such as radiotherapy, bromocriptine therapy, earlier resections, and hormonal changes (e.g., acromegaly, in which case, the ICA is usually dilated and tortuous) [10].

The 5-year survival rate of patients with involvement of ICA/CCA by the tumor is less than 5–13%, since resection of the neoplasm is usually incomplete, which often results in recurrence, especially in lesions with aggressive histology. Although the benefit of ICA/CCA resection in such cases has been proven [11, 12], it is associated with high morbidity due to arterial bleeding and/or stroke. Gardner et al. [10] sug-

gested a comprehensive algorithm for management of skull base tumors with circumferential ICA involvement. In particular, if the goal of surgery is radical resection of the neoplasm (e.g., in cases of malignancy or recurrent benign masses, especially after radiotherapy), balloon test occlusion should be considered along with the possibility of an extracranial–intracranial (EC-IC) bypass [10]. However, while grafting (e.g., with a saphenous vein graft) is an established option, it is also associated with a high morbidity rate [12]. Alternatively, if encasement of the ICA or CCA is identified on preoperative imaging, introduction of a covered stent before tumor removal may be effective for prevention of vessel injury and may allow resection of infiltrated adventitia due to formation of a neointimal lining on the luminal surface of the stent [12, 13].

For prevention of intraoperative ICA injury, simulation training providing the opportunity to study a realistic intraoperative scenario may also be very helpful. In that regard, Valentine et al. [14] suggested use of a sheep model of the carotid artery injury, which entails working in narrow nasal confines and management of the high-flow/high-pressure bleeding, which poses an immediate challenge in the operative field.

Finally, use of intraoperative neuronavigation and Doppler ultrasound are of real value during skull base tumor resection.

Management of Intraoperative Internal Carotid Artery Injury

A meta-analysis by Chin et al. [1] showed that the cavernous segment of the ICA is the one most frequently damaged during use of the endoscopic endonasal approach. Less often, the ophthalmic segment can be injured. In addition, their analysis of 50 cases reported in 25 articles gave interesting details of the methods applied for hemostasis in cases of ICA injury: packing (in 35 cases), vessel sacrifice with endoscopic clipping (in 4 cases), bipolar coagulation with the intent to seal the defect (in 3 cases), and bipolar coagulation with the intent to sacrifice the ICA (in 1 case). However, use of intraoperative or immediate postoperative angiography was reported in only 27 cases [1]. It is worth noting that good efficacy of endovascular treatment of intraoperative ICA injury has been demonstrated over the years, and this may be of great help in such circumstances [5, 15].

Once damage of the artery is evident, the surgical exposure should be extended if this is possible and can be done quickly. However, sometimes it carries too significant a risk if the control of the bleeding is not good enough. This issue may be particularly difficult in endoscopic procedures, in contrast to transcranial microsurgical approaches, which may allow much easier access to both the pre- and postdamaged segments of the ICA.

Direct repair would include suturing of the torn part of the artery, but it is usually not feasible in endoscopic surgery. Low-intensity bleeding and/or avulsion of the minor efferent vessels can be controlled by bipolar coagulation. Direct clipping of the artery is another possibility, but it is not always possible. Packing with crushed muscle is the best choice when repair is not an option [2, 9, 14, 16]. A hemostatic matrix (Floseal®; Baxter Healthcare Corp., Fremont, CA, USA) may be effectively used in cases of low-intensity bleeding, allowing the possibility of better inspection of the troublesome area and definitive control of the hemorrhage, but for management of large arterial tears, additional use of crushed muscle tissue or other complementary measures are mandatory. Introduction of a Foley balloon into the sphenoid sinus is a good maneuver to maintain hemostasis and/or to obtain safe time for transfer of the patient to the angiography room.

Endovascular repair of ICA injury is of special importance [5, 15]. There are three clinical scenarios in which endovascular therapy can be helpful. The first is a persistent arterial leak, which demands emergency treatment; in such cases, carotid sacrifice (usually with coils) with or without an EC-IC bypass should be considered. The second is pseudoaneurysm formation, which can be noted days or weeks after the initial ICA damage; it can be managed with coils, stenting, and/or a flow diverter. The third is a carotid stenosis, which can be revealed immediately after carotid injury due to an intramural hematoma or excessive packing with hemostatic materials; it should be followed up by means of computed tomography angiography (CTA) or magnetic resonance angiography (MRA), with consideration of the possibility of stenting.

Conclusion

Inadvertent damage of the ICA can be a troublesome event during skull base surgery, and the risk may be higher during tumor resection via the endoscopic endonasal approach. Certain factors associated with this complication should be carefully evaluated preoperatively. In particular, salvage procedures for recurrent neoplasms deserve specific attention, and balloon test occlusion with consideration of a preventive EC-IC bypass may be helpful. In cases of intraoperative ICA injury, its management requires immediate decisions and may include packing with hemostatic materials and/or muscle tissue, bipolar coagulation, clipping, and endovascular options.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Chin OY, Ghosh R, Fang CH, Baredes S, Liu JK, Eloy JA. Internal carotid artery injury in endoscopic endonasal surgery: a systematic review. Laryngoscope. 2016;126:582–90.
2. Padhye V, Valentine R, Paramasivan S, Jardeleza C, Bassiouni A, Vreugde S, Wormald PJ. Early and late complications of endoscopic hemostatic techniques following different carotid artery injury characteristics. Int Forum Allergy Rhinol. 2014;4:651–7.
3. Valentine R, Padhye V, Wormald PJ. Management of arterial injury during endoscopic sinus and skull base surgery. Curr Opin Otolaryngol Head Neck Surg. 2016;24:170–4.
4. AlQahtani A, Castelnuovo P, Nicolai P, Prevedello DM, Locatelli D, Carrau RL. Injury of the internal carotid artery during endoscopic skull base surgery: prevention and management protocol. Otolaryngol Clin North Am. 2016;49:237–52.
5. Aydin E, Gok M, Esenkaya A, Cinar C, Oran I. Endovascular management of iatrogenic vascular injury in the craniocervical region. Turk Neurosurg. 2018;28:72–8.
6. Duek I, Sviri GE, Amit M, Gil Z. Endoscopic endonasal repair of internal carotid artery injury during endoscopic endonasal surgery. J Neurol Surg Rep. 2017;78:e125–8.
7. Rowan NR, Turner MT, Valappil B, Fernandez-Miranda JC, Wang EW, Gardner PA, Snyderman CH. Injury of the carotid artery during endoscopic endonasal surgery: surveys of skull base surgeons. J Neurol Surg B Skull Base. 2018;79:302–8.
8. Fernandez-Miranda JC, Prevedello DM, Madhok R, Morera V, Barges-Coll J, Reineman K, Snyderman CH, Gardner P, Carrau R, Kassam AB. Sphenoid septations and their relationship with internal carotid arteries: anatomical and radiological study. Laryngoscope. 2009;119:1893–6.
9. Dal Secchi MM, Dolci RLL, Teixeira R, Lazarini PR. An analysis of anatomic variations of the sphenoid sinus and its relationship to the internal carotid artery. Int Arch Otorhinolaryngol. 2018;22:161–6.
10. Gardner PA, Snyderman CH, Fernandez-Miranda JC, Jankowitz BT. Management of major vascular injury during endoscopic endonasal skull base surgery. Otolaryngol Clin North Am. 2016;49:819–28.
11. Loré JM Jr, Boulos EJ. Resection and reconstruction of the carotid artery in metastatic squamous cell carcinoma. Am J Surg. 1981;142:437–42.
12. Nishinari K, Krutman M, Valentim LA, Chulam TC, Yazbek G, Kowalski LP, Wolosker N. Late surgical outcomes of carotid resection and saphenous vein graft revascularization in patients with advanced head and neck squamous cell carcinoma. Ann Vasc Surg. 2014;28:1878–84.
13. Markiewicz MR, Pirgousis P, Bryant C, Cunningham JC, Dagan R, Sandhu SJ, Siragusa DA, Gopinath A, Fernandes R. Preoperative protective endovascular covered stent placement followed by surgery for management of the cervical common and internal carotid arteries with tumor encasement. J Neurol Surg B Skull Base. 2017;78:52–8.
14. Valentine R, Padhye V, Wormald PJ. Simulation training for vascular emergencies in endoscopic sinus and skull base surgery. Otolaryngol Clin North Am. 2016;49:877–87.
15. Raymond J, Hardy J, Czepko R, Roy D. Arterial injuries in transsphenoidal surgery for pituitary adenoma; the role of angiography and endovascular treatment. AJNR Am J Neuroradiol. 1997;18:655–65.
16. Padhye V, Valentine R, Wormald PJ. Management of carotid artery injury in endonasal surgery. Int Arch Otorhinolaryngol. 2014;18(Suppl 2):S173–8.

Surgical Strategy in Modification of the Transpetrosal Approach to Avoid Postoperative Venous Complications: A Report of 74 Consecutive Cases

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Abstract

Background: The transpetrosal approach is a complex skull base procedure with a high risk of complications, particularly caused by injury of the venous system. It is in part related to variability of blood outflow pathways and their distinctive patterns in each individual patient.

Objective: To evaluate outcomes and complications after skull base surgery with use of the petrosal approach modifications, which selection was based on the detailed preoperative assessment of venous drainage patterns.

Methods: Overall, 74 patients, who underwent surgery via the transpetrosal approach at our institution between 2000 and 2017, were included in this study. In all cases, the venous drainage pattern was assessed preoperatively and categorized according to the predominant blood outflow pathway into four types as previously suggested by Hacker: (1) sphenoparietal sinus (SpPrt), (2) sphenobasal vein (SpB), (3) sphenopetrosal sinus (SpPS), and (4) cortical. The blood outflow through the bridging petrosal vein and the vein of Labbé was also taken into consideration. In patients with SpPrt- and a cortical-type venous drainage, the transpetrosal approach was used in a standard way. In patients with SpB-type venous drainage, limited extradural anterior petrosectomy was combined with intradural anterior petrosectomy after dural opening, superior petrosal sinus transection, tentorial cutting, Meckel's cave opening, and trigeminal nerve mobilization. In patients with SpPS-type venous drainage, after standard petrosectomy, dural opening, and tentorial cutting, SpPS ligation was done followed by 2-week interval before staged definitive tumor resection.

Results: Gross total, near-total, and subtotal resection of the lesion (meningioma, 48 cases; retrochiasmatic craniopharyngioma, 11 cases; brain stem cavernoma, 7 cases; other tumors, 8 cases) was achieved in 30 (40.5%), 24 (32.4%), and 20 (27.0%) patients, respectively. Postoperative complications that were possibly related to venous compromise were noted in 18 patients (24.3%), but neither one was major. Of these 18 patients, 9 were symptomatic, but all symptoms—aphasia (4 cases), seizures (2 cases), and confusion (3 cases)—fully resolved after conservative treatment. Overall, 13 patients, including 4 symptomatic, had signal changes on T2-weighted brain MRI, which were permanent only in 3 cases (all asymptomatic).

Conclusion: Our suggested surgical strategy can be applied to any type of the venous drainage pattern. Preoperative evaluation and intraoperative preservation of the blood outflow pathways are crucial means for safe and effective application of the transpetrosal approach.

Keywords

Anterior petrosectomy · Combined petrosectomy · Complication · Transpetrosal approach · Venous complication · Venous drainage · Venous infarction · Skull base surgery

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_4

Introduction

The transpetrosal–transtentorial approach with anterior petrosectomy combined with posterior retrolabyrinthine petrosectomy—the so-called combined transpetrosal approach (CTPA)—was first described in 1985 by Hakuba et al. [1], who used it to remove eight retrochiasmatic craniopharyngiomas. In the same year, the anterior transpetrosal approach (ATPA) was first introduced by Kawase et al. [2] for treatment of aneurysms of the lower basilar artery. Thereafter, the ATPA was also applied to remove sphenopetroclival meningiomas, as was reported by the same group in 1991 [3]. These two approaches are currently utilized rather frequently during surgery for various types of lesions adjacent to the skull base: brain stem cavernomas, epidermoid tumors, meningiomas, craniopharyngiomas, aneurysms, etc.

Nevertheless, while transpetrosal approach is occasionally used by many neurosurgeons to access sphenopetroclival, middle-to-upper clival, upper brain stem, and retrochiasmatic areas [1–16], it remains one of the most challenging procedures. Because of its complexity, the deep-seated location of operated lesions, which are surrounded by vital neurovascular structures, and the variety of venous drainage patterns, the transpetrosal approach is associated with a high rate of morbidity, especially complications caused by injury of the venous system [17–20]. Although the transpetrosal approach provides a wide operative corridor, allowing better manipulation of deep-seated lesions from multiple surgical angles, it carries a potential risk of injuring bridging veins, venous sinuses, and deep venous drainage. Furthermore, venous drainage patterns differ from patient to patient, leading to unexpected adverse events if the surgeon inadvertently compromises blood outflow pathways during the procedure.

We consider that preoperative assessment of venous drainage patterns in each patient is crucial to avoid catastrophic complications from venous outflow obstruction. Detailed surgical planning to access the lesion with preservation of venous pathways, and cautious executing the transpetrosal approach and the entire procedure to make every effort for protection and maintenance of the venous drainage on the basis of its unique pattern in each individual patient are absolutely necessary. Herein, we describe our protocol to perform safe surgery with avoidance of venous complications, which has been applied in the consecutive series of 74 patients with different mass lesions operated on via the transpetrosal approach. Reported surgical outcomes demonstrate that suggested surgical strategy can be effectively applied to any type of the venous drainage.

Materials and Methods

We retrospectively reviewed the medical records of patients operated on with the use of either ATPA or CTPA at our institution between 2000 and 2017, and were followed after surgery for >6 months. The following variables were collected and analyzed: age, sex, diagnosis, maximum lesion diameter, venous drainage pattern, selected surgical approach, extent of resection (EOR), and complications, in particular related to venous compromise. The EOR was determined on the basis of intraoperative findings and postoperative magnetic resonance imaging (MRI). Near-total resection (NTR) and subtotal resection (STR) were defined as those ones with a residual lesion volume <5% and >5% of its preoperative volume, respectively. Venous complications from the transpetrosal approach were judged on the basis of the postoperative clinical course and radiological examination, and were defined as any clinical symptoms that were possibly related to venous drainage damage (confusion, seizure, persistent headache, aphasia, etc.) and/or imaging findings, such as hemorrhagic transformation on postoperative computed tomography (CT) or high signal intensity on T2-weighted MRI performed within 72 h after the intervention.

All analyzed patients underwent treatment using the same surgical concept and protocol to avoid postoperative venous complications.

Preoperative Assessment of Venous Drainage

During preoperative evaluation, all patients in this study underwent CT venography (CTV), magnetic resonance angiography (MRA), and venography by means of digital subtraction angiography (DSA). Venous drainage patterns were categorized according to the predominant blood outflow pathway into four types based on the classification described by Hacker [21]: (1) sphenoparietal sinus (SpPrt), (2) sphenobasal vein (SpB), (3) sphenopetrosal sinus (SpPS), and (4) cortical veins with absence of the superficial middle cerebral vein (SMCV). The blood outflow through the bridging petrosal vein (PV) and the vein of Labbé was also taken into consideration.

Selection of the Surgical Approach and Surgical Strategy

The surgical approach was selected on the basis of the location, size, and projection of the tumor. The ATPA was preferred for patients with intrinsic middle-to-upper brain stem lesions or extrinsic lesions around the petroclival area that

did not extend upward beyond the tentorium incisura and caudally beyond the level of the internal auditory canal (IAC). In contrast, the CTPA was chosen in patients with retrochiasmatic lesions (occasionally, even if they were small), or large petroclival area lesions with superior extension beyond the tentorial incisura and caudal extension beyond the level of the IAC.

In patients with SpPrt- and a cortical-type venous drainage, the transpetrosal approach was used in a standard way, as has been described in detail previously [1–3]. On the other hand, special considerations were required in patients with SpB and SpPS venous drainage types. In such cases, our surgical procedure to avoid postoperative venous complications includes three important techniques: (1) extradural combined with intradural anterior petrosectomy in patients with SpB-type venous drainage; (2) safe dural incision and superior petrosal sinus (SPS) transection during tentorial cutting to avoid venous outflow obstruction from the PV and the vein of Labbé in all cases undergoing the CTPA; and (3) intentional tentorial cutting with SpPS ligation followed by a second-stage tumor resection in cases with a dominant SpPS-type venous drainage. This surgical strategy is outlined in Fig. 1.

Extradural Combined with Intradural Anterior Petrosectomy in Sphenobasal Vein Venous Drainage Type: The ATPA and CTPA share a common skull base procedure: drilling of the rhomboid area around the petrous apex, known as Kawase's triangle. This area is bounded anteriorly by the lateral edge of the trigeminal impression, medially by the petrous ridge, laterally by the greater superficial petrosal nerve (GSPN), and posteriorly by the arcuate eminence. Extradural bone drilling of Kawase's triangle was first described by Kawase et al. [2]. However, such extradural anterior petrosectomy is sometimes difficult because of its deep and narrow working space and proximity to some important anatomical structures: the petrous part of the internal carotid artery, the geniculum of the facial nerve, the cochlea, Dorello's canal, etc. During the surgical procedure, before Kawase's triangle is drilled, the middle fossa dura, including the dura propria around the foramen ovale, must be elevated to gain surgical space. However, in patients with SpB-type venous drainage, elevation of the dura propria around the foramen ovale can cause venous outflow obstruction. Therefore, we developed a new intradural procedure for anterior petrosectomy in addition to extradural drilling to create a wider and shallower working space and a less steep angle of access.

The details of extradural combined with intradural anterior petrosectomy are as follows. In usual cases, after mobilization of the temporal fossa dura and its elevation from the skull base, the middle meningeal artery (MMA) is coagulated and cut. The GSPN is dissected sharply, and extradural elevation of the dura propria along the mandibular branch of the trigeminal nerve is performed. At this step, bleeding from the cavernous sinus can be controlled easily with Gelfoam® soaked with fibrin glue. The dura is dissected until the SPS is freed from the petrous ridge. The geniculum of the facial nerve is confirmed using direct electrical stimulation. The projection of IAC is defined using the Garcia-Ibanez's technique [22]. Thereafter, Kawase's triangle can be drilled with a spacious surgical

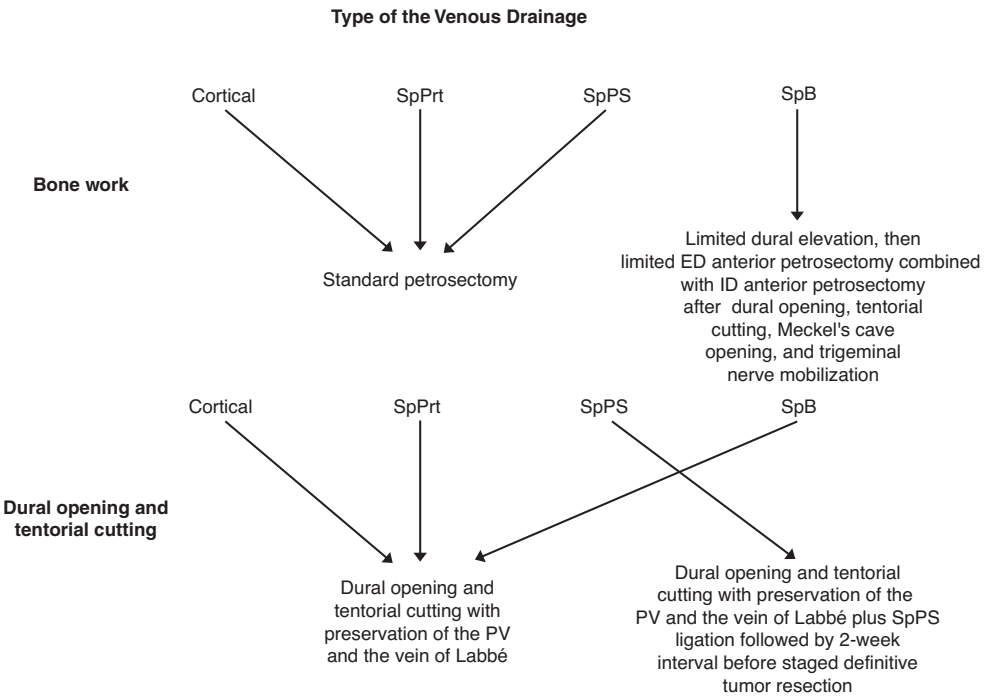

Fig. 1 Protocol of the surgical strategy used in the transpetrosal approach ("transpetrosal protocol"). *ED* Extradural, *ID* Intradural, *PV* Petrosal vein, *SpB* Sphenobasal vein, *SpPrt* Sphenoparietal sinus, *SpPS* Sphenopetrosal sinus

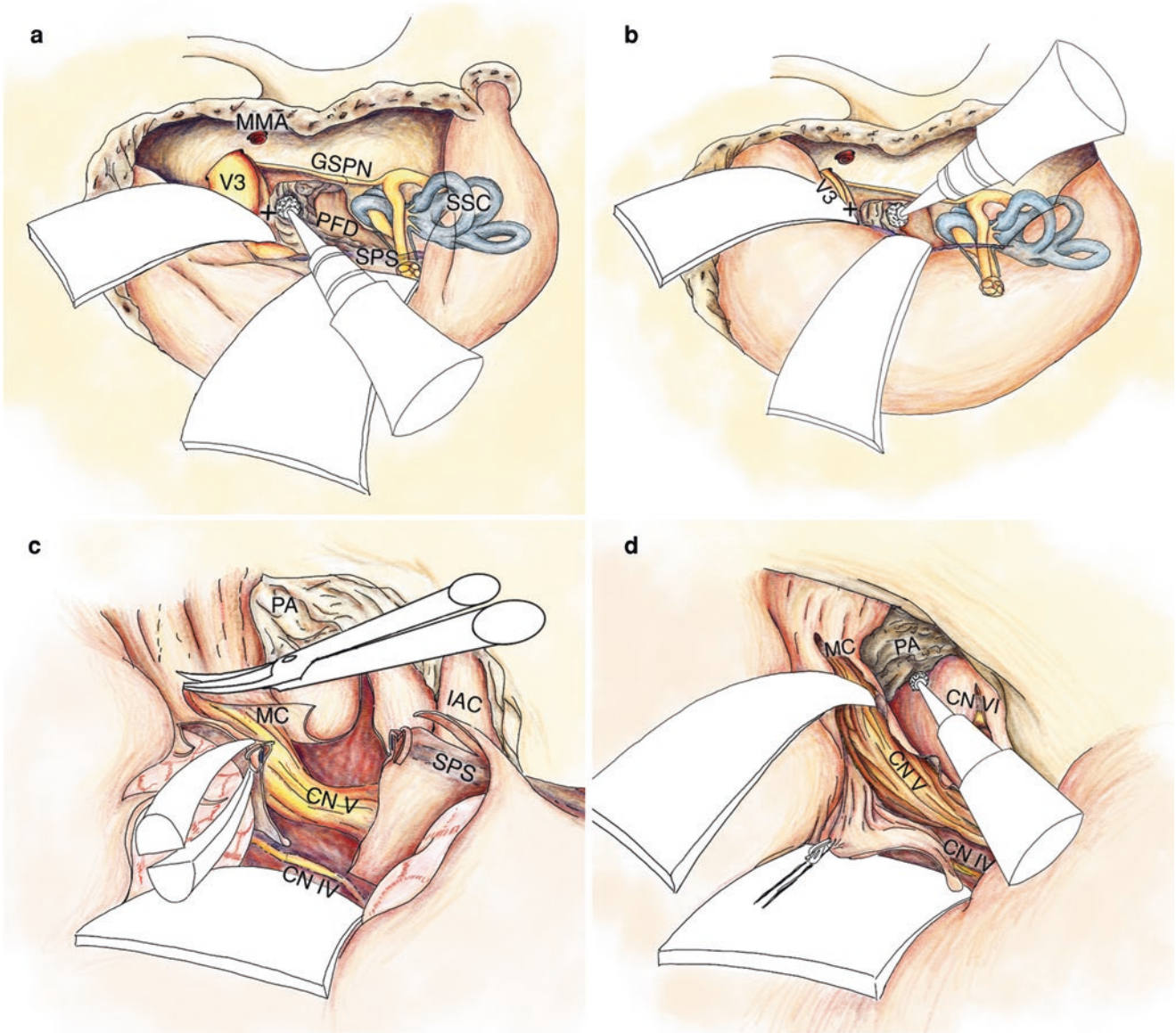

Fig. 2 Extradural combined with intradural anterior petrosectomy (AP) on the right side compared with standard AP. In a usual case, peeling of the dura propria from the mandibular branch of the trigeminal nerve (V3) provides a large working space for AP without venous occlusion (**a**). In the sphenobasal vein type of the venous drainage, limited dura propria elevation is done following by drilling of Kawase's triangle until the posterior fossa dura (PFD) is partially identified (**b**). In this case, after opening of the temporal dura and PFD, the superior petrosal sinus (SPS) was clipped and cut, and the tentorial incisura was incised from lateral to medial (**c**); Meckel's cave (MC) was then freely opened. Using a brain spatula, the trigeminal nerve (CN V) was retracted and mobilized to achieve a wider working space at the petrous apex (PA); additional intradural AP was then performed after dissection of the dura around the PA (**d**). + trigeminal impression, *CN IV* Trochlear nerve, *CN VI* Abducens nerve, *GSPN* Greater superficial petrosal nerve, *IAC* Internal acoustic canal, *MMA* Middle meningeal artery, *SSC* Superior semicircular canal. (Modified from Ohata and Baba [23], with permission)

corridor (Fig. 2a). However, in patients with SpB-type venous drainage, dural elevation is more difficult than usual. The surgeon usually encounters profound venous bleeding during elevation of the dura propria from the foramen ovale. Moreover, control of venous bleeding around the cavernous sinus with Gelfoam® soaked with fibrin glue in patients with SpB-type venous drainage can cause devastating venous outflow leading to intra- and postoperative venous obstruction and complications. Therefore, in such cases, the dura propria reflection around the foramen ovale should be limited, as it may cause venous obstruction. We elevate the temporal base dura without peeling the dura propria around the foramen ovale. However, when dural reflection cannot be maximally performed, the drilling space becomes narrower and smaller than in normal cases. Therefore, we begin the extradural drilling along the petrous ridge and Kawase's triangle until the posterior fossa dura is partially identified (Fig. 2b).

After this stage, the extradural step is terminated and changed to the intradural procedure [23]. In the ATPA, the middle fossa dura is cut downward from the lateral temporal surface along the inferior temporal lobe toward the SPS and then turned posteriorly parallel to the SPS. Next, the posterior fossa dura is incised parallel to the first dural incision as far anteriorly as possible along the inferior edge of the SPS to avoid injuring the PV. The SPS is then transected after its clip ligation close to the posterior edge of the trigeminal nerve to spare the PV. The tentorium is then cut from lateral to medial, from the point of transection of the SPS to the tentorial incisura. At this point, care is taken to avoid damaging the trochlear nerve running along the inferomedial edge of the tentorium. The dural-tentorial cutting is continued anteriorly along the lateral margin of Meckel's cave until the latter is freely opened (Fig. 2c). Then, intradurally, the trigeminal nerve is mobilized in the medial–rostral direction, away from the trigeminal impression, for visualization of the intradural petrous apex. After mobilization of the trigeminal nerve, the dura can be easily dissected out of the petrous apex. This dural flap is then flipped down. By trigeminal nerve mobilization, a wider and shallower working space is achieved for additional intradural drilling of the petrous apex [23]. Such additional intradural anterior petrosectomy allows to avoid interference with the SpB-type venous drainage (Fig. 2d), and provides a large space to confirm location of the Dorello's canal reducing the risk of abducens nerve injury during subsequent tumor resection.

Dural Incision and Tentorial Cutting in the Combined Transpetrosal Approach: To avoid obstruction of venous outflow from the vein of Labbé and the PV, during dural and tentorial sectioning the incision should be elaborated. Our related surgical technique has been reported previously elsewhere [24]. After standard craniotomy and petrosectomy for the CTPA, the middle fossa dura is cut downward from the lateral temporal surface along the inferior temporal lobe and then turned backward along the lateral edge of the SPS. Care must be taken by simultaneous observation and protection of the vein of Labbé. Subsequently, the presigmoid dura is opened anteriorly to the sigmoid sinus and parallel to it. Thereafter, the dural incision is turned 5 mm below Trautmann's triangle and then it is continued anteriorly along the inferior edge of the SPS. With this posterior fossa dural incision, the insertion point of the PV into the SPS can be inspected directly. Finally, by the connection between the middle fossa and presigmoid dural incisions, the SPS is safely ligated with a clip and then cut anteriorly to the insertion of the PV. By means of this method, the venous drainage from both the vein of Labbe and the PV remains patent.

Tentorial Cutting in Dominant Sphenopetrosal Sinus Venous Drainage Type: When the ATPA or CTPA is the only option in patients with large single dominant SpPS-type venous drainage and poor collateral venous pathways, we select a staged operation. Skull base drilling and tentorial cutting, together with intentional ligation of the SpPS at the temporal base without manipulation of the brain parenchyma, are performed in the first-stage surgery, whereas definitive tumor resection is carried on 2 weeks later to allow time for development of a collateral venous outflow. The detail of these techniques and surgical results in such cases were reported by our group previously elsewhere [25].

Results

The study population consisted of 74 patients (25 men and 49 women), with a mean age of 50 years (range 8–77 years). Clinical summary of all these cases is shown in Table 1. The most common pathology was petroclival meningioma (in 37 patients) followed by retrochiasmatic craniopharyngioma (in 11 patients), brain stem cavernoma (in 7 patients), petrocavernous meningioma (in 7 patients), petrotentorial meningioma (in 3 patients), trigeminal schwannoma (in 3 patients), clival chordoma (in 2 patients), epidermoid tumor (in 2 patients), brain stem pilocytic astrocytoma (in 1 patient), and clival meningioma (in 1 patient).

With regard to venous drainage patterns, 43 patients (58.1%) had combined venous drainage pathways that had some collaterals to each other, whereas 31 patients (41.9%) had a single dominant venous drainage channel on the side of the operation (Table 2).

Overall, CTPA and ATPA were used in 50 and 24 cases, respectively. Gross total resection (GTR) of the lesion was achieved in 30 cases (40.5%), NTR in 24 cases (32.4%), and STR in 20 cases (27.0%). There were no surgical mortality in our series. Of the total 74 patients, 18 (24.3%) had postoperative complications that were possibly related to venous compromise. Of these 18 cases, 9 were symptomatic and manifested with aphasia (4 cases), seizures (2 cases), and confusion (3 cases), whereas other nine were asymptomatic. All symptoms were temporary and fully resolved after conservative treatment. In 5 of 9 symptomatic cases no abnormal findings were revealed on postoperative MRI; the other four cases showed small transient changes in the signal intensity on T2-weighted images within the temporal lobe, which had disappeared on follow-up MRI attained on postoperative days 22, 25, 10, and 9, respectively.

Of the 18 patients with postoperative complications that were possibly related to venous compromise, 13 had signal changes on T2-weighted MRI and five had no abnormal radiological findings. In 10 of the former 13 patients, imaging abnormalities were only transient and disappeared on subsequent follow-up MRI examination. In contrast, in 3 patients, all of whom were asymptomatic, signal changes within the temporal lobe on postoperative T2-weighted MRI

Table 1 Clinical summary of 74 patients operated on via the transpetrosal approach

Case no.	Age (years)	Sex	Diagnosis	Maximum lesion diameter (mm)	Venous drainage pattern	Approach	Extent of resection[a]	Complications
1	54	Female	PCM	57.0	Cortical	CTPA	STR	None
2	57	Female	PTM	37.3	Cortical	CTPA	NTR	None
3	33	Female	Craniopharyngioma	34.3	SpPrt + large LBV	CTPA	NTR	None
4	52	Female	PCM	36.4	Cortical + large LBV	CTPA	NTR	None
5	61	Female	Craniopharyngioma	43.3	Cortical + large LBV	CTPA	STR	None
6	54	Male	PCM	47.5	SpB	CTPA	STR	None
7	54	Male	Brain stem cavernoma	37.0	SpB + large LBV	CTPA	GTR	Transient aphasia (negative MRI)
8	77	Female	Clival chordoma	31.7	Cortical + large LBV	ATPA	STR	Transient subclinical seizure with transient temporal edema (22 days)
9	38	Male	Clival chordoma	23.7	SpB + large LBV	CTPA	GTR	Asymptomatic transient temporal edema (10 days)
10	52	Male	PCM	28.7	SpB	CTPA	STR	None
11	61	Female	PCM	48.4	Cortical + large LBV	CTPA	STR	None
12	56	Female	Brain stem cavernoma	26.7	SpPrt	CTPA	GTR	None
13	17	Female	Craniopharyngioma	30.6	SpPrt + large LBV	CTPA	GTR	None
14	55	Female	PCM	42.7	SpB	CTPA	NTR	None
15	48	Male	Trigeminal schwannoma	52.0	Cortical + large LBV	ATPA	STR	None
16	50	Female	PCM	24.0	SpPrt	ATPA	GTR	None
17	62	Female	PTM	32.0	SpB + SpPrt + cortical	ATPA	NTR	None
18	71	Male	PCM	31.0	SpB	ATPA	NTR	None
19	57	Female	PCM	27.7	Cortical + large LBV	CTPA	STR	Transient aphasia with transient temporal edema (25 days)
20	53	Female	PCM	47.8	SpB + cortical	CTPA	STR	None
21	61	Female	PCM	47.0	SpB	CTPA	NTR	Transient seizure from hyponatremia (negative MRI)
22	27	Male	Brain stem cavernoma	20.1	Large SpB + cortical	ATPA	GTR	None
23	57	Female	PCM	45.0	Cortical	ATPA	STR	None
24	67	Female	PCM	30.7	SpB + cortical	ATPA	GTR	None
25	50	Male	Trigeminal schwannoma	37.0	SpB + cortical	ATPA	STR	None
26	58	Male	PCM	42.3	SpPrt + cortical	ATPA	STR	None
27	34	Male	Brain stem cavernoma	17.0	Cortical + large LBV	ATPA	GTR	None
28	49	Female	PCM	44.0	SpPS	CTPA	NTR	None
29	61	Female	Clival meningioma	28.4	Cortical	ATPA	STR	None
30	47	Female	PCM	39.6	SpPrt + cortical	CTPA	NTR	None
31	57	Female	Craniopharyngioma	43.1	SpPrt + cortical	CTPA	STR	None
32	21	Female	PCM	51.5	SpPrt	CTPA	NTR	None
33	39	Female	PCM	27.3	Large LBV + SpB	CTPA	NTR	None
34	55	Female	PCM	45.3	SpB	CTPA	NTR	None
35	60	Male	PCM	47.0	Large LBV + SpB	CTPA	NTR	None
36	43	Female	PCM	51.0	Large LBV + SpB	CTPA	STR	Asymptomatic transient temporal edema (9 days)
37	64	Female	PCM	40.0	SpPrt + SpB	CTPA	NTR	None
38	64	Female	PCM	40.6	SpPrt + cortical	CTPA	GTR	None
39	48	Female	PCM	32.7	SpPrt + cortical	ATPA	NTR	Asymptomatic small temporal contusion

40	9	Female	Craniopharyngioma	35.7	Cortical + SpB	CTPA	STR	None
41	37	Female	Craniopharyngioma	39.1	SpB + cortical	CTPA	GTR	Asymptomatic transient temporal edema (49 days)
42	45	Female	PCM	44.0	SpPrt + cortical	CTPA	GTR	None
43	8	Female	Craniopharyngioma	30.7	SpPrt + cortical	CTPA	GTR	None
44	37	Female	Craniopharyngioma	49.1	SpB + cortical	CTPA	GTR	None
45	26	Male	PCM	30.2	SpPrt + cortical	ATPA	STR	Asymptomatic permanent temporal T2 change from postoperative epidural hematoma
46	37	Female	Craniopharyngioma	13.4	SpB	CTPA	GTR	None
47	64	Female	PCM	32.3	SpB + cortical	ATPA	GTR	None
48	47	Male	PCM	45.8	Cortical + SpB	CTPA	GTR	None
49	54	Male	PCM	35.8	Large LBV	CTPA	GTR	Asymptomatic temporal contusion from bridging vein injury during tumor removal
50	49	Female	PTM	50.2	SpPrt	CTPA	GTR	None
51	12	Male	Craniopharyngioma	15.0	Large LBV	CTPA	GTR	None
52	63	Female	PCM	35.1	SpPrt + cortical	CTPA	GTR	None
53	43	Male	Craniopharyngioma	29.7	Large LBV + SpPrt	CTPA	GTR	None
54	70	Male	Brain stem PA	36.4	Large LBV	CTPA	NTR	None
55	68	Female	PCavM	43.6	Large LBV + SpB	CTPA	NTR	None
56	63	Female	PCM	36.4	SpPrt + cortical	ATPA	GTR	None
57	61	Male	PCavM	38.1	SpB	CTPA	NTR	Transient confusion (negative MRI)
58	12	Male	Epidermoid tumor	30.3	SpPS	ATPA	GTR	None
59	74	Female	PCM	41.2	SpPrt	CTPA	GTR	Transient confusion with transient temporal edema (10 days)
60	37	Male	Brain stem cavernoma	24.3	SpPrt	ATPA	GTR	Asymptomatic temporal edema (14 days)
61	49	Male	Brain stem cavernoma	36.0	SpPrt	ATPA	GTR	None
62	74	Female	PCM	41.1	SpPS	CTPA	NTR	Transient confusion with transient temporal edema (9 days)
63	48	Female	Epidermoid tumor	32.3	Cortical	CTPA	NTR	None
64	60	Female	PCM	23.4	SpB + large LBV	ATPA	GTR	None
65	54	Female	PCM	26.5	Cortical + large LBV	CTPA	STR	Transient aphasia (negative MRI)
66	24	Male	Trigeminal schwannoma	38.3	SpPrt	ATPA	GTR	None
67	48	Female	PCavM	26.1	Cortical + large LBV	CTPA	NTR	Asymptomatic transient temporal edema (75 days)
68	63	Male	PCavM	36.9	Large LBV	CTPA	NTR	None
69	69	Male	PCM	44.5	Cortical + large LBV	CTPA	STR	None
70	69	Female	PCavM	55.8	SpB + large LBV	CTPA	STR	Transient aphasia (negative MRI)
71	45	Female	Brain stem cavernoma	27.8	Cortical + large LBV	ATPA	GTR	None
72	44	Female	PCavM	59.1	Cortical	ATPA	NTR	None
73	39	Male	PCavM	53.3	Cortical	CTPA	NTR	Asymptomatic transient temporal edema (35 days)
74	72	Female	PCM	24.5	Cortical	ATPA	GTR	None

ATPA Anterior transpetrosal approach, *CTPA* Combined transpetrosal approach, *GTR* Gross total resection, *LBV* The vein of Labbé, *MRI* Magnetic resonance imaging, *NTR* Near-total resection, *PA* Pilocytic astrocytoma, *PCavM* Petrocavernous meningioma, *PCM* Petroclival meningioma, *PTM* Petrotentorial meningioma, *SpB* Sphenobasal vein, *SpPrt* Sphenoparietal sinus, *SpPS* Sphenopetrosal sinus, *STR* Subtotal resection

[a]Evaluated by intraoperative findings and postoperative magnetic resonance imaging within 72 hours

Table 2 Variation in venous drainage patterns (according to Hacker's classification) [21] among 74 patients operated on via the transpetrosal approach

Venous drainage pattern	Number of cases
Combined type	43 (58.1%)
Single type	
Cortical or large vein of Labbé	12 (16.2%)
Sphenoparietal sinus (SpPrt)	8 (10.8%)
Sphenobasal vein (SpB)	8 (10.8%)
Sphenopetrosal sinus (SpPS)	3 (4.1%)

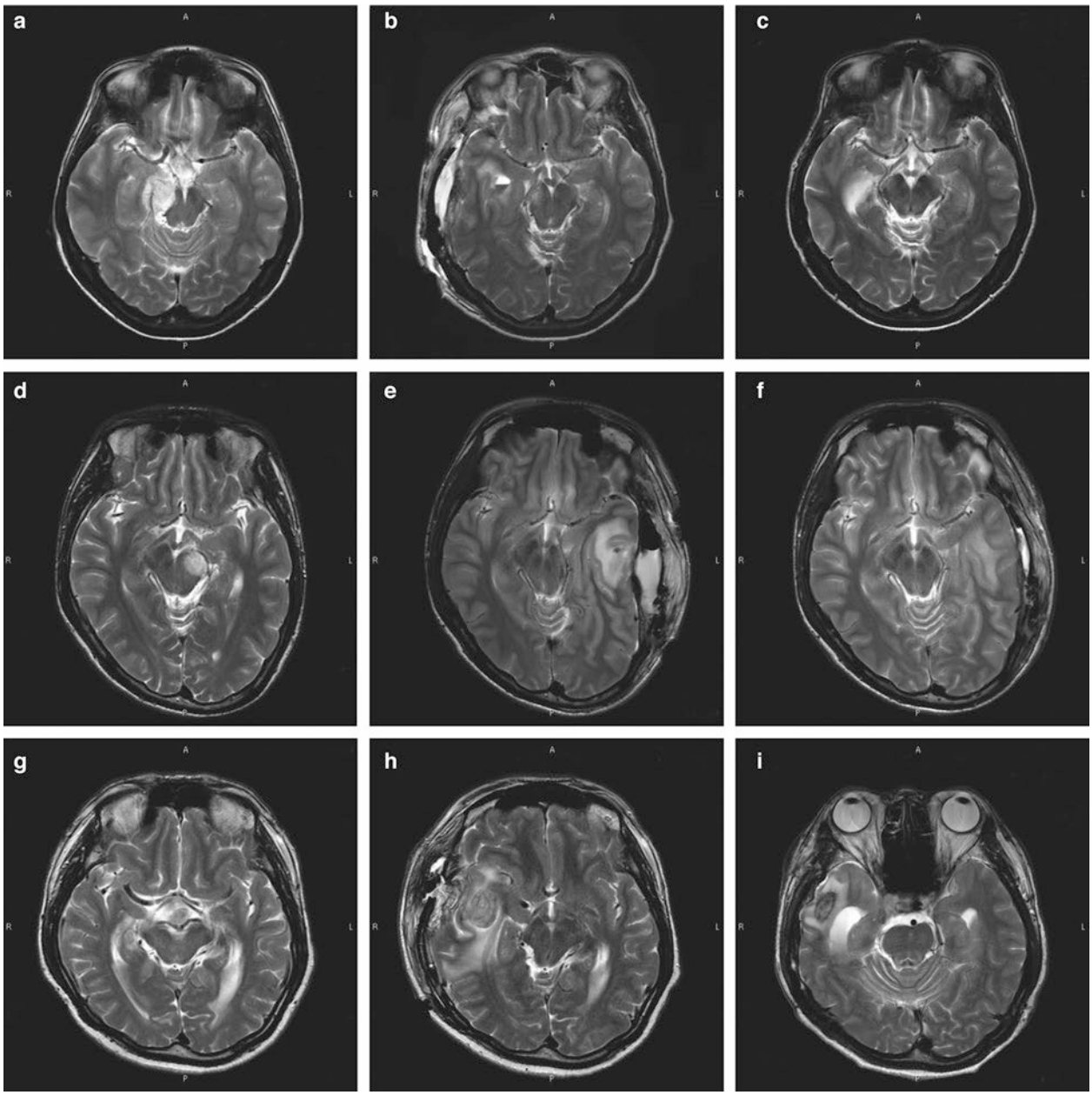

Fig. 3 T2-weighted magnetic resonance imaging (MRI) at the level of midbrain in patients operated on via the transpetrosal approach, in whom permanent signal intensity changes were observed postoperatively. *Left column*: preoperative baseline images. *Middle column*: images at 72 h after surgery. *Right column*: images at long-term follow-up. *Upper row* (Case 39): after surgery for right-side petroclival meningioma (**a**), a small intraparenchymal hemorrhage was observed in the right temporal lobe (**b**) and remained at long-term follow-up examination (**c**). *Middle row* (Case 45): after surgery for left-side petroclival meningioma (**d**), postoperative MRI revealed a nonsurgical epidural hematoma in the left temporal region (**e**), and at long-term follow-up examination a small area of T2 signal intensity changes within the left temporal lobe still remained (**f**). *Lower row* (Case 49): after surgery for right-side petroclival meningioma (**g**), a postoperative right temporal intracerebral hemorrhage was observed because of accidental injury of the mesial temporal bridging vein during tumor decompression (**h**), and these signal intensity changes remained at long-term follow-up examination (**i**). Of note, all patients were asymptomatic

were permanent (Fig. 3): they were caused by a small iatrogenic temporal contusion (in Case 39), a parenchymal injury from a postoperative nonsurgical epidural hematoma (in Case 45), and a postoperative small temporal contusion from an accidental temporal base bridging vein injury during removal of a petroclival meningioma (in Case 49). No major postoperative complications related to venous compromise were observed in our series.

Illustration of the Anterior Petrosectomy in Case of a Dominant Sphenobasal Vein-Type Venous Drainage

A 27-year-old man (Case 22) presented with sudden onset of left hemibody numbeness, hemifacial numbness, and hemiparesis. Neurological examination revealed grade 3 left hemiparesis along with House–Brackmann grade II left facial palsy. Preoperative MRI demonstrated an intraparenchymal pontine mass lesion measuring 20 mm in diameter, consistent with an appearance of cavernoma. Magnetic resonance venography showed that the SMCV dominantly drained via the sphenobasal venous pathway through the foramen ovale. The patient underwent the ATPA with preservation of this large venous drainage. During dissection of the temporal dura, we encountered profuse venous bleeding from the venous plexus around the foramen ovale and foramen spinosum. The bleeding was controlled using collagen sheets soaked with fibrin glue. Dural dissection and elevation were abandoned at this stage, and extradural combined with intradural anterior petrosectomy was performed as described above. Total lesionectomy was accomplished without intraoperative complications. The postoperative course was uneventful, and all preoperative symptoms resolved after surgery. Postoperative MRI confirmed total removal of the cavernoma. No venous compromise was evident, either clinically or radiologically (Fig. 4). This patient returned to his normal daily life without any neurological deficits.

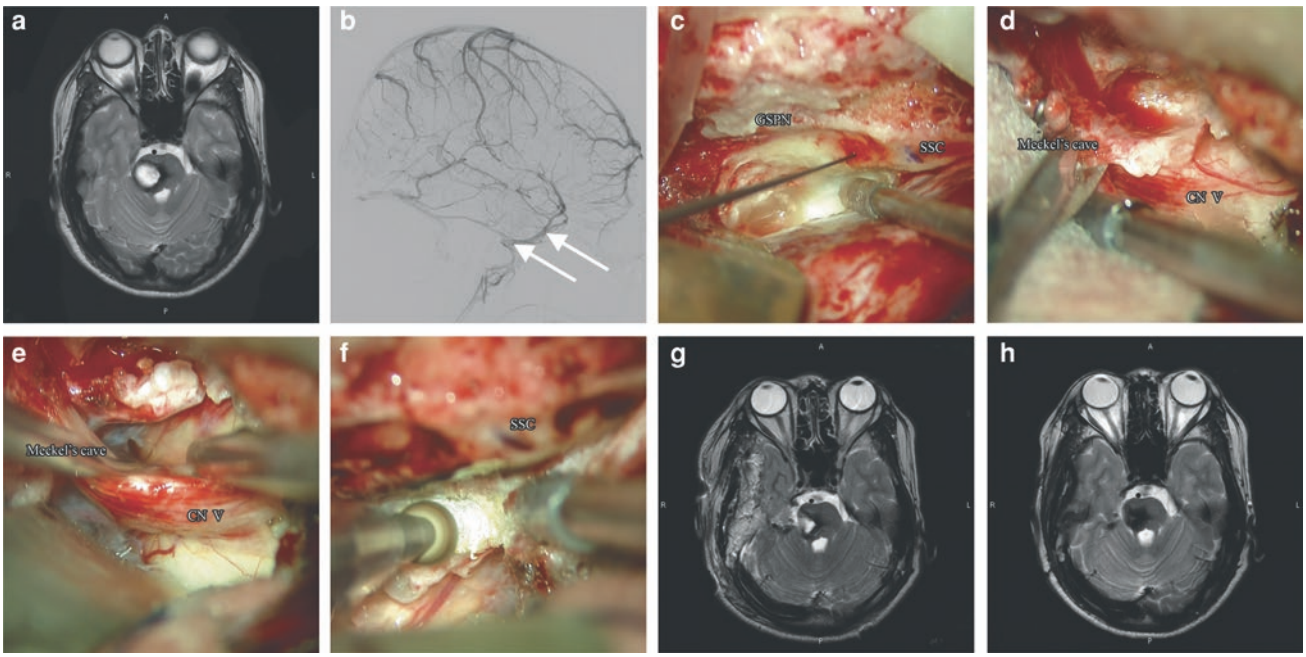

Fig. 4 A brain stem cavernoma excised via the anterior transpetrosal approach (Case 22). Preoperative T2-weighted magnetic resonance imaging (MRI) showed a right-side pontine cavernoma (**a**). A preoperative cerebral venogram of the right cerebral hemisphere (**b**) demonstrated large dominant sphenobasal vein (SpB–type venous drainage), which drained through the foramen ovale (*white arrows*). During surgery, Kawase's triangle was partially drilled until the posterior fossa dura was partially identified (**c**). After the temporal dura and the tentorial incisura were cut, Meckel's cave was opened (**d**). The trigeminal nerve (CN V) was mobilized in the medial–rostral direction (**e**) to achieve a wider and shallower angle for additional anterior petrosectomy, which was then performed after the dura around the petrous apex was dissected (**f**). T2-weighted MRI at 72 h (**g**) and at 1 year (**h**) after surgery revealed no abnormal signal intensity changes within the temporal lobe and confirmed complete removal of the lesion. *GSPN* Greater superficial petrosal nerve, *SSC* Superior semicircular canal

Discussion

The transpetrosal approach is useful to gain access to various types of deep-seated lesions adjacent to the skull base. It can provide a wide surgical window to the posterior cavernous, clival, petroclival, brain stem, and retrochiasmatic areas, with minimal brain retraction. However, because of the complexity, the time-consuming procedure, and the risk of associated morbidity, the transpetrosal approach remains challenging for neurosurgeons. Among postoperative complications, those related to venous compromise are the most catastrophic. If blood outflow from the brain is obstructed during surgery in the absence of collateral pathways, venous infarction may occur [26]; however, there is no pre- or intraoperative predictive methods to judge whether venous drainage can be sacrificed safely [27, 28].

To reduce such complications, injury of any venous structures should be avoided. As the venous drainage pattern is different in each patient, its detailed evaluation and full understanding before surgery with subsequent executing the procedure on the basis of specific individual detail of the blood outflow are the most important factors for safely performing transpetrosal approach, which are indispensable for avoidance of postoperative venous complications [28]. There are three steps in this procedure that may result in injury of venous structures: posterior petrosectomy, anterior petrosectomy, and tentorial incision. Specifically, the transverse and sigmoid sinuses can be damaged during posterior petrosectomy; SpB-type drainage can be obstructed during dural reflection around the foramen ovale in anterior petrosectomy; whereas the PV, the vein of Labbé, and SpPS can be harmed during tentorial incision and SPS transection.

Various techniques to deal with distinctive venous variations in the transpetrosal approach have been reported previously. For example, some authors encourage ligation and cutting of the SPS at its connection to the junction of transverse and sigmoid sinuses [5, 7, 29]; however, this technique carries a potential risk of injuring the PV and the vein of Labbé, which in some series reportedly led to postoperative venous complications [17, 20, 30–34]. Hafez et al. [35] introduced a new technique to preserve the SPS while performing the transpetrosal approach, but it provides too narrow operative corridor allowing only limited surgical manipulations. Although several methods have been reported to deal with dangerous venous drainage, the same operative procedures cannot be applied—or, at least, they are not easy to apply—to all variations of the blood outflow patterns [36–38]. On the other hand, the surgical strategy presented by us herein is simple and can be used consistently and safely in clinical situation with any type of venous drainage.

In cases with an SMCV that mainly drains to the SpB venous channel, occlusion of the blood outflow around the foramen ovale during peeling of the dura propria can result in major venous obstruction. Consequently, the dural reflection is limited, causing the surgical corridor to become steep and narrow. In such situation, described extradural combined with intradural anterior petrosectomy is useful.

In cases with an SMCV that mainly drains to the SpPS, intraoperative prolonged brain retraction together with impaired blood outflow after tentorial sectioning and an occluded SpPS may lead to postoperative complications. In particular, venous infarction occurs when normal blood outflow is compromised with prolonged intraoperative brain retraction, under extraordinary physiological conditions (e.g., excessive changes in systemic blood pressure), or in elderly patients [39]. Occlusion of dominant blood outflow pathways combined with brain retraction is associated with a higher risk of related complications than venous occlusion or brain compression alone [39, 40]. Staged operation may be a solution in such cases, as has been reported by our group previously [25]. The time lag between first- and second-stage procedure should be sufficiently long to allow development of anastomotic collateral venous pathways; therefore, temporal lobe retraction in the second surgery can be performed more safely without any concerns regarding blood outflow obstruction.

Although sectioning of the SPS and tentorium is a routine procedure in the transpetrosal approach to achieve a wider operative field, the optimal means of dural incision in such cases remains a matter of debate. The most important point is how to safely perform dural–tentorial cutting while preserving adequate venous drainage of the temporal lobe and posterior fossa structures, specifically through the vein of Labbé and PV. Notably, complications after PV injury have been reported previously [30–34], thus making consequences of its sacrifice unpredictable; accordingly, preservation of the PV seems important. Therefore, in all ATPA cases, we performed safe sectioning by cutting the SPS and tentorium as anteriorly as possible to avoid compromise of the venous outflow via the PV. Similarly, in cases treated with the CTPA, we developed a method of dural incision to confirm insertion of the PV into the SPS before transection of the latter, in order to avoid any reduction of venous outflow through the PV [24].

With the use of described surgical strategy in the presented series of 74 patients, there were no major complications related to venous compromise. In all patients with newly appeared postoperative symptoms (9 cases), those ones were fully relieved after conservative treatment. Although permanent T2 signal intensity changes were recognized on MRI in three cases, they did not appear to result from venous injury

during executing the transpetrosal approach. Therefore, our simple and straightforward surgical protocol to preserve blood outflow may be considered useful for prevention of venous complications.

Conclusion

Herein, we have presented our surgical strategy for safe executing the transpetrosal approach, which can be applied to any type of venous drainage pattern and allows to avoid postoperative complications caused by venous compromise. Preoperative evaluation of the venous drainage pattern in each patient and preservation of the blood outflow pathways during surgery are crucial means for safe and effective application of the transpetrosal approach.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Hakuba A, Nishimura S, Inoue Y. Transpetrosal–transtentorial approach and its application in the therapy of retrochiasmatic craniopharyngiomas. Surg Neurol. 1985;24:405–15.
2. Kawase T, Toya S, Shiobara R, Mine T. Transpetrosal approach for aneurysms of the lower basilar artery. J Neurosurg. 1985;63:857–61.
3. Kawase T, Shiobara R, Toya S. Anterior transpetrosal–transtentorial approach for sphenopetroclival meningiomas: surgical method and results in 10 patients. Neurosurgery. 1991;28:869–76.
4. Al-Mefty O, Ayoubi S, Kadri PA. The petrosal approach for the total removal of giant retrochiasmatic craniopharyngiomas in children. J Neurosurg. 2007;106(2 Suppl):87–92.
5. Al-Mefty O, Fox JL, Smith RR. Petrosal approach for petroclival meningiomas. Neurosurgery. 1988;22:510–7.
6. Bertalanffy H, Benes L, Miyazawa T, Alberti O, Siegel AM, Sure U. Cerebral cavernomas in the adult. Review of the literature and analysis of 72 surgically treated patients. Neurosurg Rev. 2002;25:1–55.
7. Cho CW, Al-Mefty O. Combined petrosal approach to petroclival meningiomas. Neurosurgery. 2002;51:708–18.
8. Erkmen K, Pravdenkova S, Al-Mefty O. Surgical management of petroclival meningiomas: factors determining the choice of approach. Neurosurg Focus. 2005;19(2):E7.
9. François P, Ben Ismail M, Hamel O, Bataille B, Jan M, Velut S. Anterior transpetrosal and subtemporal transtentorial approaches for pontine cavernomas. Acta Neurochir (Wien). 2010;152:1321–9.
10. Gross BA, Dunn IF, Du R, Al-Mefty O. Petrosal approaches to brainstem cavernous malformations. Neurosurg Focus. 2012;33(2):E10.
11. Hauck EF, Barnett SL, White JA, Samson D. The presigmoid approach to anterolateral pontine cavernomas. J Neurosurg. 2010;113:701–8.
12. Ichinose T, Goto T, Morisako H, Takami T, Ohata K. Microroll retractor for surgical resection of brainstem cavernomas. World Neurosurg. 2010;73:520–2.
13. Ohue S, Fukushima T, Kumon Y, Ohnishi T, Friedman AH. Surgical management of brainstem cavernomas: selection of approaches and microsurgical techniques. Neurosurg Rev. 2010;33:315–24.
14. Oiwa Y, Nakai K, Masaki Y, Masuo O, Kuwata T, Moriwaki H, Itakura T. Presigmoid approach for cavernous angioma in the pons—technical note. Neurol Med Chir (Tokyo) 2002;42:91–98.
15. Saito N, Sasaki T, Chikui E, Yuyama R, Kirino T. Anterior transpetrosal approach for pontine cavernous angioma—case report. Neurol Med Chir (Tokyo). 2002;42:272–4.
16. Shimamoto Y, Kawase T, Sasaki H, Shiobara R, Yamada F. Anterior transpetrosal approach to the prepontine epidermoids. Skull Base Surg. 1999;9:75–80.
17. Inamasu J, Shiobara R, Kawase T, Kanzaki J. Haemorrhagic venous infarction following the posterior petrosal approach for acoustic neurinoma surgery: a report of two cases. Eur Arch Otorhinolaryngol. 2002;259:162–5.
18. Kaplan HA, Browder J. Importance of veins in partial cerebral lobectomy. J Neurosurg. 1974;41:360–6.
19. Krisht AF, Barrow DL, Al-Mefty O, Dawson R, Shengelala G, Bonner G. Venous anatomy of the vein of Labbé complex. In: Hakuba A, editor. Surgery of the intracranial venous system. New York: Springer; 1996. p. 36–42.
20. Leonetti JP, Reichman OH, Silberman SJ, Gruener G. Venous infarction following translabyrinthine access to the cerebellopontine angle. Am J Otol. 1994;15:723–7.
21. Hacker H. Normal supratentorial veins and dural sinus. In: Newton TH, Potts DG, editors. Radiology of the skull and brain. Saint Louis: Mosby; 1974. p. 1851–77.
22. Garcia-Ibanez E, Garcia-Ibanez JL. Middle fossa vestibular neurectomy: a report of 373 cases. Otolaryngol Head Neck Surg. 1980;88:486–90.
23. Ohata K, Baba M. Anterior transpetrosal–transtentorial approach. In: Hakuba A, editor. Surgical anatomy of the skull base. Tokyo: Miwa Shoten; 1996. p. 77–107.
24. Immadoel Haq IB, Susilo IR, Goto T, Ohata K. Dural incision in the petrosal approach with preservation of the superior petrosal vein. J Neurosurg. 2016;124:1074–8.
25. Savardekar AR, Goto T, Nagata T, Ishibashi K, Terakawa Y, Morisako H, Ohata K. Staged 'intentional' bridging vein ligation: a safe strategy in gaining wide access to skull base tumors. Acta Neurochir (Wien). 2014;156:671–9.
26. Al-Mefty O, Krisht A. The dangerous veins. In: Hakuba A, editor. Surgery of the intracranial venous system. New York: Springer; 1996. p. 338–45.
27. Guppy KH, Origitano TC, Reichman OH, Segal S. Venous drainage of the inferolateral temporal lobe in relationship to transtemporal/transtentorial approaches to the cranial base. Neurosurgery. 1997;41:615–20.
28. Sakata K, Al-Mefty O, Yamamoto I. Venous consideration in petrosal approach: microsurgical anatomy of the temporal bridging vein. Neurosurgery. 2000;47:153–61.
29. Al-Mefty O, Ayoubi S, Kadri PA. The petrosal approach for the resection of retrochiasmatic craniopharyngiomas. Neurosurgery. 2008;62(5 Suppl 2 Operative):ONS331–6.
30. Koerbel A, Gharabaghi A, Safavi-Abbasi S, Samii A, Ebner FH, Samii M, Tatagiba M. Venous complications following petrosal vein sectioning in surgery of petrous apex meningiomas. Eur J Surg Oncol. 2009;35:773–9.
31. Koerbel A, Wolf SA, Kiss A. Peduncular hallucinosis after sacrifice of veins of the petrosal venous complex for trigeminal neuralgia. Acta Neurochir (Wien). 2007;149:831–3.
32. Masuoka J, Matsushima T, Hikita T, Inoue E. Cerebellar swelling after sacrifice of the superior petrosal vein during microvascular decompression for trigeminal neuralgia. J Clin Neurosci. 2009;16:1342–4.
33. Strauss C, Naraghi R, Bischoff B, Huk WJ, Romstöck J. Contralateral hearing loss as an effect of venous congestion at the ipsilateral inferior colliculus after microvascular decom-

pression: report of a case. J Neurol Neurosurg Psychiatry. 2000;69:679–82.
34. Strauss C, Neu M, Bischoff B, Romstöck J. Clinical and neurophysiological observations after superior petrosal vein obstruction during surgery of the cerebellopontine angle: case report. Neurosurgery. 2001;48:1157–61.
35. Hafez A, Nader R, Al-Mefty O. Preservation of the superior petrosal sinus during the petrosal approach. J Neurosurg. 2011;114:1294–8.
36. Gupta SK, Salunke P. Intradural anterior petrosectomy for petroclival meningiomas: a new surgical technique and results in 5 patients: technical note. J Neurosurg. 2012;117:1007–12.
37. Ichimura S, Yoshida K, Kagami H, Inaba M, Orii M, Kitamura Y, Saga I, Toda M. Epidural anterior petrosectomy with subdural visualization of sphenobasal vein via the anterior transpetrosal approach—technical case report. Neurosurg Rev. 2012;35:609–14.
38. Shibao S, Toda M, Orii M, Fujiwara H, Yoshida K. Various patterns of the middle cerebral vein and preservation of venous drainage during the anterior transpetrosal approach. J Neurosurg. 2016;124:432–9.
39. Nakase H, Shin Y, Nakagawa I, Kimura R, Sakaki T. Clinical features of postoperative cerebral venous infarction. Acta Neurochir (Wien). 2005;147:621–6.
40. Ohata K, Haque M, Morino M, Nagai K, Nishio A, Nishijima Y, Hakuba A. Occlusion of the sigmoid sinus after surgery via the presigmoidal–transpetrosal approach. J Neurosurg. 1998;89:575–84.

Injury of the Internal Carotid Artery During Dissection of a Craniopharyngioma via the Pterional Approach: Case Report

Kazuhiro Hongo, Keiichi Sakai, Tetsuya Goto, and Tetsuyoshi Horiuchi

Abstract

Among the various causes of intraoperative neurosurgical complications, a major arterial injury is one of the most devastating. Herein, the authors present a case of a 76-year-old patient who underwent removal of a craniopharyngioma via the pterional approach and experienced severe damage of her sclerotic left internal carotid artery because it was retracted excessively by a brain spatula, which resulted in complete sacrifice of the vessel. Despite stable parameters on intraoperative monitoring of motor evoked potentials and sufficient collateral blood flow, confirmed by Doppler flowmetry, a large infarct in the left cerebral hemisphere was noted after surgery. Although retraction of movable arteries, veins, and cranial nerves can often be done safely during neurosurgical procedures for effective exposure of the operative field, forced displacement of a sclerotic internal carotid artery in its paraclinoid portion anchored to the fixed distal dural ring should definitely be avoided because it poses a significant risk of major vessel damage.

Keywords

Arterial injury · Brain retraction · Cerebral infarction · Complication · Craniopharyngioma · Neurosurgery · Postoperative stroke · Preventive measures · Pterional approach

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Introduction

Among the various causes of neurosurgical complications, arterial injury is one that may induce a prominent postoperative neurological deficits, which may be particularly severe if a major artery is damaged. Such an unfavorable event may occasionally result from retraction of a vessel by a brain spatula. This surgical technique is used routinely during neurosurgical procedures for effective exposure of the operative field during clipping of intracranial aneurysms or skull base tumor resection [1–5]. However, if the vessel is sclerotic, excessive retraction from the site where its proximal part is anchored to the fixed structure, such as the distal dural ring for the internal carotid artery (ICA), may result in damage of the vascular wall. Herein, we report a case of a severe arterial injury during dissection of a craniopharyngioma in an elderly patient and discuss possible preventive measures for avoidance of such a complication.

Case Report

A 76-year-old woman noticed gradual worsening of visual acuity, and her initial ophthalmological examination revealed a lateral upper-quadrant visual field defect in the right eye. Subsequent computed tomography (CT) and magnetic resonance imaging (MRI) demonstrated a contrast-enhancing sellar mass (maximal diameter 33 mm) with a prominent suprasellar extension, multiple intralesional cysts, and calcifications (Fig. 1). She was referred to our center for surgical treatment. At admission, her visual acuity was 0.3 in the right eye and 1.0 in the left eye, and there was right-side hemianopsia, which was more prominent in the right eye. Endocrinological examination did not demonstrate hormonal changes, besides an increase in the prolactin level to 52.2 ng/mL. The diagnosis of craniopharyngioma was established, and tumor resection was planned.

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_5

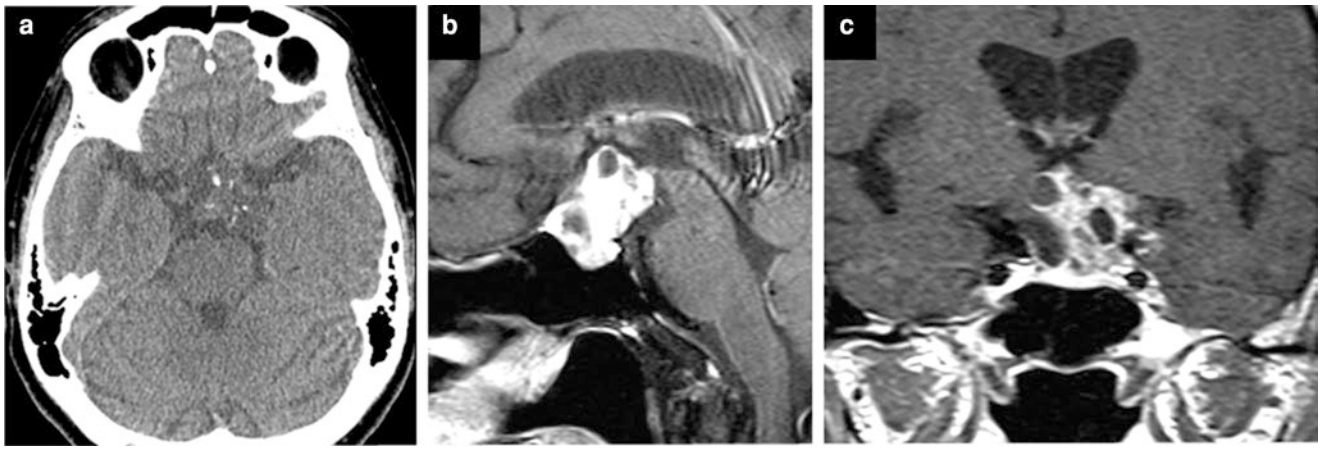

Fig. 1 Preoperative imaging of a 76-year-old woman with a visual field defect. Plain computed tomography (**a**) and sagittal (**b**) and coronal (**c**) postcontrast T1-weighted magnetic resonance imaging demonstrate a contrast-enhancing sellar mass (maximal diameter 33 mm) with a prominent suprasellar extension, multiple intralesional cysts, and calcifications

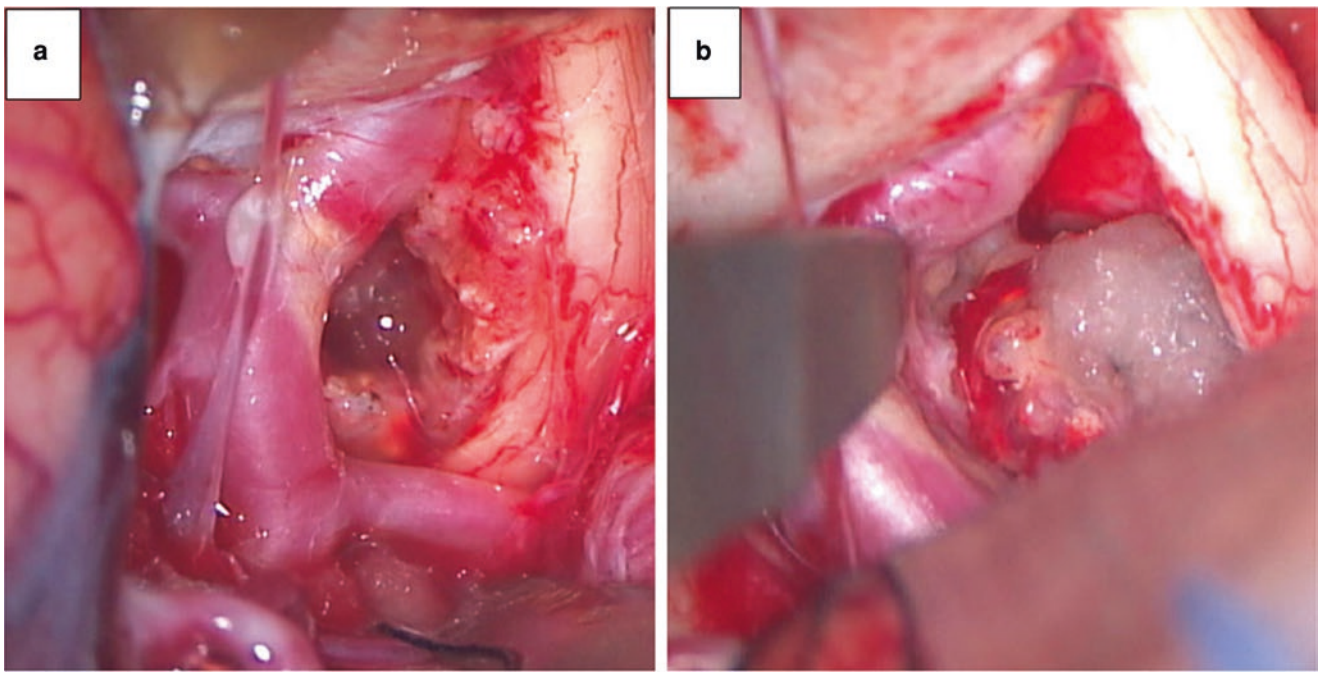

Fig. 2 Intraoperative photographs during removal of a craniopharyngioma via the left-side pterional approach. The left internal carotid artery, demonstrating severe sclerotic changes (**a**), was retracted laterally by a brain spatula to widen the opticocarotid space (**b**)

Surgery

Surgery was performed under general anesthesia, with the patient in a supine position. Left-side frontotemporal craniotomy with zygomatic osteotomy was done. The dura mater was opened, and the Sylvian fissure was widely dissected as appropriate. Initially, the part of the tumor located in the prechiasmatic cistern was removed to decompress the right optic nerve. Thereafter, the lesion was accessed via the opticocarotid space, and the left ICA was repeatedly retracted laterally by a brain spatula to widen the operative field (Fig. 2). During this manipulation, excessive bleeding was noted and a small hole in the medial wall of the severely sclerotic ICA was revealed. During compression of the bleeding point with a spatula adjusted to maintain anterograde carotid blood flow, the anterior clinoid process was removed to obtain access to the proximal ICA. Attempts to suture the tearing arterial wall with 8-0 nylon were unsuccessful and, in fact, resulted in gradual enlargement of the hole. This eventually led to complete breakage of the ICA, which necessitated both proximal and distal permanent vessel clipping. Nevertheless, the motor evoked potentials

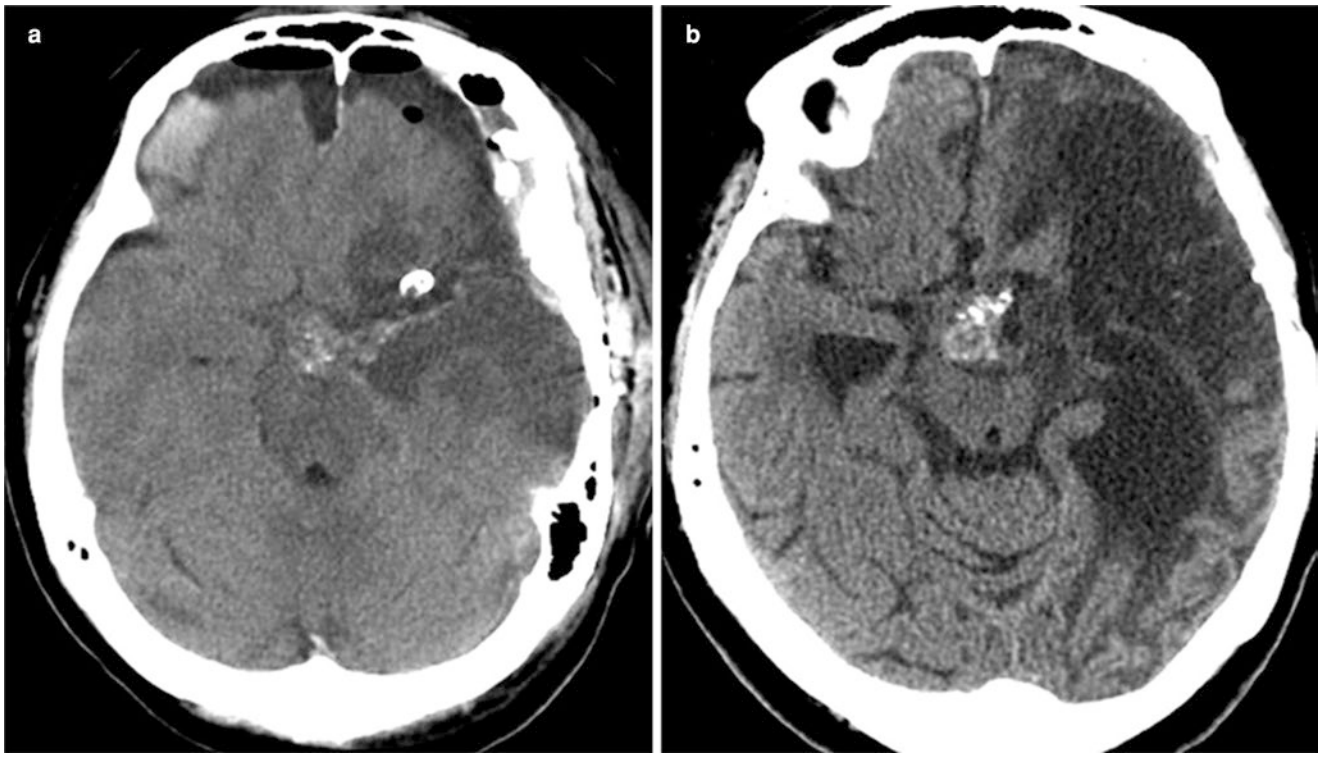

Fig. 3 Computed tomography 2 days (**a**) and 4 years (**b**) after partial removal of a craniopharyngioma complicated by intraoperative injury and complete sacrifice of the left internal carotid artery demonstrate a large infarct in the left cerebral hemisphere

(MEP) did not show attenuation, and Doppler flowmetry demonstrated good blood flow within the distal ICA and the left middle cerebral artery (MCA) due to collateral blood flow through the posterior communicating and anterior communicating arteries. Therefore, emergency vascular reconstruction with a high-flow bypass for brain revascularization was considered unnecessary.

The tumor around the left ICA was further removed to obtain adequate decompression of the left optic nerve. The pituitary stalk was identified and kept intact. Since the MEP temporarily decreased during surgical manipulations around the posterior communicating artery, no further lesion removal was attempted. Immaculate hemostasis was accomplished, and the procedure was completed in the regular way.

Postoperative Course

Immediately after surgery, the patient showed right-side hemiplegia. CT demonstrated the residual tumor and a large infarct in the left cerebral hemisphere (Fig. 3a). Upon postoperative recovery, the patient was transferred to a neurorehabilitation facility. Follow-up CT four years after surgery demonstrated a stable residual tumor, along with severe atrophic changes in the left cerebral hemisphere (Fig. 3b).

Discussion

In the presented case, the left ICA was inadvertently injured during surgery because of excessive retraction by a brain spatula, and, as was noticed retrospectively on the intraoperative video, a subadventitial hemorrhage occurred just before laceration of the arterial wall and the appearance of major bleeding. Several important lessons can be learned from this unfavorable experience for avoidance of such a complication in one's practice.

First, during neurosurgical procedures, major arteries, their branches, cerebral veins, and cranial nerves can often be safely retracted to some extent, which depends on their movability without stretching. In many cases, this can be very helpful for effective exposure of the operative field. However, excessive retraction of sclerotic arteries should be avoided because their walls may be too fragile.

Second, any displacement of the paraclinoid portion of the ICA should always be done very carefully and gently because of its tight proximal anchoring to the fixed distal dural ring. This makes the situation different from those involving the more movable MCA or basilar artery.

Third, visualization of the operative field from different angles may allow one to avoid the need for prominent retraction of critical anatomical structures, and minimal displacement of arteries and cranial nerves with a brain spatula or

other microsurgical instruments may provide a sufficient view behind them [1–5]. As a rule of thumb, neurosurgical procedures directed at clipping of intracranial aneurysms or skull base tumor resection should be consistently conducted under direct visual control, which requires frequent changes in the positioning of the operating microscope.

Finally, severe postoperative hemodynamic abnormalities may appear despite stable parameters on intraoperative monitoring of the MEP and even confirmation of sufficient collateral blood flow by Doppler flowmetry, indicating the diagnostic limitations of these routinely applied techniques, which should be taken into consideration during surgical decision-making.

Conclusion

Excessive retraction of a sclerotic ICA in its paraclinoid portion is accompanied by a significant risk of vessel injury and should be avoided, whenever possible, to prevent major postoperative neurological deterioration.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Hongo K, Tanaka Y, Horiuchi T, Tada T, Kobayashi S. Internal carotid artery rotation technique to expose an aneurysm neck: technical note. Neurosurgery. 2003;52:455–7.
2. Kobayashi S, Kyoshima K, Gibo H, Hegde SA, Takemae T, Sugita K. Carotid cave aneurysms of the internal carotid artery. J Neurosurg. 1989;70:216–21.
3. Sugita K, Kobayashi S. Aneurysm. In: Sugita K, editor. Microneurosurgical atlas. Berlin: Springer; 1985. p. 10–135.
4. Sugita K, Kobayashi S, Takemae T, Matsuo K, Yokoo A. Direct retraction method in aneurysm surgery: technical note. J Neurosurg. 1980;53:417–9.
5. Sugita K, Kobayashi S, Takemae T, Tada T, Tanaka Y. Aneurysms of the basilar artery trunk. J Neurosurg. 1987;66:500–5.

Catastrophic Outcome Following Apparently Trivial Nondominant Transverse Sinus Injury During Resection of a Tentorial Meningioma: Case Report

Keki E. Turel and Mazda K. Turel

Abstract

A 52-year-old man was admitted to our hospital with symptoms of raised intracranial pressure and cerebellar dysfunction caused by a medium-sized (4 cm in diameter) tentorial meningioma with an infratentorial extension. Preoperative magnetic resonance imaging showed that the tumor indented and possibly partially invaded the adjacent junction of the nondominant transverse and sigmoid sinuses. The contralateral dominant transverse sinus was fully patent. Total surgical removal of the lesion was done through the left retrosigmoid approach. During dissection of the meningioma, some bleeding from the venous sinus was noted, which was easily controlled by packing with hemostatic materials. The initial postoperative period was unremarkable, but approximately 48 h after surgery, acute clinical deterioration caused by hemorrhagic venous infarction of the left cerebellar hemisphere and brain stem developed and necessitated urgent reoperation for the evacuation of hematoma and brain decompression. Thereafter, the patient remained in a prolonged coma with a severe neurological deficit. After several years of extensive neurorehabilitation, he was able to walk with support but had a tracheostomy, required a feeding tube, and voided with a urinary catheter. Such a catastrophic outcome after an apparently trivial nondominant transverse sinus injury during resection of a tentorial meningioma raises the question whether reconstruction of the sinus wall with preservation of its patency might have prevented this complication in our patient.

Keywords

Cerebral venous infarction · Complication · Neurosurgery · Tentorial meningioma · Transverse sinus thrombosis

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Introduction

Tentorial meningiomas represent approximately 5% of all intracranial meningiomas, usually occur in women, and most often manifest with symptoms of raised intracranial pressure (ICP) and cerebellar dysfunction, whereas a cranial nerve deficit is rare [1, 2]. Surgical removal is the method of choice for management of these tumors. Nevertheless, an important role of the adjacent dural sinuses in venous drainage of the brain makes resection of a tentorial meningioma challenging even if the intervention is performed by experienced hands [3]. In different series, the postoperative morbidity rates have ranged from 19% to 77% [4]. The complexity of the operation is increased further if the tumor extends into both supra- and infratentorial compartments.

Herein, we present a case of 52-year-old man who underwent total excision of a tentorial meningioma with an infratentorial extension. He experienced a turbulent postoperative course caused by hemorrhagic venous infarction of the cerebellum, which resulted in severe permanent neurological deficit.

Case Report

A 52-year-old businessman was admitted to our hospital with a 6-month history of a progressive headache, imbalance while walking, and occasional mental clouding. There were no episodes of vomiting, diplopia, seizures, loss of consciousness, motor weakness, or sensory disturbances. A neurological examination revealed signs of left cerebellar dysfunction with gait ataxia, but his motor, sensory, and cranial nerve functions were well preserved. Magnetic resonance imaging (MRI) disclosed a medium-sized (4 cm in diameter) extra-axial contrast-enhanced tumor compressing the left cerebellar hemisphere, with a

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_6

broad-based attachment to the tentorium, which was highly suggestive of a meningioma (Fig. 1). According to the MRI, the tumor indented and possibly partially invaded an adjacent junction of the transverse and sigmoid sinuses. Magnetic resonance venography (MRV) showed good filling of the dominant transverse sinus on the contralateral (right) side.

Surgery

The patient was operated on in the prone ("Concorde") position. A left retrosigmoid craniotomy was done, and the tentorial meningioma was revealed. The tumor attachment to the tentorium was coagulated and cut, and internal debulking of the mass was performed. The interface between the tumor capsule and the adjacent cerebellum was well preserved, which facilitated their separation and total excision of the mass lesion. At the final stage of surgery, during dissection of the residual portion of the meningioma from the junction of the transverse and sigmoid sinuses, some bleeding from the sinus was noted, which was easily controlled by packing with Surgicel® and Gelfoam®. Total tumor removal was accomplished, complete hemostasis was attained, the dura mater was closed, the bone flap was replaced, and the wound was sutured in layers.

Postoperative Course

Initially, the postoperative recovery of the patient was unremarkable. He stayed overnight in the intensive care unit and was transferred to the ward on the day after surgery. At that time, computed tomography (CT) demonstrated the usual postoperative tissue changes, with no evidence of any hemorrhage or hydrocephalus (Fig. 2a–c).

However, on the second postoperative day (approximately 48 h after the operation), a sudden-onset headache occurred, accompanied by several episodes of vomiting, rapid deterioration of consciousness, and bradycardia. Urgent CT showed hemorrhagic venous infarction of the left cerebellar hemisphere and brain stem, with compression of the fourth ventricle and acute obstructive hydrocephalus (Fig. 2d–f). An emergency reoperation was done, entailing evacuation of a hematoma and infarcted tissue of the left cerebellar hemisphere, followed by lax duraplasty and removal of the bone flap. An Ommaya reservoir was implanted into the lateral ventricle for control of the hydrocephalus. Immediate postoperative CT confirmed appropriate removal of the blood clot, adequate internal and external decompression, and no worsening of the hydrocephalus (Fig. 3).

During the first postoperative week, the patient was kept on a ventilator. During this time, his Glasgow Coma Scale (GCS) score was 4T (out of 10T), skew deviation of the eyes with reacting pupils was observed, and the cough reflex was preserved. Thereafter, a tracheotomy was done. MRI two weeks after the reoperation showed abnormal signal hyperintensity in the area of the right basal ganglia and internal capsule, residual blood within both lateral ventricles, and widespread hyperintensity with restricted diffusion in the periaqueductal region, ventral pons, and dorsal midbrain, suggestive of ischemic tissue injury (Fig. 4a–c). MRV showed occlusion of the left transverse sinus and a patent dominant right transverse sinus, with preserved drainage through the superficial and deep brain venous system (Fig. 4d, e).

The patient underwent extensive neurorehabilitation. Four years later, he was able to walk with support but had a tracheostoma, required a feeding tube, and voided with a urinary catheter.

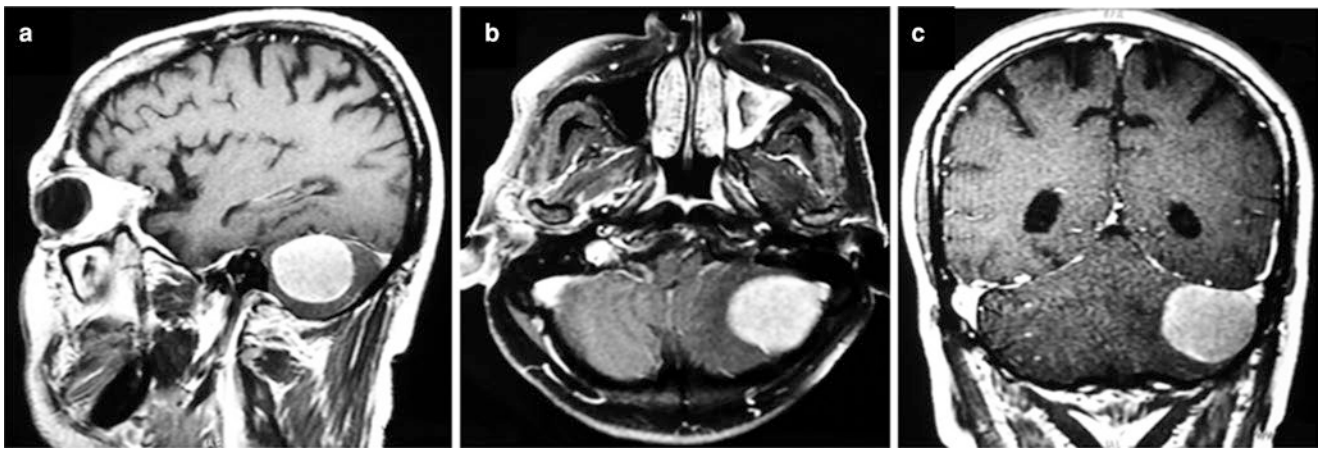

Fig. 1 Preoperative postcontrast T1-weighted magnetic resonance imaging in the sagittal (**a**), axial (**b**), and coronal (**c**) planes demonstrates a tentorial meningioma compressing the left cerebellar hemisphere, with indentation and possible invasion of the adjacent junction of the transverse and sigmoid sinuses

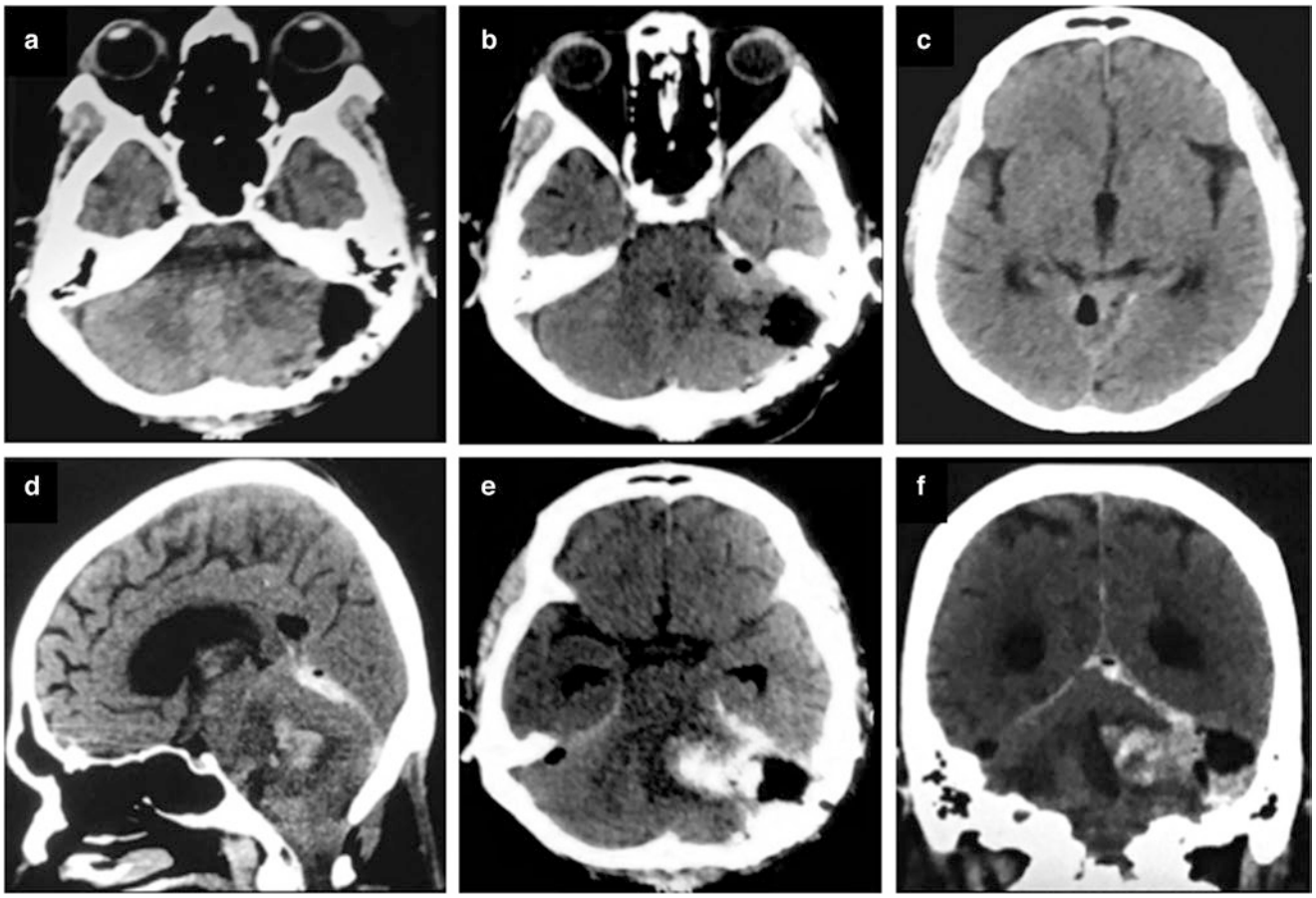

Fig. 2 Computed tomography after tumor resection (*upper row*) and at the time of the patient's clinical deterioration 2 days after surgery (*lower row*). While only usual postoperative tissue changes after complete removal of the mass were demonstrated initially (**a**–**c**), a subsequent urgent examination disclosed hemorrhagic venous infarction of the left cerebellar hemisphere and brain stem, with compression of the fourth ventricle and acute obstructive hydrocephalus (**d**–**f**)

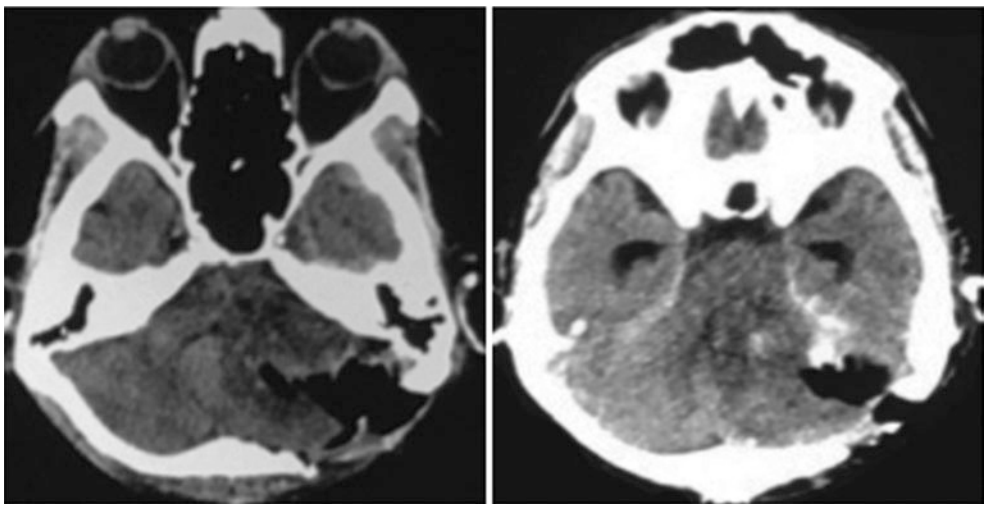

Fig. 3 Computed tomography after emergency reoperation, demonstrating removal of a hematoma and appropriate internal and external decompression

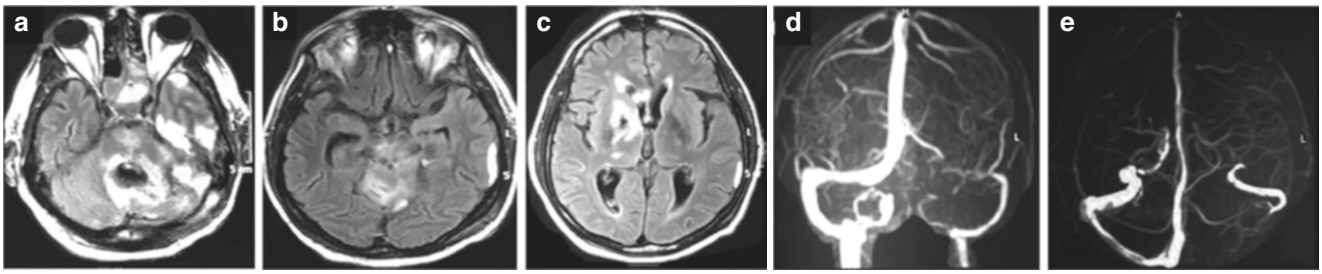

Fig. 4 Fluid-attenuated inversion recovery magnetic resonance imaging and magnetic resonance venography 2 weeks after emergency reoperation, demonstrating diffuse hyperintensity in the periaqueductal region, ventral pons, and dorsal midbrain (**a**, **b**); abnormal signal hyperintensity in the area of the right basal ganglia and internal capsule (**c**); and an occluded left transverse sinus and patent dominant right transverse sinus (**d**, **e**)

Discussion

During planning of surgery for tumors affecting the major dural sinuses, a decision should be made as to whether to undertake conservative or aggressive resection. The former usually includes debulking of the mass, separation of its surface from the adjacent neurovascular structures, maximal removal of the neoplasm with excision of any involved portion of the dura mater, and dissection of the lesion from the outer wall of the venous sinus, but without manipulation of the sinus itself. In contrast, the more aggressive surgical strategy entails opening of the sinus and removal of the tumor portion inside it, followed by sinus reconstruction or ligation [1, 2, 4]. Of note, radical surgical removal of meningiomas invading the major dural sinuses still remains controversial, and it is widely considered that near-total or subtotal resection may be sufficient in such cases.

For determination of the optimal treatment strategy, many surgeons rely on the status of the venous circulation, and their clinical decision-making is influenced by the anticipated risks, which are (obviously) regarded differently in cases with a stenotic but still patent sinus rather than a completely occluded sinus [5–7]. MRV is an invaluable imaging modality for noninvasive preoperative evaluation of the venous anatomy, the patency of the venous sinuses, and the outflow patterns, including the presence of large draining veins, collateral vessels, or aberrant drainage pathways. In cases of tentorial meningiomas, evaluation of the venous blood flow through the deep and superficial cerebral veins is particularly important. Special emphasis should be put on assessment of the vein of Labbé and the location of its entry into the transverse sinus with regard to the area of tumor attachment [1].

In the presented case, preoperative imaging showed that the lesion barely indented the junction of the nondominant transverse and sigmoid sinuses, with good filling of the dominant transverse sinus on the contralateral side. It is generally believed that tumor removal can usually be done rather safely if the patency of the adjacent venous sinus is preserved before surgery [5]. Therefore, we decided to achieve complete removal of the tentorial meningioma but did not plan to manipulate the transverse sinus. The latter was, however, inadvertently opened in its distal part (at the junction with sigmoid sinus) during dissection of the mass. Considering that this sinus was nondominant, it was packed with hemostatic materials, which provided good control of venous bleeding. The question remains as to whether reconstruction of the sinus wall and preservation of the sinus patency would have prevented our patient's catastrophic complication and poor outcome.

Conclusion

Resection of a tentorial meningioma involving the transverse sinus should be carefully planned on an individual case-by-case basis. The surgical decision-making should be based on multiple issues, including (but not limited to) general prognostic factors (e.g., the patient's age), the anatomy of the venous outflow, the patency of the sinus and the degree of its invasion by the tumor, and the practical experience of the surgeon. Nevertheless, in addition to meticulous preoperative planning of the mass removal, one should always be ready to encounter an inadvertent sinus injury during surgery; thus, an applied management strategy for such an event should be prearranged in detail and borne in mind.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Mazur MD, Cutler A, Couldwell WT, Taussky P. Management of meningiomas involving the transverse or sigmoid sinus. Neurosurg Focus. 2013;35(6):E9.
2. Nanda A, Patra DP, Savardekar A, Maiti TK, Konar SK, Notarianni C, Guthikonda B, Bir SC. Tentorial meningiomas: reappraisal

of surgical approaches and their outcomes. World Neurosurg. 2018;110:e177–96.
3. Shukla D, Behari S, Jaiswal AK, Banerji D, Tyagi I, Jain VK. Tentorial meningiomas: operative nuances and perioperative management dilemmas. Acta Neurochir (Wien). 2009;151:1037–51.
4. Aguiar PH, Tahara A, de Almeida AN, Kurisu K. Microsurgical treatment of tentorial meningiomas: report of 30 patients. Surg Neurol Int. 2010;1:36.
5. Biroli A, Talacchi A. Surgical management of lateral tentorial meningiomas. World Neurosurg. 2016;90:430–9.
6. Hashemi M, Schick U, Hassler W, Hefti M. Tentorial meningiomas with special aspect to the tentorial fold: management, surgical technique, and outcome. Acta Neurochir (Wien). 2010;152:827–34.
7. Xiu C, Ma S, Zhang H, Wang Y, Yang J. Tentorial meningiomas: surgical options, clinical feature and management experience in 43 patients. Clin Neurol Neurosurg. 2015;130:128–33.

Postoperative Intratumoral or Peritumoral Hematomas After Vestibular Schwannoma Resection

Tetsuya Goto, Toshihiro Ogiwara, Kohei Kanaya, Ridzky Firmansyah Hardian, Yoshiki Hanaoka, Yu Fujii, Shunsuke Ichinose, and Kazuhiro Hongo

Abstract

Background: Surgical removal of a vestibular schwannoma is a complex and challenging procedure, which may be complicated by development of postoperative hematomas, particularly after incomplete resection of the tumor.

Objective: To investigate the occurrence of postoperative intra- or peritumoral hematomas after surgery for a vestibular schwannoma.

Methods: This retrospective study evaluated 49 patients (age range 17–78 years) with a vestibular schwannoma, who were treated surgically via the lateral suboccipital approach between 2011 and 2016. The tumors ranged in size from 0 mm (in a case of an intracanalicular lesion) to 56 mm. In 30 cases (61%), total or near-total resection was accomplished, and in 19 cases (39%), subtotal or partial resection was done. On the basis of their bleeding tendency during tumor removal, the patients were divided into a "less-bleeding" (38 cases; 78%) and a "more-bleeding" (11 cases; 22%) subgroups.

Results: A maximal vestibular schwannoma diameter >30 mm, patient age >60 years, and more bleeding during tumor removal were significantly associated with incomplete (subtotal or partial) resection. In six cases (12%), serial computed tomography after surgery demonstrated a postoperative hematoma, which was caused by insufficient irrigation of the surgical field (in two cases) or resulted from peritumoral hemorrhage (in two cases), intratumoral hemorrhage (in one case), or both intra- and peritumoral hemorrhage (in one case). The latter patient required urgent reoperation. In all cases, postoperative hematomas occurred after incomplete (subtotal or partial) resection of a vestibular schwannoma, and their development was significantly associated with more bleeding during tumor removal.

Conclusion: For avoidance of postoperative hematomas, careful hemostasis is required after completion of vestibular schwannoma removal, especially in cases with incomplete resection and an excessive bleeding tendency of the tumor tissue.

Keywords

Complication · Postoperative hematoma · Risk factors · Surgery · Vestibular schwannoma

Introduction

Surgical removal of a vestibular schwannoma (VS) still represents a complex and challenging procedure. When dissection from the adjacent functionally important structure(s) is difficult, part of the tumor is frequently intentionally left *in situ* for prevention of facial palsy, maintenance of hearing, and avoidance of brain stem dysfunction [1, 2]. After subtotal or partial resection of a VS, many patients may undergo regular surveillance with neuroimaging without any additional treatment [1, 2], whereas in cases of tumor regrowth, stereotactic radiosurgery (SRS) may be done. Nevertheless, incomplete resection of a VS is sometimes complicated by postoperative hematomas, which may lead to major neurological deterioration [3–5]. The aim of this retrospective study was to investigate the incidence of postoperative intra- or peritumoral hematomas after VS resection and to evaluate risk factors associated with this complication.

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_7

Table 1 Clinical characteristics of the 49 patients with vestibular schwannomas who were included in the present series

Clinical characteristic	Value
Sex (*n*)	
Male	23 (47%)
Female	26 (53%)
Age (years)	
Range	17–78
Mean	52
Maximal tumor diameter before surgery (mm)	
Range	0–56
Mean	27
Extent of resection (*n*)	
Total	20 (41%)
Near-total	10 (20%)
Subtotal	13 (27%)
Partial	6 (12%)
Bleeding tendency during tumor removal (*n*)	
Less bleeding	38 (78%)
More bleeding	11 (22%)
Postoperative hematoma (*n*)	6 (12%)

Materials and Methods

Between April 2011 and December 2016, 49 patients underwent surgery for VS at Shinshu University Hospital. This series included five cases of neurofibromatosis, one patient primarily treated with SRS, and four patients with initially implanted ventriculoperitoneal shunts.

The main characteristics of the study cohort are presented in Table 1. There were 23 men (47%) and 26 women (53%), aged from 17 to 78 years (mean age 52 years). The tumor size was measured as maximal diameter of its intracisternal portion at the level of the internal auditory canal on preoperative axial magnetic resonance imaging (MRI), which ranged from 0 mm (in a case of an intracanalicular VS) to 56 mm; the mean maximal diameter was 27 mm. All surgeries were done via the lateral suboccipital approach under comprehensive neurophysiological control (evoked facial electromyogram mapping, spontaneous facial electromyogram monitoring, facial motor evoked potential monitoring, auditory brain stem response monitoring, and cochlear nerve action potential monitoring) [6].

The extent of resection (EOR) and the bleeding tendency during VS removal were evaluated on the basis of the patients' operative records. The EOR was categorized as total (complete removal of the tumor), near-total (>99% removal), subtotal (90–99% removal), or partial (<90% removal). Regarding the bleeding tendency during tumor removal, the patients were divided into "less-bleeding" and "more-bleeding" subgroups: the former included cases with easy hemostasis during internal decompression and dissection of the VS, whereas the latter included tumors demonstrating somewhat excessive bleeding that was difficult to control by conventional methods.

Postoperative computed tomography (CT) was routinely performed immediately after surgery (on postoperative day [POD] 0) and on POD 1 and POD 7.

Statistical Analysis

A two-sided Fisher's exact test was used for statistical comparison of the evaluated variables. The level of statistical significance was defined as $P < 0.05$.

Results

Total, near-total, subtotal, and partial VS resections were attained in 20 cases (41%), 10 cases (20%), 13 cases (27%), and 6 cases (12%), respectively. A less-bleeding tendency and a more-bleeding tendency during tumor removal were noted in 38 cases (78%) and 11 cases (22%), respectively. Major complications after surgery were encountered in two patients (4%): persistent severe facial nerve palsy and a postoperative hematoma requiring reoperation (one case each).

Postoperative Hematomas

Postoperative intra- and/or peritumoral hematomas were identified on postoperative serial CT in six cases (12%).

In two patients (a 25-year-old woman and a 56-year-old man), hematomas were revealed on POD 0, were located in the cisternal portion, and did not increase in size on serial CT examinations; thus, they were considered to result from insufficient irrigation of the surgical field (Fig. 1); both patients had a smooth recovery from anesthesia and an uncomplicated postoperative course, and no additional treatment was required.

In four other patients who had a hematoma, it was evidently caused by postoperative bleeding, since it appeared on CT on POD 1 but was absent on POD 0. In two of them (a 43-year-old woman and a 50-year-old woman), the hematoma was located only in the resection cavity and was considered to result from postoperative peritumoral hemorrhage (Fig. 2); both patients had a smooth recovery from anesthesia and an uncomplicated postoperative course, and no additional treatment was required. In one patient (a 78-year-old woman with prominently reduced activities of daily living before surgery), a hematoma was caused by postoperative intratumoral hemorrhage (Fig. 3); she showed no neurological deterioration after surgery and was transferred to her referring physician for further treatment. Finally, in one patient (a 62-year-old woman with neurofibromatosis type 1), a hematoma was caused by

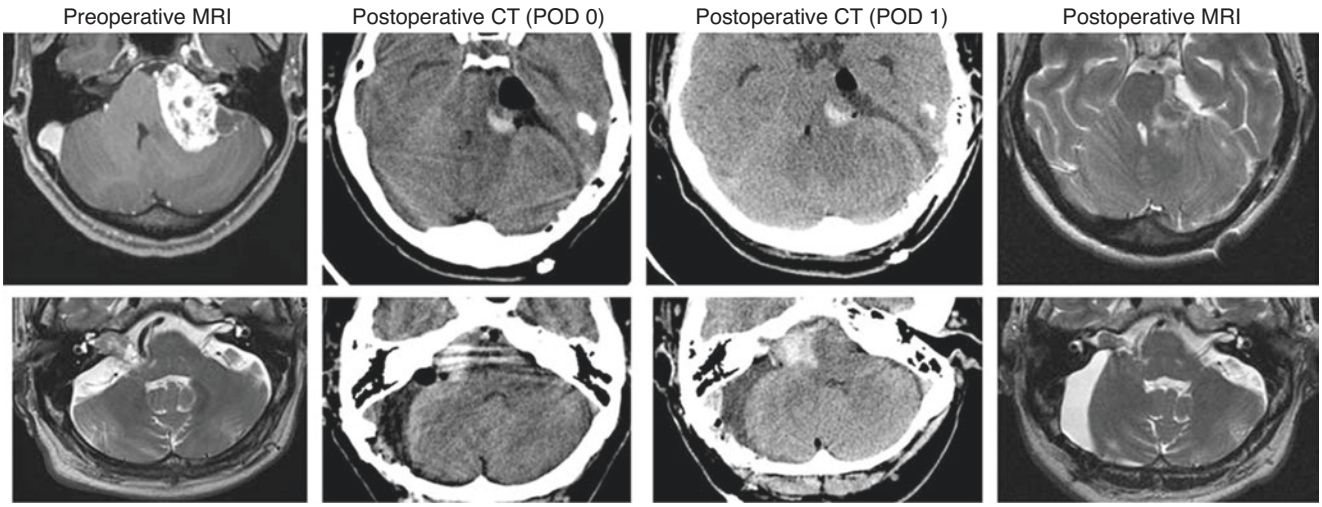

Fig. 1 Serial imaging in two patients with a hematoma after resection of a vestibular schwannoma, caused by insufficient irrigation of the surgical field. *Upper row*: images of a 25-year-old woman with a left-side tumor (maximal diameter 43 mm), which underwent partial resection characterized by a more-bleeding tendency. *Lower row*: images of a 56-year-old man with a right-side tumor (maximal diameter 13 mm), which underwent partial resection characterized by a more-bleeding tendency. *CT* Computed tomography, *MRI* Magnetic resonance imaging, *POD* Postoperative day

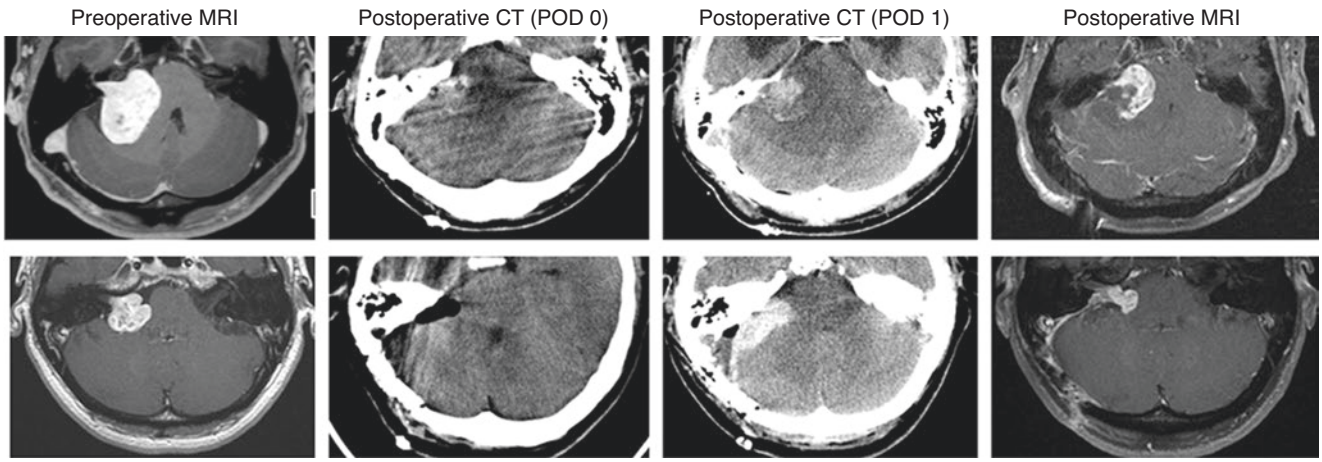

Fig. 2 Serial imaging in two patients with a hematoma after resection of a vestibular schwannoma, caused by postoperative peritumoral hemorrhage. *Upper row*: images of a 43-year-old woman with a right-side tumor (maximal diameter 41 mm), which underwent partial resection characterized by a more-bleeding tendency. *Lower row*: images of a 50-year-old woman with a right-side tumor (maximal diameter 25 mm), which underwent subtotal resection characterized by a more-bleeding tendency. *CT* Computed tomography, *MRI* Magnetic resonance imaging, *POD* Postoperative day

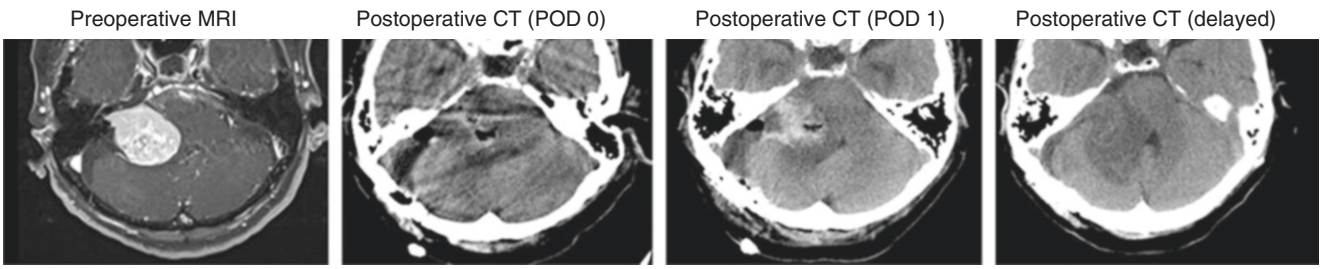

Fig. 3 Serial imaging in a patient with a hematoma after resection of a vestibular schwannoma, caused by postoperative intratumoral hemorrhage. This 78-year-old woman had a right-side tumor (maximal diameter 45 mm), which underwent partial resection characterized by a less-bleeding tendency. *CT* Computed tomography, *MRI* Magnetic resonance imaging, *POD* Postoperative day

both intra- and peritumoral (cerebellar) hemorrhage (Fig. 4). She had a a smooth recovery from anesthesia but complained of nausea. Clinical deterioration was noted 10 h after her surgery, when CT showed a postoperative hematoma. Salvage reoperation with the aim of hematoma removal was done; thereafter, the patient demonstrated a full recovery without any neurological deficit. It was suspected afterward that her cerebellar hemorrhage might have been caused by excessive cerebellar retraction during the initial surgery or might have resulted from occlusion of the superior petrosal vein.

Results of Statistical Analysis

The results of the statistical analysis are summarized in Fig. 5. Incomplete tumor resection (subtotal or partial) was done in 16 of 26 patients with either a maximal VS diameter >30 mm or age >60 years, and in 3 of 23 patients with a maximal VS diameter <30 mm and age <60 years (62% versus 13%; $P = 0.001$). Postoperative hematomas were noted in six of 19 patients after incomplete (subtotal or partial) tumor resection, but none occurred after complete (total or

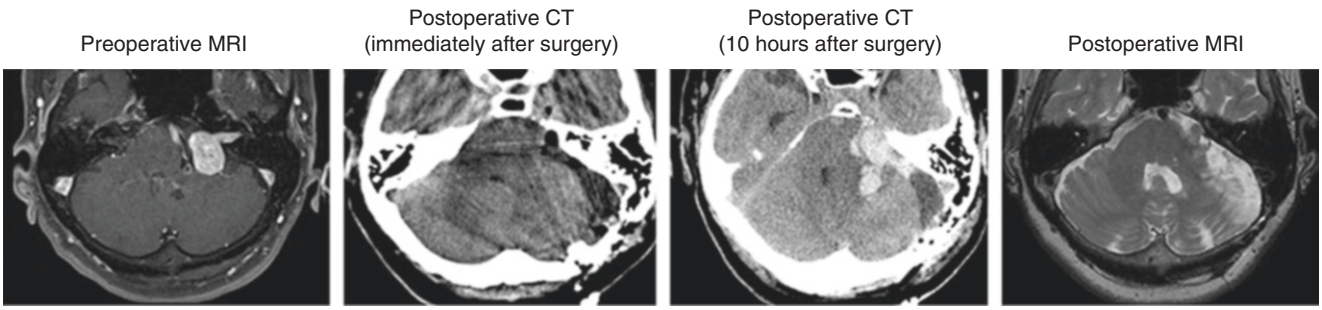

Fig. 4 Serial imaging in a patient with a hematoma after resection of a vestibular schwannoma, caused by postoperative intra- and peritumoral (cerebellar) hemorrhage. This 62-year-old woman with neurofibromatosis type 1 had a left-side tumor (maximal diameter 24 mm), which underwent subtotal resection characterized by a more-bleeding tendency. Clinical deterioration 10 h after the initial surgery necessitated salvage reoperation aimed at hematoma removal, resulting in full recovery of the patient. *CT* Computed tomography, *MRI* Magnetic resonance imaging, *POD* Postoperative day

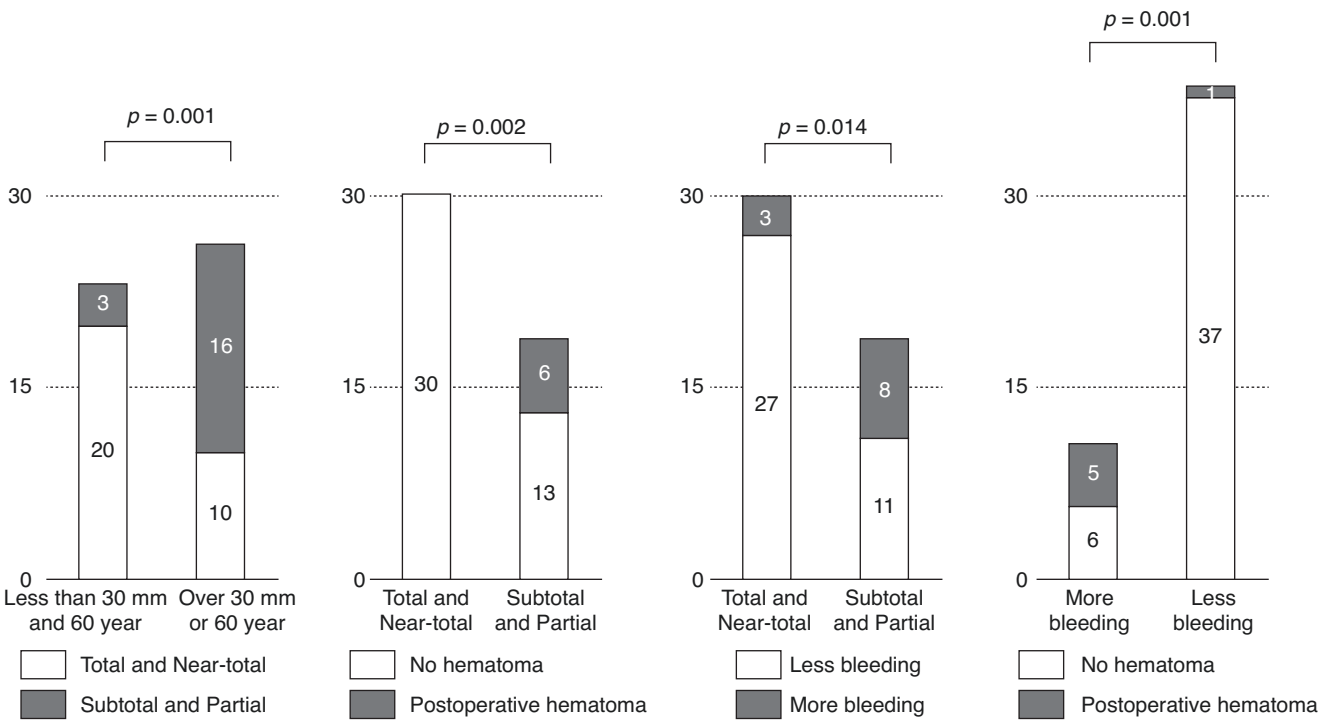

Fig. 5 Summary of the comparative analysis. The number of patients in each subgroup is indicated. All differences were statistically significant

near-total) resection (21% versus 0%; $P = 0.002$). More bleeding during tumor removal was noted in eight of 19 patients with incomplete (subtotal or partial) resection and in three of 30 patients with complete (total or near-total) resection (42% versus 10%; $P = 0.014$). Postoperative hematomas occurred in five of 11 patients with more bleeding during tumor removal and in one of 38 patients with less bleeding (45% versus 3%; $P = 0.001$).

Discussion

Surgery for a VS should be aimed not only at total tumor removal but also at optimal preservation of neurological function, and the EOR in such cases can be limited by a number of factors. First of all, advanced age of the patient may negatively impact the EOR, since prolonged operation under general anesthesia should preferably be avoided in elderly persons because of their fragile general condition. Moreover, total VS removal is not mandatory in these individuals, considering the benign nature of the tumor and its slow growth rate. While the effectiveness of adjuvant SRS for control of a residual VS after surgery decreases gradually over long-term follow-up [7, 8], this should not be a problem in those patients whose life expectancy is somewhat limited anyway. Second, the large size of a VS may prevent its total removal, since, in such cases, the adjacent facial and cochlear nerves are usually tightly adherent to the tumor capsule; thus, the risk of their mechanical damage during dissection is much higher than in cases of small and medium-sized masses. Finally, an excessive bleeding tendency during tumor removal may force the surgeon to stop the resection procedure [9]. All of these factors were significantly associated with incomplete resection in this presented series.

In cases of VS, the chosen surgical technique and postoperative management should minimize the risk of intraoperative bleeding and prevent postoperative hemorrhage. Appropriate positioning of the patient on the operating table is important, since a higher head position during surgery and reduced flexion of the neck improve venous outflow, decrease intracranial pressure, reduce bleeding, and facilitate attainment of hemostasis. During tumor removal, insertion of cottonoids around the mass prevents inflow of blood and irrigation fluid into the depth of the operative field. It may be particularly helpful for avoidance of intracisternal blood collection in cases of excessive bleeding from the tumoral tissue. Since bipolar coagulation produces heat, which may injure the adjacent cranial nerves [10], its use for hemostasis, particularly in critical areas, should be very careful. Alternatively, various local hemostatic materials and fibrin glue [11] are frequently applied, although they are less effective for attainment of hemostasis than bipolar coagulation. At the end of the surgery, before dural closure, the effectiveness of hemostasis should be controlled with the Valsalva maneuver (transient breath holding), and good irrigation of the operative field should be done for elimination of residual blood clots and tissue debris. In the early postoperative period, arterial blood pressure control is mandatory, as is constant monitoring of the neurological status and the general condition of the patient for early detection of any deterioration.

Nevertheless, even if bleeding has been stopped during surgery, delayed postoperative hemorrhage may still occasionally occur, and its risk may be increased in the presence of a residual tumor. Although insufficient intraoperative hemostasis and/or inadequate control of arterial blood pressure after surgery are usually considered the primary causes of such an event, there may be other reasons for it. In the present series, it was significantly associated with incomplete resection and an increased bleeding tendency during tumor removal. Indeed, a residual vascular-rich VS [9] may be prone to hemorrhage due to rearrangement of blood flow, especially if venous drainage was interrupted by coagulation of the tumor surface. On the other hand, peritumoral hemorrhage may result from the hemodynamic changes caused by excessive cerebellar retraction during the initial surgery and/or damage of the superior petrosal venous complex. Careful preservation of veins, particularly those located at the interface between the surface of the tumor and the cerebellum, may reduce the risk of such complications.

Conclusion

Postoperative hematomas after surgery for VS occur significantly more often after incomplete resection and in cases with an excessive bleeding tendency during tumor removal. In such cases, special attention should be given to attainment of effective intraoperative hemostasis. According to our experience, in the majority of patients, intra- or peritumoral hemorrhage after subtotal or partial resection of VS does not impact the recovery from anesthesia and the postoperative course, but occasionally it may cause significant clinical deterioration and necessitate reoperation. Therefore, adherence to measures that may prevent such a complication is very important.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Sanna M, Taibah A, Russo A, Falcioni M, Agarwal M. Perioperative complications in acoustic neuroma (vestibular schwannoma) surgery. Otol Neurotol. 2004;25:379–86.
2. Starnoni D, Daniel RT, Tuleasca C, George M, Levivier M, Messerer M. Systematic review and meta-analysis of the technique of subtotal resection and stereotactic radiosurgery for large vestibu-

lar schwannomas: a “nerve-centered” approach. Neurosurg Focus. 2018;44(3):E4.
3. Horowitz SW, Leonetti JP, Azar-Kia B, Anderson D. Postoperative radiographic findings following acoustic neuroma removal. Skull Base Surg. 1996;6:199–205.
4. Iannella G, de Vincentiis M, Di Gioia C, Carletti R, Pasquariello B, Manno A, Angeletti D, Savastano E, Magliulo G. Subtotal resection of vestibular schwannoma: evaluation with Ki-67 measurement, magnetic resonance imaging, and long-term observation. J Int Med Res. 2017;45:1061–73.
5. Kageji T, Nagahiro S, Mizobuchi Y, Nakajima K. Postoperative hematoma requiring recraniotomy in 1149 consecutive patients with intracranial tumors. Oper Neurosurg (Hagerstown). 2017;13:392–7.
6. Goto T, Muraoka H, Kodama K, Hara Y, Yako T, Hongo K. Intraoperative monitoring of motor evoked potential for the facial nerve using a cranial peg-screw electrode and a “threshold-level” stimulation method. Skull Base. 2010;20:429–34.
7. Watanabe S, Yamamoto M, Kawabe T, Koiso T, Yamamoto T, Matsumura A, Kasuya H. Stereotactic radiosurgery for vestibular schwannomas: average 10-year follow-up results focusing on long-term hearing preservation. J Neurosurg. 2016;125(Suppl):64–72.
8. Iwai Y, Yamanaka K, Ishiguro T. Surgery combined with radiosurgery of large acoustic neuromas. Surg Neurol. 2003;59:283–91.
9. Yamakami I, Kobayashi E, Iwadate Y, Saeki N, Yamaura A. Hypervascular vestibular schwannomas. Surg Neurol. 2002;57:105–12.
10. Elliott-Lewis EW, Mason AM, Barrow DL. Evaluation of a new bipolar coagulation forceps in a thermal damage assessment. Neurosurgery. 2009;65:1182–7.
11. Jackson MR. Fibrin sealants in surgical practice: an overview. Am J Surg. 2001;182(2 Suppl):1S–7S.

Enhance Safety in Aneurysm Surgery: Strategies for Prevention of Intraoperative Vascular Complications

Uwe Spetzger

Abstract

Complications during surgery for intracranial aneurysms can be devastating. Notorious pitfalls include premature rupture, parent vessel occlusion, local cerebral injury and brain contusion, and incomplete neck obliteration. These unfavorable intraoperative events can result in major neurological deficits with permanent morbidity and even mortality. Herein, the author highlights the relevant surgical strategies used in his daily practice of aneurysm surgery (e.g., aneurysm clipping with adenosine-induced temporary cardiac arrest), application of which may help prevent vascular complications and enhance surgical safety through reduction of the associated risks, thus allowing improvement of postoperative outcomes. Overall, all described methods and techniques should be considered as small pieces in the complex puzzle of prevention of vascular complications during aneurysm surgery.

Keywords

Adenosine-induced temporary cardiac arrest · Aneurysm clipping · Cerebrovascular neurosurgery · Complication · Error analysis · Intracranial aneurysm · Neurosurgery · Outcome · Preventive measures · Surgical morbidity · Treatment

Introduction

The number of endovascularly treated intracranial aneurysms is continuously rising worldwide. Nevertheless, complex broad-based and, especially, partially thrombosed aneurysms with prominent compressive effects on adjacent neuronal structures are generally treated with clipping [1, 2], while their management is clearly associated with certain risks. Avoidance of intraoperative vascular complications in aneurysm surgery is the consistent goal, since they can be really devastating. Every neurosurgeon has his or her personal experience with severe postoperative neurological deficits, sometimes even after completely uneventful procedures [3, 4]. This emphasizes the need for refinements of microsurgical strategies and techniques to avoid associated morbidity and to improve treatment safety and results.

This review summarizes the author's personal experience with more than 750 microsurgical procedures directed at clip occlusion of cerebral artery aneurysms focusing on relevant issues encountered in his daily practice of such surgeries, with the objective of sharing some strategic ideas, which may help to minimize associated complications. Different sources of errors are highlighted, and this should improve the level of microsurgical aneurysm treatment. Tips and tricks in the subtleties of aneurysm clipping—for example, dealing with damaged small perforators—are presented. The place of various monitoring methods and procedures is mentioned, since all of them are aimed at reducing surgical risks and improving the postoperative outcomes of neurosurgical patients. Finally, the author's own experiences with aneurysm clipping under temporary cardiac arrest induced by adenosine are discussed. Decisive steps in surgical management are practically demonstrated in selected illustrative cases.

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_8

Contemporary Strategies for Intracranial Aneurysm Treatment

The overall principle of the contemporary cerebrovascular neurosurgery is safe and complete occlusion of the intracranial aneurysm with only minor or even no surgically induced morbidity. The guarantee of perfect long-term success is definite and ultimate treatment, which presumes adequate reconstruction of the parent vessel wall by clip application on the aneurysm neck, with unimpaired cerebral blood flow (CBF) both during and after the intervention. This requires a perfectly trained microvascular neurosurgeon with high expertise and profound experience in the challenging field of cerebrovascular disease.

Nowadays, modern high-end neuroradiological imaging modalities allow for perfect preplanning surgical procedures [5]. Detailed three-dimensional (3D) depiction of the anatomy and additional information about the flow characteristics of any vascular lesion provide an opportunity for individually tailored surgical approach and an adapted strategy for management of unruptured, as well as ruptured, intracranial aneurysms. However, despite all these sophisticated technologies, all neurosurgeons during their careers have seen aneurysms that are not treatable by clip occlusion. Today, interdisciplinary decision-making as to whether the patient is an appropriate candidate for endovascular or microsurgical treatment is routinely established at nearly every cerebrovascular center, which usually rely on their own comparative morbidity and mortality data for selection of the optimal treatment algorithms on an individualized basis [6, 7].

Meanwhile, the broad armamentarium of modern endovascular techniques allows tailored management of various complex aneurysms. Therefore, in such clinical situations the number of microsurgically treated lesions is steadily decreasing, although, in the foreseeable future, endovascular treatment will not replace clipping completely [8]. However, the low case load creates a problem in the education and training of young neurosurgeons. Probably, practical use of computer-generated models [9], 3D-printed silicon specimens, and animal or cadaver models [10–12] could improve this situation (Fig. 1). Education and teaching (especially practical training in cerebrovascular microsurgery) form an important keystone and investment in prevention of surgical complications. Intensive intraoperative mentorship and stepwise continuous upgrade of microsurgical practice will be mandatory for ultimate optimization of the surgical skills of the upcoming generation of cerebrovascular experts.

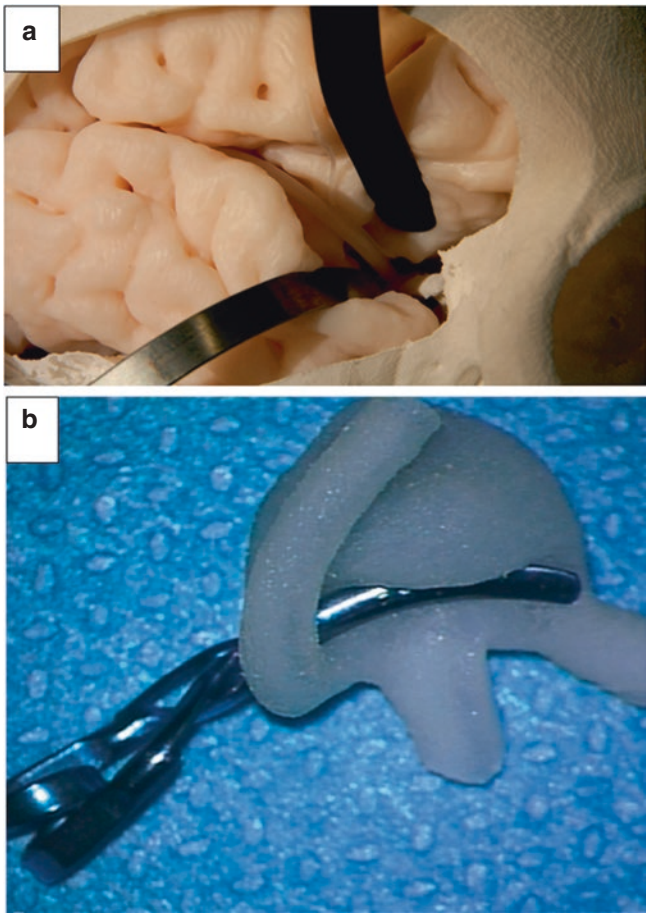

Fig. 1 Practical microsurgical training of clip application in a three-dimensional printed plastic model (Kezlex®; Ono & Co., Tokyo, Japan). The clip was inserted under a microscopic view in the depth of the Sylvian fissure of a silicon model, closely mimicking real intraoperative conditions (**a**). Taking out the soft and hollow clipped plastic aneurysm model and turning it around demonstrated insufficient occlusion with a small remnant at the tip of the clip branch (**b**)

Clue

Microsurgery will gradually diminish its role and develop more and more into a subspeciality in the cerebrovascular disease treatment, since various endovascular techniques have become the main management option in such cases. Nevertheless, we have to focus our training on talented young neurosurgeons to maintain high-level expertise in the field, because in the next decades, microsurgical clip occlusion will still remain the optimal modality for many selected patients with complex intracranial aneurysms.

Microsurgical Techniques

Self-evidently, meticulous microsurgical dissection and preparation of the operative field play highly important key roles in reducing surgery-induced morbidity. Optimal anatomical exposure of the aneurysm neck and dome is a prerequisite for correct clip application. Navigation and computer-assisted 3D depiction of the vessel and aneurysm anatomy are helpful. In particular, it can be much easier and

more straightforward to direct approach, secure location, and clearly detect an aneurysm of the middle cerebral artery (MCA) or pericallosal artery with the help of neuronavigation. Extended dissections and accompanying damage of surrounding neuronal tissue in a search for the lesion can be avoided by using this nearly universally available image-guided technology.

The overall aim of the neurosurgeon is to reduce harm to the patient's brain, which presumes avoidance of the intraoperative impairment of CBF. Respect for and maintenance of the patient's individual hemodynamics are most important.

During surgery, CBF may be impaired *locally* or *globally*. One reason is direct local damage of the vessel by surgical instruments during dissection. This may seem trivial, but it is important to use only adequate, advanced, specialized, and intact instruments for delicate aneurysm preparation for clipping. In particular, the tip of the suction device should be controlled before its use to ensure that it has no sharp edges. Only apply proper microscissors for arachnoid incision, opening of the Sylvian fissure, and sharp dissection of the adjacent environment around the aneurysm. Use of atraumatic intact microdissectors for gentle preparation of the vulnerable aneurysm neck and dome is a prerequisite. Pay attention to the venous system and try not to sacrifice dominant veins during access to and work in the target area. Attempt to preserve the entire venous drainage, especially during executing subtemporal and transsylvian approaches [13].

Another reason for local impairment of CBF is damage of the parent vessel during clip application. For example, an intimal lesion can be induced by use of temporary clips [14]. This is an underestimated but potential cause of surgically induced thromboembolic events, particularly in cases of severely calcified parts of the vessel wall with massive atheromatous plaques. These calcified plaques are often located close to a bifurcation or in the proximal internal carotid artery (ICA). If possible, try to avoid a temporary clipping maneuver in these severely altered vessels.

A basic tip is to prepare the temporary clips and the permanent clip in advance. Have these clips available in a holder before the craniotomy starts; this avoids hyperactive trouble and bustle in the event of premature aneurysm rupture. Additionally, consider the occlusion pressure of various clips [15], because the closing forces differ depending not only on the manufacturer but also on the clip's shape and material. Generally, the closing forces of present-day clips increase linearly from the tip to the base of the clip blades [16].

Furthermore, local harm and impairment of local or regional CBF can be induced by the spatula compression [17, 18]. Inadequate spatula pressure is a source of impaired microcirculation and venous congestion in the underlying tissue, which may result in local intracerebral hemorrhage and/or brain contusion [19–21]. Therefore, brain relaxation by optimal positioning of the patient's head along with perfect anesthesia regimens are mandatory to avoid a need for tense cerebral retraction. Using silicon-covered spatulas with soft margins can be somewhat helpful, but the overall strategy should involve either no or only minimal retraction. Use the spatula only for holding and brain surface protection. Recheck the spatula compression during the ongoing surgical procedure several times, and try to reduce it as much as possible. These simple measures constitute an essential step to reduce intraoperative CBF-related complications due to unnecessary brain retraction [22].

Complete occlusion of the aneurysm neck, especially if it is calcified, can be a challenge, and multiple clips are sometimes necessary to achieve this goal. Inadequate clip application can create regional impairment of the CBF and even permanent ischemic deficits [23]. Nowadays, intraoperative CBF monitoring (using micro-Doppler ultrasonography [24–26] or indocyanine green [ICG] fluorescence videoangiography [27]) is routinely applied as a powerful tool that can help prevent many of these pitfalls.

Global impairment of CBF should also be avoided. An important piece of advice to the anesthesiologist is not to lower the arterial blood pressure too much during the operation. Particularly in elderly patients with untreated arterial hypertension and in those ones with impaired cerebral autoregulation in case of severe subarachnoid hemorrhage (SAH), a profound and, especially, long-term reduction of the systemic arterial blood pressure could result in a chronically impaired blood supply and may lead to brain infarction [28].

Clue

A thorough preplanning of the procedure and accurate and elaborated execution of surgery will minimize the risk of occurrence of critical intraoperative errors. These preventive measures particularly include neuroradiological depiction of all related anatomical details of the aneurysm and adjacent structures. Additionally, appropriate positioning of the patient's head during surgery is crucially important, as well as maximal brain relaxation by means of adequate anesthesia and cerebrospinal fluid (CSF) drainage, correct craniotomy location, and selection of the optimal surgical approach to access the target area. On the basis of preoperative imaging, the neurosurgeon can select the best fitting permanent clip in advance of intervention. Be always prepared for possible premature aneurysm rupture. For meticulous dissection, use only advanced specialized instruments. Complete occlusion of the aneurysm neck should be the goal of surgery, but optimal reconstruction of the vessel wall without impairment of CBF should be the overall microsurgical treatment strategy. As a matter of course, appropriate experience and surgical skills of the neurosurgeon are fundamental. Of note, microsurgical skillfulness is scientifically nontransparent and hardly measurable quality.

Temporary Clipping

Temporary clipping of the parent artery is an established surgical method in aneurysm surgery, used for reduction of pressure within the lesion in case of difficulties during its preparation for permanent clip application and for emergency control of bleeding in case of premature rupture [29–31]. It is generally accepted that a duration of 3 min for temporary clip occlusion of the cerebral artery is safe. With sufficient collateral blood flow and retrograde circulation, even much longer temporary clip occlusion intervals can be tolerated without associated ischemic deficits. Probably, individualized patient CBF models with specific algorithms could help to predict the threshold of the tolerable ischemic interval. These data could make temporary clipping effects more predictable and safer. In the future, verification of these mathematical models may possibly be confirmed intraoperatively by laser Doppler scanning, optical microangiography, or optical coherence tomography [32].

Usually, after such induced short-term interruption of regional CBF, no permanent neurological deficits occur [33–35]. However, repeated clip applications to the same part of the artery, especially if it is affected by atherosclerosis, could be risky and may result in ischemic brain injury accompanied by neurological deficits [36]. Additionally, repeated short-term clipping of the vessel could amount to a critical time period, also incurring an ischemic brain damage. However, it has not been evaluated appropriately whether repeated and multistep temporary clip application with intermittent short-term reperfusion is more favorable strategy, than one-step temporary clipping [37, 38]. Additionally, application of multiple temporary clips around an aneurysm sometimes creates a busy operative field with limited space for surgical manipulations, and this could hamper the permanent clipping. Generally, the indication for and use of temporary clips should be strictly reviewed, because this maneuver carries potential risks for the occluded vessel and for the integrity of its wall, as well as possibilities of neurovascular injury and ischemic brain damage.

Clue

Temporary clipping of the parent vessel during surgery for intracranial aneurysm is potentially harmful procedure, which provokes ischemia of the supplied cerebral territory. Additionally, even specifically designed temporary clips with reduced closing forces can damage the vessel wall, with a risk of a consequent neurological deficit. Therefore, the risk/benefit ratio of using temporary clips should be considered very carefully and individually.

Intraoperative Monitoring

Many methods of intraoperative monitoring are currently available, and various related procedures are used routinely in aneurysm surgery [39]. Generally, it is important to distinguish between electrophysiological and CBF monitoring techniques. Of note, even an advanced multimodal monitoring setup combining several sophisticated methods, offers no definitive guarantee of avoiding severe postoperative neurological deficits.

Intraoperative Electrophysiological Monitoring

For more than 30 years, somatosensory evoked potentials (SSEP) monitoring has been reported to be a helpful measure to detect and prevent neurological complications in aneurysm surgery [40–42]. Indeed, relative decreases of the SSEP amplitude may indicate neuronal injury, but their absence is no guarantee of uneventful progression of the procedure. In fact, use of SSEP monitoring did not demonstrate unambiguous reduction in the incidence of neurological complications after aneurysm surgery. The predictive value of motor evoked potentials (MEP) monitoring has been showed to be more beneficial, especially during temporary clipping of the parent artery. Investigation of the diagnostic accuracy of various evoked potentials monitoring techniques in predicting postoperative neurological deficits in intracranial aneurysm surgery suggests that transcranial MEP or direct cortical MEP have greater efficacy than SSEP [43]. Nevertheless, indefinite sensitivity, specificity, and diagnostic accuracy of these methods in predicting postoperative neurological deficits is one of the main problems; another issue is their vulnerability to effects of anesthesia, including administration of various anesthetics, specifically propofol, and neuromuscular-blocking drugs [44].

Intraoperative Cerebral Blood Flow Monitoring with Ultrasonography

Checking CBF with micro-Doppler ultrasonography has been routine procedure in aneurysm surgery for many years [45]. This is a straightforward, inexpensive, and reliable method used for confirmation of intra-arterial blood flow, even in small perforators. A change in the flow profile (and a consequent specific change in the sound) is a perfect indicator of the clip-induced stenosis of a vessel or of the vasospasm caused by mechanical manipulations of the neurosurgeon. Micro-Doppler ultrasonography is the quickest and easiest technique for intraoperative CBF monitoring, and it should be used con-

sistently in cerebrovascular neurosurgical procedures. In some cases, it could be helpful to link the Doppler probe with neuronavigation [46].

Quantitative CBF measurement is a bit more sophisticated and cumbersome because of the configuration of the semicircular tip of the ultrasound probe [47, 48]. Therefore, one needs to have some experience to handle it adequately and cover the vessel appropriately to achieve correct blood flow assessment. Use of these probes carries a slightly higher risk of damaging small perforating vessels; however, this method reveals much more detailed information concerning the parameters of CBF [49]. Specifically, quantitative ultrasound CBF measurement is necessary in cerebral revascularization procedures and significantly enhances the value of bypass surgery.

Intraoperative Cerebral Blood Flow Monitoring with Fluorescent Dyes

Intraoperative fluorescence videoangiography is an established diagnostic procedure in ophthalmology and has been frequently used in vascular neurosurgery, since integration of the essential optical filters into high-end operating microscopes is allowing an excellent workflow [27, 50]. Particularly, this method has gained wide acceptance during intracranial aneurysm surgery due to lowering the rates of incomplete clipping and occlusion of surrounding vessels [51]. Intraoperative fluorescence videoangiography is performed using intravenous administration of different dyes. Fluorescein has a shorter wavelength (approximately 500 nm) than ICG (approximately 820 nm), and creates greater fluorescent intensity and contrast. Therefore, it seems to be better than ICG for detecting small perforators during microsurgical clipping. However, there are some disadvantages of fluorescein. It remains in vessels for several minutes after injection, and the washout of its fluorescent intensity is somewhat delayed. For these reasons, fluorescein is not suitable for evaluation of the venous system. For repeated use, especially during clip repositioning, ICG videoangiography is more effective. Overall, given their different properties, fluorescein and ICG videoangiography play complementary roles during microsurgical treatment of aneurysms [52]. With either method, slow contrast filling of the clipped lesion is a confirmation of its incomplete occlusion.

The general limitation of the videoangiography with use of either dye is that its range of visual assessment is restricted to the field of view of the operating microscope. Under the limited and straight angle, cerebral vessels covered by brain tissue, blood clots, or the applied clip cannot be observed well enough. Specifically, when the aneurysm is partially covered by the parent artery or clips, the possibility of a residual neck cannot be ruled out definitely. Recently, use of endoscopes integrating fluorescence videoangiography technology has been reported [53]. In particular, use of angled endoscopes improves the ability to view less accessible regions, especially those posterior to the aneurysm clip. Thus, endoscopic fluorescence videoangiography can visualize and confirm vessel patency in areas that were previously hidden under microscopic view. Additional advantages are higher magnification and the fact that fluorescence can be visualized for much longer time interval with an endoscope than with a microscope [54].

In general, intraoperative fluorescence videoangiography is a simple and reliable method that provides real-time information in detecting the patency of parent, branching, and perforating arteries. However, its efficacy in cases of large or giant wide-necked aneurysms, and thick-walled atherosclerotic vessels is limited. Moreover, as the sole means of definite confirmation of the appropriate clip application with complete aneurysm neck occlusion, fluorescence videoangiography is not sufficient. Intraoperative or postoperative 3D digital subtraction angiography (DSA) is still the gold standard for final evaluation of the aneurysm surgery results [55].

Intraoperative Cerebral Blood Flow Monitoring with Radiological Imaging

Modern 3D rotational DSA is still the gold standard in diagnosis of intracranial aneurysms and evaluation of their treatment [5]. Particularly, it represents the ultimate means for confirmation of adequate and complete clip occlusion of a lesion [55]. Moreover, it may be expected that installations and use of hybrid vascular operating rooms equipped with high-quality imaging modalities allowing for intraoperative DSA will increase in the future [56]. Intraoperative DSA is time consuming and technically demanding investigation, which requires major logistic infrastructure. Moreover, its use is potentially associated with procedure-related morbidity and increased complication rates. However, various studies have demonstrated that intraoperative DSA reveals a significant number of cases of unexpected vessel occlusion or stenosis, as well as residual aneurysm filling [50]. The most important drawback of DSA is its limited ability to assess the patency of very small perforating arteries.

At present, utilization of intraoperative computed tomography (CT) and magnetic resonance imaging (MRI) is not routine in aneurysm surgery, because such advanced technology is not readily available everywhere and the workflow of its application for radiological examination during the procedure is time-consuming and relatively cumbersome.

Clue

Multimodal intraoperative monitoring is a helpful tool and has become established as a routine adjunct in aneurysm surgery. Intraoperative MEP monitoring is superior to SSEP monitoring in predicting postoperative neurological deficits. Fluorescence videoangiography and micro-Doppler ultrasonography are superior to electrophysiological monitoring in detecting inadvertent vessel occlusion. Both electrophysiological monitoring and CBF monitoring are relevant indicators of intraoperative problems that are either incipient or have already happened, but these techniques provide only a warning of a possible brain dysfunction or disturbances of its blood supply. Although it maintains certain security, guidance by intraoperative monitoring alone does not guarantee an ideal postoperative neurological outcome. The key point is that the neurosurgeon discerns an alert not only from multimodal intraoperative monitoring, but from his or her own target-orientated observations as well.

Cardiac Arrest with Adenosine for Complex Aneurysm Clipping

Cardiac arrest with intravenous administration of adenosine is an underestimated method in present-day cerebrovascular neurosurgery [57–59]. In our experience, intravenous bolus injection of 18 mg of adenosine induces a short temporary cardiac arrest for several seconds (Fig. 2). The consequent lowering of the mean arterial pressure (MAP) produces a significant reduction in the tension of the aneurysm wall. This condition makes preparation of the aneurysm rupture site (if it exists), clip application on the aneurysm neck, and remodeling of the vessel wall safer and easier [60, 61].

Use of adenosine is well established, and it is an authorized medication, mainly applied in cardiology to treat patients with supraventricular tachycardia. The clinical effect of adenosine usually occurs 8–14 s after intravenous bolus injection. Pharmacologically, adenosine creates atrioventricular nodal blockade of the heart, resulting in bradycardia and

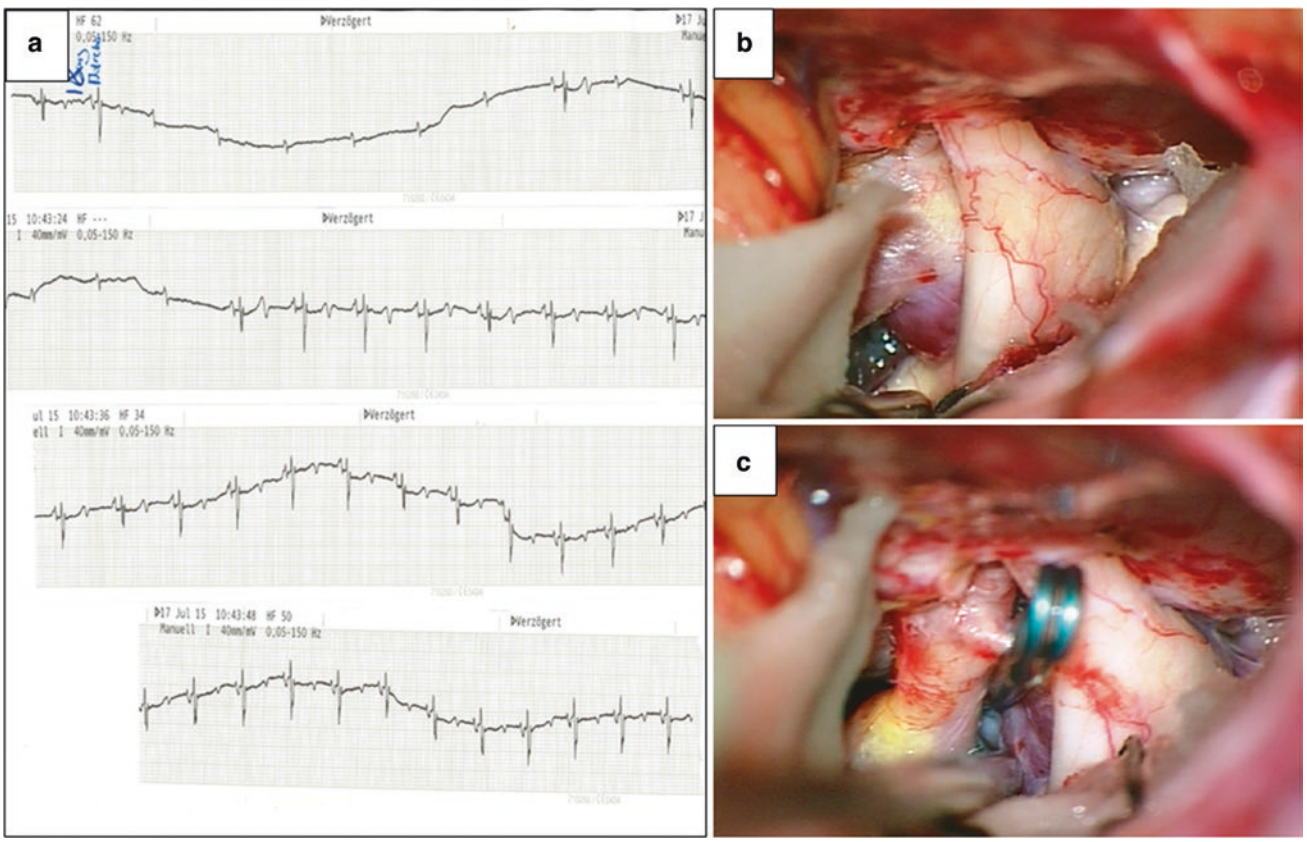

Fig. 2 Microsurgical clipping with preplanned adenosine-induced cardiac arrest in a 62-year-old woman with visual disturbances caused by a large medially located unruptured aneurysm of the left internal carotid artery (ICA). Intraoperative electrocardiography demonstrated cardiac arrest 13 s after intravenous administration of 18 mg of adenosine, with spontaneous restarting of the heartbeat and without any rebound phenomena such as tachycardia or elevated blood pressure (**a**). An intraoperative microscopic view via a left-side minipterional approach showed the base of the ICA aneurysm with massive compression of the left optic nerve and the chiasm (**b**). Complete occlusion of the ICA aneurysm under temporary cardiac arrest was achieved using a straight Yaşargil titanium clip with a 17.5-mm blade length (**c**). After puncture of the aneurysm, the optic nerve and chiasm were adequately decompressed

a decrease in cardiac output. This leads to a rapid drop in the MAP and finally ends in a temporary and short-term cardiac arrest. The half-life of adenosine is highly variable and can range from 1.5 to 20 s. The drug is cleared rapidly from the patient's blood by uptake into erythrocytes and vascular endothelial cells.

One problem is that we do not really have specific guidelines on bolus dosing yet. Some studies indicated a linear relationship between the applied dose of adenosine and the duration of asystole and MAP reduction [57, 58], which was also observed in our own patients. According to the author's experience and several reports in the literature, 1 mg of adenosine results in approximately 1 s of asystole, on average [59].

Our initial clinical experiences with adenosine-induced cardiac arrest in a total of 17 patients (10 men and 7 women), with a mean age of 59 years and average body weight of 78 kg, have been promising. We usually start with an intravenous bolus application of 18 mg of adenosine. All patients are supplied with defibrillation pads glued onto their chest and connected to a heart defibrillator. However, we have never needed to use defibrillation, because in all cases the sinus rhythm has restored spontaneously. No rebound phenomena have been seen after the temporary cardiac arrest. None of the patients have shown tachycardia or elevated arterial blood pressure after the spontaneous restarting of the heartbeat. The procedure resulted in short-term temporary bradycardia and decrease of MAP below 20 mmHg. The mean duration of the induced cardiac arrest has been 11 s (range 7–18 s). In 6 patients, we repeated the bolus injection of adenosine during surgery; multiple bolus were given 2–4 times during preparation of the operative field, dissection of the aneurysm, and clipping itself. No pharmacologically induced morbidity or mortality have been seen. The only disadvantage has been the relatively short duration of the MAP reduction. However, 10–15 s with a totally slack and soft aneurysm is usually sufficient enough for the relevant step of preparation and for safe and unhindered clip application. The essential point is to have an adequate clip with open blades in front of the tense and stiff aneurysm. Then induce cardiac arrest and, during the relaxation of the aneurysm wall, you have enough time to position and ultimately close the clip on the aneurysm neck appropriately.

Rapid ventricular pacing during cerebrovascular surgery is a comparable alternative to intravenous adenosine administration [62, 63]. Its advantage is that the period of functional cardiac arrest is more steerable; thus, the duration of CBF interruption can be extended, and the neurosurgeon has more time for preparation of the aneurysm and related manipulations. Proof of which strategy is associated with lesser morbidity is not available. The author does not have his own clinical experience with rapid ventricular pacing for cardiac arrest in aneurysm surgery.

Clue

Adenosine-induced cardiac arrest for aneurysm surgery is an easy and straightforward strategy and a perfect method of CBF interruption. The disadvantage is that the cardiac arrest lasts for only a few seconds providing relatively short period of profound systemic hypotension. However, the associated perioperative morbidity is low, and in the author's series of 17 patients, no rebound phenomena, such as tachicardia or reactive hypertension, have been seen. We use adenosine-induced cardiac arrest for surgical treatment of complex aneurysms because, in our experience, it reduces the need for, duration of, and complications associated with temporary clip application.

Handling of Damaged Small Perforating Arteries

The anatomical situation around anterior communicating artery (AComA) aneurysms is particularly complicated because there are many small lenticulostriate arteries arising from the A1 segment. Typically, these perforating arteries run perpendicularly into the anterior perforated substance and complicate circular mobilization of the A1 segment on the way to the target area, especially in cases of severe SAH. Damage of these minor vessels and, in particular, a surgically induced lesion of the recurrent artery of Heubner could produce significant neurological and neuropsychological deficits [64]. Intensive irrigation along the A1 segment and cisternal washout of the liquid blood and blood clots around it are helpful to improve visualization of small perforators in patients with severe SAH. This measure can help prevent intraoperative vascular damage with a surgical instrument or from traction by a spatula.

Usually, the mechanism of trauma to these small perforating arteries running perpendicularly to the trunk of the main vessel is related to their overstretching during preparation of the operative field for clipping of the aneurysm. The main site of damage is the right-angled connection of the perforator and the parent artery. If injury happens, take away the traction of the vessel by the instrument or spatula. Try to visualize the lesion site exactly by increasing the magnification and the illumination under the operating microscope. If you see blood coming out of a laceration point, do not try to coagulate it immediately, because that will usually enlarge the small opening in the vessel wall or occlude the perforator completely. The goals are to not sacrifice the vessel and to try to maintain its patency.

First, perform temporary clipping near the laceration point to lower the local blood pressure and the tension of the damaged arterial wall. Thereafter, reduce the power and output of your bipolar coagulation system to a very low energy level.

Use clean, nonsticking, and pointed bipolar forceps, and give a short and single coagulation impulse targeted at the opening of the vessel wall. Finally, release the temporary clip and, if necessary, wrap a small piece of cottonoid around the injury point. Immediately after this manipulation, always control the blood flow via micro-Doppler ultrasonography or fluorescence videoangiography. Only if it is not possible to maintain its patency should the perforator be coagulated to avoid severe rebleeding.

Clue

In cases of severe SAH caused by ruptured aneurysm, try to improve visualization of the operative field by its continuous irrigation, and be aware of the specific local anatomical situation of the perforating arteries to prevent their injury. If a perforator is damaged, localize the laceration site exactly under maximum magnification of the operating microscope. Thereafter, first, reduce the pressure within the parent artery by its temporary clipping, and then try to coagulate the defect of the vessel wall with very low power.

Strategic Pearls and Technical Clues

During recent years, several technical advancements have influenced our strategies and decision-making during management of cerebrovascular diseases. Particularly, we have seen a trend for miniaturization of craniotomies. However, the main keys to successful microsurgical clipping of an aneurysm generally remain the same as before.

The positioning of the patient's head is still a crucial point in enabling the target area to be reached atraumatically, without severe brain retraction. Improper positioning can be a major error in surgical treatment of an aneurysm and can cause massive problems due to inadequate access, poor visualization, and a cumbersome operative field.

As a matter of course, well-established neuroanesthesia with reduced intracranial pressure and carefully managed CBF is absolutely necessary. For optimal brain relaxation, use of the CSF drainage is indicated in nearly every clinical scenario during treatment of patients with SAH.

Exact determination of the surgical strategy is also important. All required surgical steps should be clearly defined before the intervention is started [65]. In the case of multiple aneurysms, a tentative order should be established for their sequential management, and surgical approach may have to be modified, especially if clipping of bilateral aneurysms is intended [66, 67].

Always plan to integrate existing damage of the brain caused by aneurysm rupture into your surgical approach. For example, local intracerebral hemorrhage in the gyrus rectus could be the decisive factor in selection of the craniotomy side for management of ruptured AComA aneurysm—after partial resection of the gyrus and careful removal of the blood clot, you will gain more space for surgical manipulations and a better overview of the operative field. However, be aware that the rupture site of the aneurysm dome usually points directly into the blood clot, so before removal of the latter, try to prepare the aneurysm neck and to get a clear visualization and exact comprehension of the local vessel anatomy and the aneurysm positioning and angioarchitecture. After meticulous preparation of the so-called less dangerous zones of the lesion environment, the next step follows. Removal of the blood clot around the aneurysm dome is more risky and a less predictable maneuver, but it allows for creation of additional space facilitating global overview of the local anatomy and providing better options for secure clip application. This universal strategy—to prepare the less dangerous parts around the rupture site first—will generally prevent inadvertent premature rupture of the aneurysm. Such a complication, especially if it happens at the early stage of the procedure and cannot be immediately controlled, is very dangerous and significantly increases postoperative morbidity and mortality [68, 69].

An important microsurgical maneuver in treatment of complex ICA aneurysms is detachment of their wall at its adhesion to the dura mater of the skull base or tentorial rim. Strictly avoid applying traction to the temporal lobe during opening of the Sylvian fissure to approach the target area, particularly, in cases of the posterior communicating artery (PComA) aneurysms pointing laterally (Fig. 3a, b), which carry an additional risk [70]. If their dome is stuck under the tentorial rim (Fig. 3c), early and abrupt temporal lobe retraction with a spatula or a suction tube can provoke a premature and awful rupture of the lesion. The crucial point is that in those cases where the dome is fixed to the dura, the rupture site could be at the base of the aneurysm. Moreover, a tear may even extend on the ICA wall, which is a severe complication associated with significant postoperative morbidity and mortality. Therefore, careful circumferential dissection of these ICA-PComA aneurysms with gentle detachment from the dura mater is the key point in their microsurgical management. Sometimes enlargement of the field of view and the space for manipulation around the aneurysm by epidural or intradural drilling of the osseous skull base structures is necessary (Fig. 3d–g). In some cases, it may be also reasonable to insert an endoscope to inspect the close surroundings of the aneurysm. Althoug in this very narrow operative corridor, endoscopic inspection carries the risk of premature rupture if the traction is applied to the ICA or the fixed aneurysm wall, the combination of microsurgery and endoscopic assistance can be rather useful in specific situations [71], especially if you can control and steer the insertion and the way back of the endoscope under the microscope. An advantage is to have both visualization modalities available simultaneously

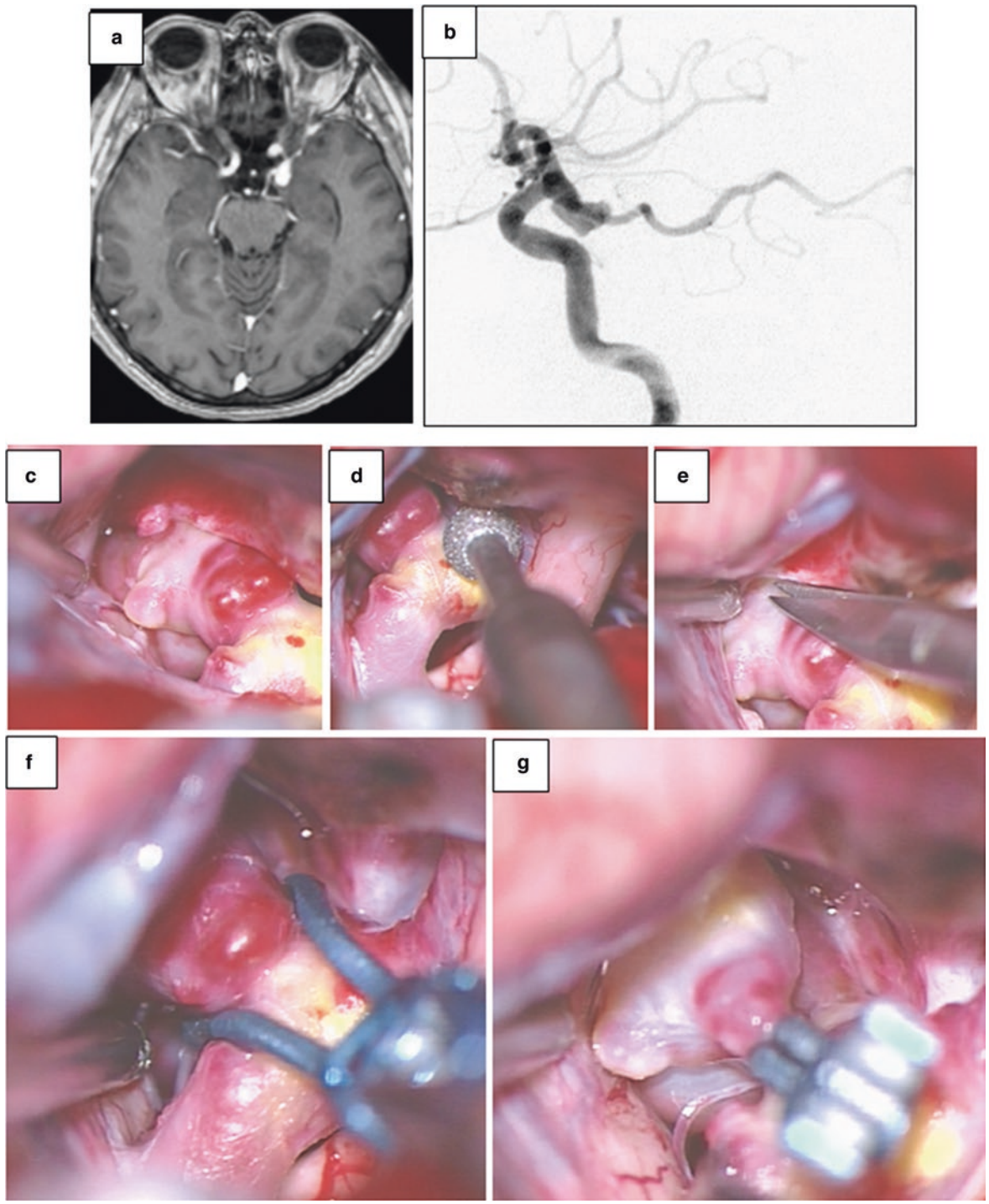

Fig. 3 Diagnostic imaging and detail of microsurgical treatment of a 58-year-old man with a left-side complex internal carotid artery (ICA) aneurysm manifesting with progressive external left-side ophthalmoplegia caused by chronic oculomotor nerve compression. Axial postcontrast T1-weighted magnetic resonance imaging (**a**) and a lateral view on digital subtraction angiography (**b**) demonstrated a left-side multilobulated ICA aneurysm as a cause of the ophthalmological symptoms, along with a fetal-type posterior cerebral artery (PCA). Intraoperative photography showing microscopic views via a left-side pterional approach demonstrated the calcified ICA and the base of the multilobulated aneurysm, the dome of which was stuck under the tentorial rim. Neither the PCA, nor the oculomotor nerve were visible initially (**c**). Intradural drilling of the anterior clinoid process was performed using a 4-mm diamond burr to gain more space laterally for preparation and visualization of the PCA (**d**). The next surgical step was resection of the adhesions and meticulous detachment of the aneurysm wall from the tentorial rim. The preparation was performed with sharp curved scissors and dissectors (**e**). Final inspection of the PCA and the oculomotor nerve was done under adenosine-induced temporary cardiac arrest. A second bolus injection of adenosine was given for definite clipping using a bayonet-shaped straight Sugita titanium clip II (T2) with a 14-mm blade length (**f**). The clip occluded the aneurysm with preservation of a perforating artery (**g**); thereafter, opening of the dome for final inspection and decompression of the oculomotor nerve was accomplished

or to be able to switch them back and forth unhindered. This scenario, with both the microscopic and the endoscopic view on one display, is adequately realized in the new Zeiss Kinevo® 900 (Carl Zeiss Meditec AG, Jena, Germany). Visualization through operating microscopes is usually limited due to a straight line of sight, and the final clip position and distal tips of clip blades can be better controlled with the angled view through an integrated endoscopic system. Therefore, we routinely use endoscopic inspection tool integrated into the Zeiss Kinevo® 900 to ensure the complete occlusion by looking behind the clipped aneurysm neck. Endoscope-assisted microsurgery also provides additional anatomical information on the location of the oculomotor nerve and the course of small perforators arising from PComA.

Clue

Technical flaws during aneurysm surgery should be ruled out by use of perfect equipment in an adequate manner. Human errors can be prevented by careful preplanning and responsible, purposeful executing the procedure. Elaborate plan of the surgical approach, craniotomy, and general operative strategy in each individual case is highly important. Appropriate positioning of the patient's head is crucial. Meticulous, skillful, and gentle microsurgical dissection and preparation of the aneurysm for clipping is pivotal. Complete occlusion of the aneurysm neck is the aim, but reconstruction of the parent vessel without compromise of CBF and associated morbidity is the main issue.

In retrospect, an error can often be seen as the logical consequence of a concatenation of minor circumstances. Thus, experience with errors, their evaluation and processing, and subsequent detailed analyses are very important. Essentially, avoidance of strategic errors is based on experience. Therefore, advanced mentorship with stepwise intraoperative teaching of microsurgical techniques is a prerequisite for success in aneurysm surgery, since the subtleties of clipping procedures are discovered through a sequential and long-term learning process. To learn from defeat is mandatory, but it is much better to avoid defeat through anticipatory surgical precaution.

Conclusion

Complications during surgery for intracranial aneurysms could be devastating. Application of the relevant operative strategies described herein may help to enhance the surgical safety through reduction of the associated risks, thus allowing for improvement of the postoperative outcomes. Overall, all highlighted methods and techniques should be considered as small pieces in the complex puzzle of prevention of vascular complications during aneurysm surgery.

Acknowledgments Empathically, I want to thank my mentors and friends Joachim M. Gilsbach, Helmut Bertalanffy, and Takanori Fukushima for their intensive training and teaching in the field of vascular microsurgery.

Conflict of Interest Statement Uwe Spetzger, MD, has a contractual relationship with Carl Zeiss Meditec, Inc., and has received financial compensation for this.

References

1. Kamide T, Tabani H, Safaee MM, Burkhardt JK, Lawton MT. Microsurgical clipping of ophthalmic artery aneurysms: surgical results and visual outcomes with 208 aneurysms. J Neurosurg. 2018;129:1511–21.
2. von Schilling A, Spetzger U. Clipping of a partially thrombosed giant VA aneurysm. Neurosurg Focus. 2015;38(Video Suppl 1):V18.
3. Drake CG. Management of cerebral aneurysm. Stroke. 1981;12:273–83.
4. Rinne J, Hernesniemi J, Niskanen M, Vapalahti M. Analysis of 561 patients with 690 middle cerebral artery aneurysms: anatomic and clinical features as correlated to management outcome. Neurosurgery. 1996;38:2–11.
5. Hochmuth A, Spetzger U, Schumacher M. Comparison of three-dimensional rotational angiography with digital subtraction angiography in the assessment of ruptured cerebral aneurysms. AJNR Am J Neuroradiol. 2002;23:1199–205.
6. Dengler J, Maldaner N, Gläsker S, Endres M, Wagner M, Malzahn U, Heuschmann PU, Vajkoczy P. Outcome of surgical or endovascular treatment of giant intracranial aneurysms, with emphasis on age, aneurysm location, and unruptured aneuryms: a systematic review and meta-analysis. Cerebrovasc Dis. 2016;41:187–98.
7. Platz J, Wagner M, Güresir E, You SJ, Konczalla J, de Rochemont RD, Berkefeld J, Seifert V. Early diffusion-weighted MRI lesions after treatment of unruptured intracranial aneurysms: a prospective study. J Neurosurg. 2017;126:1070–8.
8. König A, Spetzger U, editors. Surgery of the skull base: practical diagnosis and therapy. Heidelberg: Springer; 2018.
9. Kimura T, Morita A, Nishimura K, Aiyama H, Itoh H, Fukaya S, Sora S, Ochiai C. Simulation of and training for cerebral aneurysm clipping with 3-dimensional models. Neurosurgery. 2009;65:719–26.
10. Aboud E, Aboud G, Al-Mefty O, Aboud T, Rammos S, Abolfotoh M, Hsu SP, Koga S, Arthur A, Krisht A. "Live cadavers" for training in the management of intraoperative aneurysmal rupture. J Neurosurg. 2015;123:1339–46.
11. Spetzger U, von Schilling A, Brombach T, Winkler G. Training models for vascular microneurosurgery. Acta Neurochir Suppl. 2011;112:115–9.
12. Spetzger U, Reul J, Weis J, Bertalanffy H, Thron A, Gilsbach JM. Microsurgically produced bifurcation aneurysms in a rabbit model for endovascular coil embolization. J Neurosurg. 1996;85:488–95.
13. Nakase H, Kempski OS, Heimann A, Takeshima T, Tintera J. Microcirculation after cerebral venous occlusions as assessed by laser Doppler scanning. J Neurosurg. 1997;87:307–14.
14. Gertz SD, Rennels ML, Forbes MS, Kawamura J, Sunaga T, Nelson E. Endothelial cell damage by temporary arterial occlusion with surgical clips: study of the clip site by scanning transmission and electron microscopy. J Neurosurg. 1976;45:514–9.
15. Dujovny M, Wackenhut N, Kossovsky N, Gomes CW, Laha RK, Leff L, Nelson D. Minimum vascular occlusive force. J Neurosurg. 1979;51:662–8.

16. Horiuchi T, Rahmah NN, Yanagawa T, Hongo K. Revisit of aneurysm clip closing forces: comparison of titanium versus cobalt alloy clip. Neurosurg Rev. 2013;36:133–8.
17. Andrews RJ, Bringas JR. A review of brain retraction and recommendations for minimizing intraoperative brain injury. Neurosurgery. 1993;33:1052–64.
18. Houkin K, Takahashi A, Abe H. Proper usage of brain retractors in the interhemispheric fissure based on MRI microanatomy: technical note. Surg Neurol. 1994;41:16–8.
19. Andrews RJ, Muto RP. Retraction brain ischemia: mannitol plus nimodipine preserves both cerebral blood flow and evoked potentials during normoventilation and hyperventilation. Neurol Res. 1992;14:19–25.
20. Lownie S, Wu X, Karlik S, Gelb AW. Brain retractor edema during induced hypotension: the effect of the rate of return of blood pressure. Neurosurgery. 1990;27:901–6.
21. Yokoh A, Sugita K, Kobayashi S. Clinical study of brain retraction in different approaches and diseases. Acta Neurochir (Wien). 1987;87:134–9.
22. Yokoh A, Sugita K, Kobayashi S. Intermittent versus continuous brain retraction: an experimental study. J Neurosurg. 1983;58:918–23.
23. Jabbarli R, Pierscianek D, Wrede K, Dammann P, Schlamann M, Forsting M, Müller O, Sure U. Aneurysm remnant after clipping: the risks and consequences. J Neurosurg. 2016;125:1249–55.
24. Gilsbach JM, Hassler WE. Intraoperative Doppler and real time sonography in neurosurgery. Neurosurg Rev. 1984;7:199–208.
25. Kapsalaki EZ, Lee GP, Robinson JS 3rd, Grigorian AA, Fountas KN. The role of intraoperative micro-Doppler ultrasound in verifying proper clip placement in intracranial aneurysm surgery. J Clin Neurosci. 2008;15:153–7.
26. Stendel R, Pietilä T, Al Hassan AA, Schilling A, Brock M. Intraoperative microvascular Doppler ultrasonography in cerebral aneurysm surgery. J Neurol Neurosurg Psychiatry. 2000;68:29–35.
27. Raabe A, Nakaji P, Beck J, Kim LJ, Hsu FP, Kamerman JD, Seifert V, Spetzler RF. Prospective evaluation of surgical microscope–integrated intraoperative near-infrared indocyanine green videoangiography during aneurysm surgery. J Neurosurg. 2005;103:982–9.
28. Smrcka M, Ogilvy CS, Crow RJ, Maynard KI, Kawamata T, Ames A 3rd. Induced hypertension improves regional blood flow and protects against infarction during focal ischemia: time course of changes in blood flow measured by laser Doppler imaging. Neurosurgery. 1998;42:617–25.
29. Lavine SD, Masri LS, Levy ML, Giannotta SL. Temporary occlusion of the middle cerebral artery in intracranial aneurysm surgery: time limitation and advantage of brain protection. J Neurosurg. 1997;87:817–24.
30. McDermont MW, Durity FA, Borozny M, Mountain MA. Temporary vessel occlusion and barbiturate protection in cerebral aneurysm surgery. Neurosurgery. 1989;25:54–62.
31. Samson D, Batjer HH, Bowman G, Mootz L, Krippner WJ Jr, Meyer YJ, Allen BC. A clinical study of the parameters and the effects of temporary arterial occlusion in the management of intracranial aneurysms. Neurosurgery. 1994;34:22–9.
32. Baran U, Zhu W, Choi WJ, Omori M, Zhang W, Alkayed NJ, Wang RK. Automated segmentation and enhancement of optical coherence tomography–acquired images of rodent brain. J Neurosci Methods. 2016;270:132–7.
33. Buchthal A, Belopavlovic M, Mooij JJA. Evoked potential monitoring and temporary clipping in cerebral aneurysm surgery. Acta Neurochir (Wien). 1988;93:28–36.
34. Charbel FT, Ausman JL, Diaz FG, Malik GM, Dujovny M, Sanders J. Temporary clipping in aneurysm surgery: techniques and results. Surg Neurol. 1991;36:83–90.
35. Ogilvy CS, Carter BS, Kaplan S, Rich C, Crowell RM. Temporary vessel occlusion for aneurysm surgery: risk factors for stroke in patients protected by induced hypothermia and hypertension and intravenous mannitol administration. J Neurosurg. 1996;84:785–91.
36. Staarmann B, O'Neal K, Magner M, Zuccarello M. Sensitivity and specificity of intraoperative neuromonitoring for identifying safety and duration of temporary aneurysm clipping based on vascular territory, a multimodal strategy. World Neurosurg. 2017;100:522–30.
37. Alkan T, Kahveci N, Goren B, Korfali E, Ozluk K. Effects of interrupted and uninterrupted occlusion of the basilar artery on cerebral blood flow, and on neurological and histological outcome in rats with subarachnoid hemorrhage. Arch Physiol Biochem. 2001;109:154–60.
38. Steinberg GK, Panahian N, Sun GH, Maier CM, Kunis D. Cerebral damage caused by interrupted, repeated arterial occlusion versus uninterrupted occlusion in a focal ischemic model. J Neurosurg. 1994;81:554–9.
39. Grasso G, Landi A, Alafaci C. Multimodal intraoperative neuromonitoring in aneurysm surgery. World Neurosurg. 2017;101:763–5.
40. Friedman WA, Chadwick GM, Verhoeven FJ, Mahla M, Day AL. Monitoring of somatosensory evoked potentials during surgery for middle cerebral artery aneurysms. Neurosurgery. 1991;29:83–8.
41. Momma F, Wang AD, Symon L. Effects of temporary arterial occlusion on somatosensory evoked responses in aneurysm surgery. Surg Neurol. 1987;27:343–52.
42. Schramm J, Koht A, Schmidt G, Pechstein U, Taniguchi M, Fahlbusch R. Surgical and electrophysiological observations during clipping of 134 aneurysms with evoked potential monitoring. Neurosurgery. 1990;26:61–70.
43. Chung J, Park W, Hong SH, Park JC, Ahn JS, Kwun BD, Lee SA, Kim SH, Jeon JY. Intraoperative use of transcranial motor/sensory evoked potential monitoring in the clipping of intracranial aneurysms: evaluation of false-positive and false-negative cases. J Neurosurg. 2018;130:936–48.
44. Thomas B, Guo D. The diagnostic accuracy of evoked potential monitoring techniques during intracranial aneurysm surgery for predicting postoperative ischemic damage: a systematic review and meta-analysis. World Neurosurg. 2017;103:829–40.
45. Gilsbach JM. Intraoperative Doppler sonography in neurosurgery. Vienna: Springer; 1983.
46. Malinova V, von Eckardstein K, Rohde V, Mielke D. Neuronavigated microvascular Doppler sonography for intraoperative monitoring of blood flow velocity changes during aneurysm surgery—a feasible monitoring technique. Clin Neurol Neurosurg. 2015;137:79–82.
47. Charbel FT, Hoffman WE, Misra M, Hannigan K, Ausman JI. Role of a perivascular ultrasonic micro-flow probe in aneurysm surgery. Neurol Med Chir (Tokyo). 1998;38(Suppl):35–8.
48. Charbel FT, Gonzales-Portillo G, Hoffman WE, Ostergren LA, Misra M. Quantitative assessment of vessel flow integrity for aneurysm surgery: technical note. J Neurosurg. 1999;91:1050–4.
49. Amin-Hanjani S, Meglio G, Gatto R, Bauer A, Charbel FT. The utility of intraoperative blood flow measurement during aneurysm surgery using an ultrasonic perivascular flow probe. Neurosurgery. 2006;58(4 Suppl 2):ONS305–12.
50. Marbacher S, Mendelowitsch I, Grüter BE, Diepers M, Remonda L, Fandino J. Comparison of 3D intraoperative digital subtraction angiography and intraoperative indocyanine green video angiography during intracranial aneurysm surgery. J Neurosurg. 2018;131:64–71.
51. Suzuki K, Kodama N, Sasaki T, Matsumoto M, Ichikawa T, Munakata R, Muramatsu H, Kasuya H. Confirmation of blood flow in perforating arteries using fluorescein cerebral angiography during aneurysm surgery. J Neurosurg. 2007;107:68–73.
52. Lane B, Bohnstedt BN, Cohen-Gadol AA. A prospective comparative study of microscope-integrated intraoperative fluorescein and

indocyanine videoangiography for clip ligation of complex cerebral aneurysms. J Neurosurg. 2015;122:618–26.
53. Bruneau M, Appelboom G, Rynkowski M, Van Cutsem N, Mine B, De Witte O. Endoscope-integrated ICG technology: first application during intracranial aneurysm surgery. Neurosurg Rev. 2013;36:77–85.
54. Mielke D, Malinova V, Rohde V. Comparison of intraoperative microscopic and endoscopic ICG angiography in aneurysm surgery. Oper Neurosurg. 2014;10:418–25.
55. Washington CW, Zipfel GJ, Chicoine MR, Derdeyn CP, Rich KM, Moran CJ, Cross DT, Dacey RG Jr. Comparing indocyanine green videoangiography to the gold standard of intraoperative digital subtraction angiography used in aneurysm surgery. J Neurosurg. 2013;118:420–7.
56. Alexander TD, Macdonald RL, Weir B, Kowalczuk A. Intraoperative angiography in cerebral aneurysm surgery: a prospective study of 100 craniotomies. Neurosurgery. 1996;39:10–8.
57. Groff MW, Adams DC, Kahn RA, Kumbar UM, Yang BY, Bederson JB. Adenosine-induced transient asystole for management of a basilar artery aneurysm: case report. J Neurosurg. 1999;91:687–90.
58. Guinn NR, McDonagh DL, Borel CO, Wright DR, Zomorodi AR, Powers CJ, Warner DS, Lam AM, Britz GW. Adenosine-induced transient asystole for intracranial aneurysm surgery: a retrospective review. J Neurosurg Anesthesiol. 2011;23:35–40.
59. Lee SH, Kwun BD, Kim JU, Choi JH, Ahn JS, Park W, Yun JH. Adenosine-induced transient asystole during intracranial aneurysm surgery: indications, dosing, efficacy, and risks. Acta Neurochir (Wien). 2015;157:1879–86.
60. Bebawy JF, Gupta DK, Bendok BR, Hemmer LB, Zeeni C, Avram MJ, Batjer HH, Koht A. Adenosine-induced flow arrest to facilitate intracranial aneurysm clip ligation: dose–response data and safety profile. Anesth Analg. 2010;110:1406–11.
61. Bendok BR, Gupta DK, Rahme RJ, Eddleman CS, Adel JG, Sherma AK, Surdell DL, Bebawy JF, Koht A, Batjer HH. Adenosine for temporary flow arrest during intracranial aneurysm surgery: a single-center retrospective review. Neurosurgery. 2011;69:815–21.
62. Konczalla J, Platz J, Fichtlscherer S, Mutlak H, Strouhal U, Seifert V. Rapid ventricular pacing for clip reconstruction of complex unruptured intracranial aneurysms: results of an interdisciplinary prospective trial. J Neurosurg. 2018;128:1741–52.
63. Saldien V, Menovsky T, Rommens M, Van der Steen G, Van Loock K, Vermeersch G, Mott C, Bosmans J, De Ridder D, Maas AI. Rapid ventricular pacing for flow arrest during cerebrovascular surgery: revival of an old concept. Neurosurgery. 2012;70(2 Suppl Operative):270–5.
64. Hütter BO, Kreitschmann-Andermahr I, Mayfrank L, Rohde V, Spetzger U, Gilsbach JM. Functional outcome after aneurysmal subarachnoid hemorrhage. Acta Neurochir Suppl. 1999;72:157–74.
65. Kamide T, Burkhardt JK, Tabani H, Safaee MM, Lawton MT. Preoperative prediction of the necessity for anterior clinoidectomy during microsurgical clipping of ruptured posterior communicating artery aneurysms. World Neurosurg. 2018;109:e493–501.
66. Caplan JM, Sankey E, Gullotti D, Wang J, Westbroek E, Hwang B, Huang J. Contralateral approach for clipping of bilateral anterior circulation aneurysms. Neurosurg Focus. 2015;39(Video Suppl 1):V9.
67. Spetzger U, Rohde V, Mayfrank L, Bertalanffy H, Gilsbach J. Unilateral approach in multiple bilateral cerebral aneurysms. Surg Cereb Stroke (Jpn). 1998;26:20–5.
68. Batjer H, Samson D. Intraoperative aneurysmal rupture: incidence, outcome and suggestions for surgical management. Neurosurgery. 1986;18:701–7.
69. Sheth SA, Hausrath D, Numis AL, Lawton MT, Josephson SA. Intraoperative rerupture during surgical treatment of aneurysmal subarachnoid hemorrhage is not associated with an increased risk of vasospasm. J Neurosurg. 2014;120:409–14.
70. Yamamoto J. Clipping of posteriorly projecting large posterior communicating aneurysm via transsylvian anterior temporal approach. Neurosurg Focus. 2015;39(Video Suppl 1):V15.
71. Otani N, Morimoto Y, Fujii K, Toyooka T, Wada K, Mori K. Flexible ultrathin endoscope integrated with irrigation suction apparatus for assisting microneurosurgery. World Neurosurg. 2017;108:589–94.

Management of Intraoperative Rupture of Intracranial Aneurysms: Agony and Ecstasy

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Abstract

Intraoperative rupture (IOR) of an intracranial aneurysm is a serious complication, often with catastrophic consequences that are difficult to manage even by the best hands. Like most surgical complications, this one is better to avoid than to treat, but any vascular neurosurgeon should know how to deal with IOR of an aneurysm, because it is bound to occur. The aims of this study were to evaluate the incidence and factors associated with IOR during clipping of intracranial aneurysms, to analyze strategies for controlling hemorrhage in such cases, and to assess outcomes. Overall, 911 cases of intracranial aneurysms, which were treated surgically by the author during 26 years of his professional career, were reviewed. IOR was never noted during clipping of an unruptured intracranial aneurysm (65 cases) but was encountered in 49 of 846 cases (5.8%) presenting with subarachnoid hemorrhage. This complication occurred most often in cases of internal carotid artery aneurysms (22 cases; 45%), followed by anterior communicating artery aneurysms (12 cases; 24%), distal anterior cerebral artery aneurysms (6 cases; 12%), middle cerebral artery aneurysms (6 cases; 12%), and posterior circulation aneurysms (3 cases; 6%). IOR was mostly encountered during early surgery (within 3 days) after the ictus (26 cases; 53%) and most frequently occurred during dissection of the aneurysm (26 cases; 53%). Overall, 22 patients (45%) had good outcome, 18 (37%) had variable morbidity, and 9 (18%) died. Fatal consequences of IOR were noted only in cases of big or multilobulated internal carotid artery aneurysms. Detailed planning of the surgical procedure, application of meticulous microdissection techniques, and anticipation of possible intraoperative incidents during intervention aimed at clipping of an intracranial aneurysm can reduce the risk of IOR, as well as the associated morbidity and mortality.

Keywords

Aneurysm clipping · Causative factors · Complication · Intracranial aneurysm · Intraoperative rupture · Management · Microsurgery · Neurosurgery · Outcome · Subarachnoid hemorrhage

Introduction

Intraoperative rupture (IOR) is the most dramatic and potentially devastating complication of either endovascular or open surgical occlusion of intracranial aneurysms [1, 2]. Whereas during endovascular procedures, IOR of an aneurysm is encountered in approximately 2–5% of cases and is associated with high morbidity and mortality, its rate during open surgery ranges widely (from 3% to 50%) and its consequences are related to many additional factors [3–12]. Although minor leaks and small bleeds (which are not uncommon during clip application on the aneurysm neck) are usually controlled effectively and do not impact the outcome [10], significant IOR has a clear association with a poor prognosis, particularly in cases of basilar artery (BA) aneurysms [13, 14]. This complication increases the risks of vasospasm, delayed cerebral ischemia, permanent neurological deficits, and death. The associated mortality rates may be as high as 36–70%, especially in cases of parent vessel occlusion [15].

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_9

Since the introduction of the microsurgical technique for clipping of intracranial aneurysms, the problem of IOR, its management, and its impact on outcomes have been investigated in multiple studies and widely discussed in the medical literature by distinguished cerebrovascular neurosurgeons [4, 13, 15–29]. In particular, M. G. Yaşargil has devoted significant attention to this problem [27, 28]. The objective of the present study was evaluation of this complication in the practice of the author during 26 years of his professional career, with analysis of the incidence, predisposing factors, management strategies, and outcomes.

Materials and Methods

Overall, 911 consecutive cases of unruptured (65 cases) or ruptured (846 cases) intracranial aneurysms, which underwent surgical management by a single neurosurgeon, were reviewed retrospectively.

Aneurysm Surgery

For all anterior circulation aneurysms, standard pterional craniotomy was done, with the exception of distal anterior cerebral artery (ACA) aneurysms, which were accessed via unilateral parasagittal frontal or frontoparietal craniotomy. BA bifurcation aneurysms were generally operated on via the subtemporal–transpetrous approach. For other posterior circulation aneurysms, midline bilateral suboccipital craniotomy or retromastoid unilateral suboccipital craniotomy were utilized.

In the absence of obstructive hydrocephalus or a large intracranial hematoma, after induction of anesthesia, lumbar drain was introduced, and approximately 10–15 mL of cerebrospinal fluid (CSF) was gradually evacuated after completion of the craniotomy before opening of the dura mater. In all cases with moderate-to-severe ventriculomegaly (as demonstrated by computed tomography [CT]), intraventricular drain was inserted and CSF was evacuated.

The arterial blood pressure during surgery was maintained at a level 10–20 mmHg lower than that prior to anesthesia induction. An operating microscope and standard microsurgical techniques were used in all cases. In recent years, we have used intraoperative neuronavigation to locate some aneurysms (e.g., aneurysms of the distal ACA). Temporary clips were used intermittently only in cases of complex aneurysm dissection and were applied in maximal proximity to the lesion. Permanent clips were selected as appropriate, since a clip tray with all configurations of clips was readily available, as well as variable clip appliers of different configurations.

Results

IOR was not noted in any case of an unruptured intracranial aneurysm but was encountered in 49 patients presenting with subarachnoid hemorrhage (SAH). Thus, the incidence rates of this complication in all cases in the present series and during surgery for ruptured intracranial aneurysms were 5.4% and 5.8%, respectively.

Characteristics of Ruptured Aneurysms

A summary of the cases of IOR that occurred during surgery for intracranial aneurysms is presented in Table 1.

Table 1 Characteristics of cases of intraoperative aneurysm rupture in the present series

Characteristic	Number of cases
Total number of cases	49 (100%)
Location of the aneurysm	
ICA (including PComA)	22 (45%)
AComA	12 (24%)
Distal ACA	6 (12%)
MCA	6 (12%)
BA	1 (2%)
AICA	1 (2%)
PICA	1 (2%)
Size and architecture of the aneurysm	
Big	8 (16%)
Irregularly shaped	14 (29%)
Multilobulated	11 (22%)
Blister	5 (10%)
Regular/thin-walled	11 (22%)
Timing of surgery after aSAH	
Early (≤3 days)	26 (53%)
Intermediate (4–10 days)	15 (31%)
Delayed (>15 days)	8 (16%)
Stage of surgery	
Induction of anesthesia	4 (8%)
Craniotomy	2 (4%)
Aneurysm access	3 (6%)
Aneurysm dissection	26 (53%)
Aneurysm clipping	12 (24%)
Other	2 (4%)
Intensity of bleeding at IOR	
Mild-to-moderate	40 (82%)
Severe	9 (18%)
Outcome after IOR	
Good	22 (45%)
Recovery with various deficits	18 (37%)
Death	9 (18%)

ACA Anterior cerebral artery, *AComA* Anterior communicating artery, *AICA* Anterior inferior cerebellar artery, *aSAH* Aneurysmal subarachnoid hemorrhage, *BA* Basilar artery, *ICA* Internal carotid artery, *IOR* Intraoperative rupture, *MCA* Middle cerebral artery, *PComA* Posterior communicating artery, *PICA* Posterior inferior cerebellar artery

This complication was encountered most often in cases of internal carotid artery (ICA) aneurysms (22 cases; 45%), followed by anterior communicating artery (AComA) aneurysms (12 cases; 24%), distal ACA aneurysms (6 cases; 12%), middle cerebral artery (MCA) aneurysms (6 cases; 12%), and posterior circulation aneurysms (3 cases; 6%). Big aneurysms (10–25 mm in diameter), irregularly shaped aneurysms, or multilobulated aneurysms were noted, overall, in 33 cases (67%). In 26 cases (53%), IOR was encountered during early surgery (within 3 days) after aneurysmal SAH. With regard to the stage of surgery, IOR happened most frequently during dissection of the aneurysm (26 cases; 53%) followed by clipping (12 cases; 24%), induction of anesthesia (4 cases; 8%), access to the aneurysm before its dissection (3 cases; 6%), and the craniotomy procedure (2 cases; 4%). The intensity of bleeding during IOR was characterized as mild-to-moderate in 40 cases (82%) and severe in 9 cases (18%). In total, 22 patients (45%) had a good postoperative outcome, 18 (37%) recovered with some deficits, and 9 (18%) died. Fatal consequences of IOR were noted only in cases of big or multilobulated ICA aneurysms.

Discussion

IOR is a serious event during surgery for an intracranial aneurysm—a complication that even the best neurosurgeons find difficult to treat and that often leads to catastrophic consequences. Although (like most surgical complications) this one is better avoided than managed, any vascular neurosurgeon should know how to deal with IOR of an aneurysm, because it is bound to occur. Also, it is important to acknowledge certain factors that may be related to higher risks of IOR of an aneurysm.

Definition of Intraoperative Rupture

In the neurosurgical literature, the definition of IOR of an aneurysm has been rather variable, reflecting the personal considerations of individual authors. Generally, this term indicates any egress of blood from the aneurysm during surgery [7, 30, 31]. Usually, minor leaks or small bleeds that occur during clip application are not considered IOR, since they may be easily controlled, usually simply by closing of the clip blades [1, 4, 7, 9, 10, 15]. More detailed definitions of the term "IOR" have been suggested. For example, Houkin et al. [32] considered intraoperative premature rupture as a rupture that occurs before securing of the parent arteries or the neck of the aneurysm and that is out of control, at least temporarily; Chandler et al. [33] defined this complication as bleeding that interrupts and alters the flow of the microsurgical procedure; whereas Sandalcioglu et al. [9] emphasized the importance of differentiating IOR after opening of the dura mater into those that occur without any control versus those that are easily controllable.

In our opinion, IOR should be considered an iatrogenic neurovascular surgical adverse event with variable manifestations and related consequences. We define a premature rupture of the aneurysm as one that occurs before securing of the parent artery or dissection of the aneurysm neck, results in massive bleeding that is hardly controllable by means of small microsurgical suction (<2 mm in diameter), and necessitates use of two or more large-sized suctions.

Incidence of Intraoperative Rupture

Data from the literature suggest a rather variable incidence of IOR of intracranial aneurysms, ranging from 3% to 50% [3, 9, 34–36]. In older surgical series, this complication was noted more often, probably reflecting lack of sufficient experience of aneurysm surgery at the beginning of the microsurgical era. The reported incidence rates of IOR were 18% (a relatively low rate in comparison with others) in a series published by Graf and Nibbelink [37] in 1974, 61% in a series published by Pertuiset [23] in 1979 (with rupture of a distal aneurysmal sac in 90% of cases), 26% in a series published by Kassell et al. [4] in 1981, and 24% in a series published by Yaşargil and Smith [28] in 1982. However, with routine use of an operating microscope and microsurgical techniques, the rates of IOR during surgery for intracranial aneurysms in the largest surgical series have been significantly reduced. For example, according to a report published in 2005, Leipzig et al. [2] encountered this complication in 6.7% of cases during surgery for 1694 saccular aneurysms. This seems comparable to our experience presented herein (a 5.8% IOR rate during surgery for 846 ruptured aneurysms); in addition, it should be emphasized that we never experienced this complication in elective surgery for 65 unruptured aneurysms.

Thus, the incidence of IOR during surgery for intracranial aneurysms differs from one time period to another and is closely related to the place of practice, the surgeon and his or her professional experience, the surgical infrastructure, and the availability of advanced technical and technological intraoperative applications.

Location, Size, and Architecture of Aneurysms

As noted previously, the location, size, and morphology of an aneurysm are important factors related to IOR, which have been widely discussed in the neurosurgical literature [2, 15, 38–41].

There is no consensus on the relation of the aneurysm location to the risk of its IOR; in an analysis of their extensive experience, Sundt et al. [42] did not find such an association. While anterior circulation aneurysms generally

constitute the majority of cases of IOR (which corresponds well to our data), it is evident that those lesions are much more common than posterior circulation aneurysms; thus, the number of surgeries performed to clip them is overwhelmingly greater. Different studies have linked the increased risk of this complication to various locations of the aneurysm. For example, Schramm and Cedzich [10] suggested that the frequency of IOR is higher in cases of AComA aneurysms; Leipzig et al. [2] noted this in cases of AComA, posterior communicating artery (PComA), and posterior inferior cerebellar artery (PICA) aneurysms; whereas it was also proposed that the risk of this complication may be somewhat lower in cases of MCA aneurysms. These findings, however, have not been confirmed consistently.

In the series presented herein, out of 49 cases of IOR, there were 46 anterior circulation aneurysms. Those ones (22 cases) were most frequently related to the ICA (being mainly proximal ICA aneurysms, ophthalmic aneurysms, PComA aneurysms, or those arising from the dorsomedial wall of ICA), whereas AComA aneurysms were encountered less often (12 cases). According to our experience, ventrally (anteriorly) projected ICA aneurysms and dorsally (posteriorly) projected ICA aneurysms are more prone to IOR. In general, however, we consider that the location of the aneurysm *per se* is not a significant factor in development of this complication and that other causes should be taken into consideration. For example, in our cases of distal ACA aneurysms, IOR was mainly related to improper positioning of the craniotomy and inappropriate dissection of the pericallosal cistern during accessing of the aneurysm, whereas during surgery for MCA aneurysms, this complication was mainly encountered during opening of the Sylvian fissure, evacuation of hematomas, or separation of perforators and arterial branches in the vicinity of the aneurysm.

It has been considered that the risk of IOR is rather low in the case of a small aneurysm [11] but substantially increases if its diameter exceeds 10 mm. The thing is that an increase in the size of the aneurysm may be associated with thinning of the aneurysm wall and an increase in its fragility, making it more prone to rupture. However, our series included just 8 cases (16%) of big aneurysms (10–25 mm in diameter).

On the other hand, in nearly half of our patients (25 cases; 51%), IOR was encountered in cases of irregularly shaped or multilobulated intracranial aneurysms. In addition, blister aneurysms, which are generally considered exceptionally fragile, were noted in 5 cases (10%). These morphological features are seemingly associated with higher risks of IOR, which, in such cases, may be related to a deficiency in wall resilience, partial thrombosis, and adherence of the dome to the brain and the arachnoid membrane, all of which reduce the dissection space and facilitate rupture. It should be noted, however, that in 11 cases (22%), we encountered IOR in cases of seemingly regular (albeit probably thin-walled) aneurysms, which indicates that this complication may occasionally happen even in rather routine cases.

Timing of Surgery

Although there is no definite association between the risk of IOR and the severity of SAH according to the Hunt and Hess grading scale [43], many neurosurgeons consider that the timing of surgery for a ruptured intracranial aneurysm is the most critical factor in this complication. Early surgery is associated with the highest risk, which may be related to several factors, including a fragile dome, a fresh liquid blood clot, obliterated subarachnoid space, and edematous brain tissue [20]. In the series reported by Lakićević et al. [14], IOR was encountered in 27.54%, 24.27%, and 3% of cases during early surgery (performed within 72 h after acute SAH), intermediate surgery (performed within 4–10 days), or late surgery (performed after 10 days) for intracranial aneurysms.

In concordance, in our series presented herein, 53% of all cases of IOR were encountered during early surgery for a ruptured aneurysm, 31% during intermediate surgery, and 16% during delayed surgery (performed after 15 days). This should be taken into consideration, since contemporary treatment protocols generally entail early management of ruptured aneurysms for prevention of rebleeding [40]. Nevertheless, some studies have reported similar incidence rates of IOR during early and late surgery for intracranial aneurysms [4].

Stage of Surgery

IOR may occur at any stage of a neurosurgical procedure aimed at clipping of the aneurysm—during preinduction or induction of anesthesia, craniotomy, opening of the dura mater, initial exposure of the brain, introduction of intraventricular drain, retraction of the brain during access to the aneurysm, evacuation of a hematoma, dissection of the aneurysm, or clipping itself.

Although it is relatively uncommon, rupture of an aneurysm during preinduction or induction of anesthesia, or during the initial stage of surgery (e.g., skin incision), can produce catastrophic consequences and is associated with high mortality. Development of a complication at that stage may be related to several factors that disrupt the fine balance between the mean arterial pressure, intracranial pressure, and transmural pressure on the aneurysm wall. Those factors include sudden changes in hemodynamics during induction of anesthesia (particularly if it is accompanied by coughing or gagging), pin placement for skull fixation, and surgical incision [44–46]. Tsementzis and Hitchcock [47] addressed the problem of the intracranial aneurysm rupture during induction of anesthesia and noted that although it happens in just 1–2% of cases, the associated mortality rate is up to 75%. In their study based on 404 cases of intracranial aneurysm surgery, eight patients (2%) had a rupture at the time of induction of anesthesia or intubation, and in seven of them, either a complicated intubation or coughing during intubation were noted, possibly indicating that airway

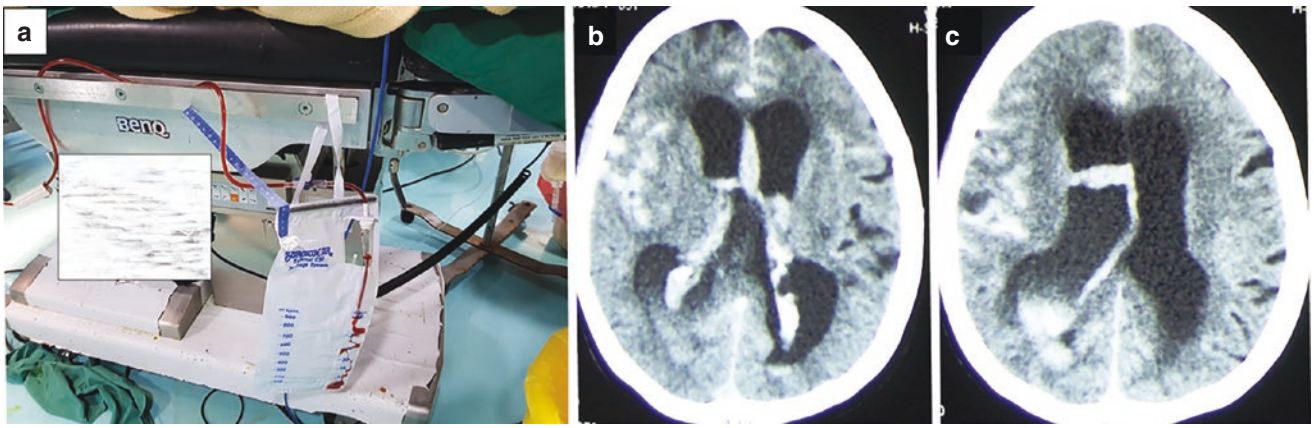

Fig. 1 Rupture of an anterior communicating artery aneurysm during induction of anesthesia, manifested by a sudden increase in blood pressure, tachycardia, and appearance of fresh blood in the lumbar cerebrospinal fluid drain (**a**). Rebleeding was confirmed by emergency computed tomography of the brain (**b**, **c**)

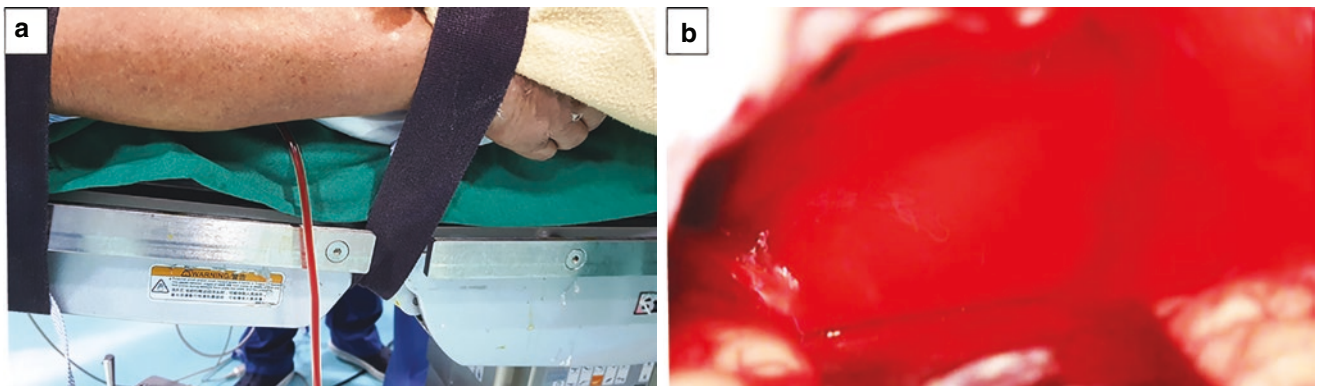

Fig. 2 Rupture of an internal carotid artery–posterior communicating artery aneurysm during craniotomy, manifested by appearance of fresh blood in the lumbar cerebrospinal fluid drain (**a**). Subsequently, as the surgery continued, a large amount of fresh blood in the basal subarachnoid cisterns was noted (**b**)

manipulation and a resultant sympathetic surge could have been a contributing factor [47].

In our series presented herein, there were 4 cases of the aneurysm rupture at induction of anesthesia, which manifested with sudden increases in systolic and diastolic blood pressure (by 30–50 mmHg and by 20–30 mmHg, respectively, in comparison with their preinduction levels), tachycardia, and appearance of fresh blood in the lumbar CSF drain (Fig. 1a). This complication could be due to hemodynamic alterations caused by inappropriately light sedation and muscular relaxation [47, 48]. All procedures were abandoned, and the patients were transferred for CT, which confirmed significant rebleeding (Fig. 1b, c). Two patients with occlusive hydrocephalus underwent intraventricular drainage but unfortunately died thereafter. In two other patients, ventricular drainage was deemed unnecessary; they were sedated and ventilated, underwent surgery the next day, and subsequently demonstrated good recovery.

IOR during the craniotomy procedure is also rather rare [13, 15]. At this stage, the complication may be caused by high-frequency vibrations due to use of power tools for placement of burr holes and cutting of the bone, nibbling by rongeurs, or drilling of calvarial bone or the skull base (e.g., the temporal bone, sphenoid wing, or anterior clinoid process). In our experience, there have been 2 cases of IOR at the time of craniotomy, which manifested with appearance of fresh blood in the lumbar CSF drain (Fig. 2a), while the vital parameters of patients were stable. As these surgeries were continued, fresh subarachnoid blood was noted (Fig. 2b).

Nevertheless, most commonly (especially in cases of ruptured aneurysms), IOR occurs during the microsurgical part of the procedure [1, 4, 5, 7–10, 12, 13, 15, 21, 22, 25–27, 32]. It may be encountered during access to the aneurysm before its dissection (e.g., during opening of the dura mater, arachnoid membrane, and basal subarachnoid cisterns; retraction of edematous brain tissue; and/or evacuation of subdural, subarachnoid, and intraparenchymal hematomas). On the basis of their experience with 398 patients, Houkin et al. [32] noted IOR of an aneurysm at this stage of surgery in 6% of

cases. The possible causes of the complication included blunt dissection, traction during dissection (in 8.3% of cases), retraction of the brain (in 12.5% of cases), hematoma evacuation (in 12.5% of cases), and anatomical miscalculation of the aneurysm location; at the same time, IOR occurred with comparable frequency during right-hand and left-hand dissections (29% versus 33.3%).

In our experience, IOR during access to the aneurysm occurred in three patients: one with an AComA aneurysm and two with MCA aneurysms. Detailed analysis did not reveal any errors in the microsurgical technique (Figs. 3, 4), and we considered that IOR of the aneurysms in these cases was somewhat unavoidable. High-risk cases of such very early premature rupture may be predicted on the basis of a combination of several unfavorable factors, including high-grade SAH, a large amount of subarachnoid blood (i.e., a greater Fisher group), the presence of an intracerebral and/or subdural hematoma, and signs of rerupture of the aneurysm before surgery (e.g., during angiography), which should be considered during pre- and intraoperative decision-making and selection of the optimal treatment strategy.

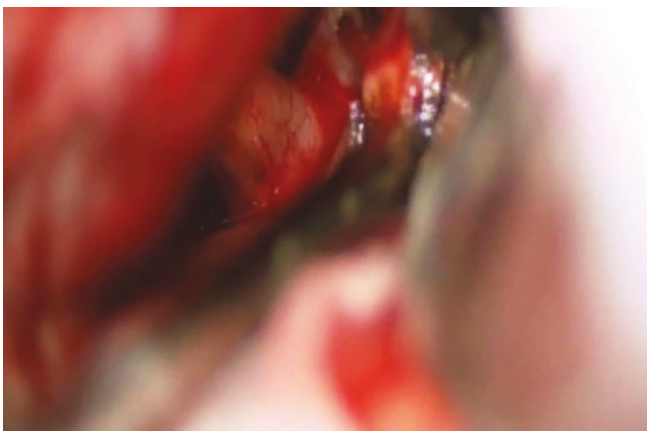

Fig. 3 Access to an anterior communicating artery aneurysm, which ruptured during opening of the chiasmatic cistern

Still, the majority of IOR occurs during dissection of the aneurysm complex [2, 14, 27, 28, 30, 32, 33, 35, 45]. It was reconfirmed in our series: in more than half of the patients (26 cases; 53%), the complication was noted at that stage of surgery. Other authors have also previously noted that the risk of IOR during dissection of the aneurysm is higher in cases of ruptured aneurysms with acute SAH than in unruptured or remotely ruptured ones [2, 42], which well corresponds to our own experience presented herein. Several other possible predisposing factors for IOR during dissection of the aneurysm were defined as well, including the size and location of the aneurysm, a large amount of subarachnoid blood, the presence of an intracerebral hematoma, a greater extent of brain edema, and elevated systolic blood pressure during the procedure.

Our surgical strategy entails routine use of an operating microscope (allowing appropriate illumination of the surgical field and high magnification), utilization of a standard microsurgical technique, wide opening of basal subarachnoid cisterns, minimal use of temporary clips (unless it is necessitated by the complex architecture of the aneurysm), and maintenance of the arterial blood pressure during surgery at a level 10–20 mmHg lower than that prior to anesthesia induction, particularly during dissection of the aneurysm. In addition, at that stage of surgery, we use very low-power bipolar coagulation and low-pressure thumb-controlled microsuction. These measures may have decreased the incidence of IOR but did not eliminate the risk of this complication completely (Figs. 5, 6, 7, 8, 9, 10, 11). In the majority of cases, IOR was encountered during the final phase of dissection of

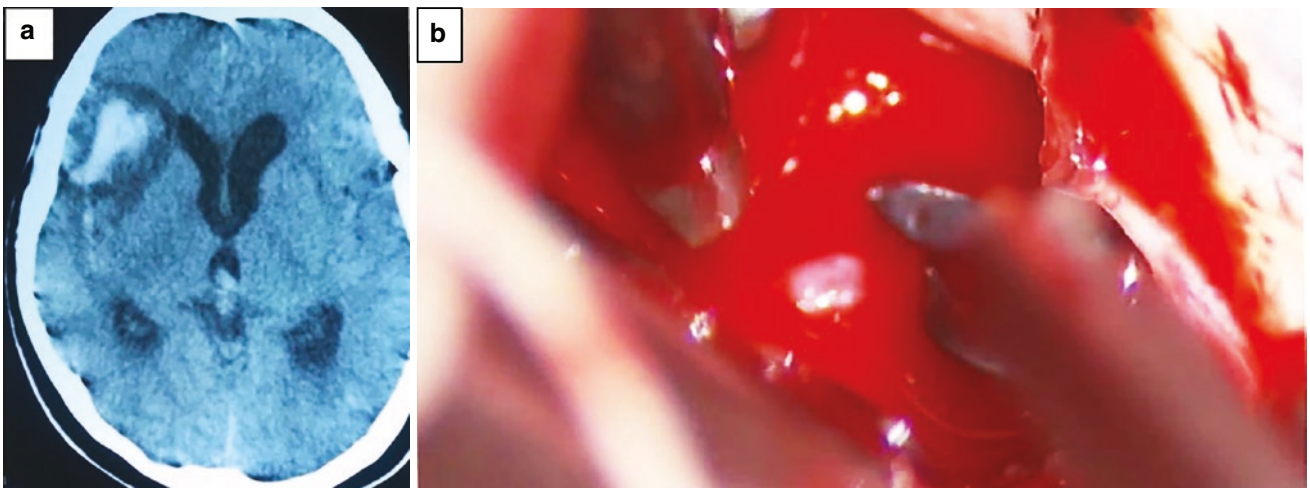

Fig. 4 Preoperative computed tomography (**a**) in a patient with a ruptured right-side middle cerebral artery aneurysm accompanied by an intracerebral hematoma. Surgical clipping of the aneurysm was complicated by its rupture during removal of the hematoma (**b**)

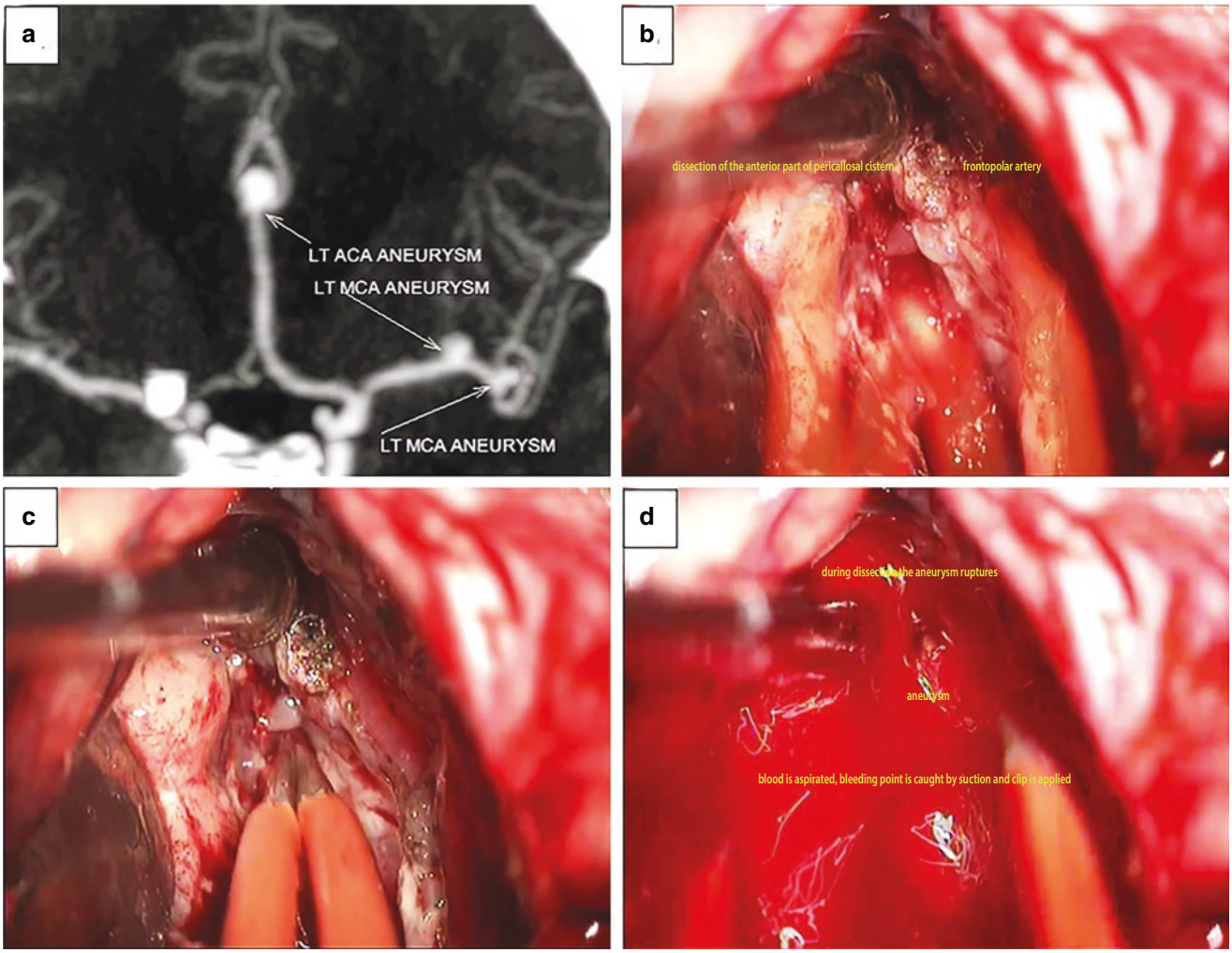

Fig. 5 Three-dimensional computed tomography angiography (**a**) in a patient with multiple intracranial aneurysms. A distal left-side anterior cerebral artery aneurysm ruptured during its dissection (**b**–**d**). *ACA* Anterior cerebral artery, *LT* Left, *MCA* Middle cerebral artery

the arachnoid around the aneurysm complex and during attempts to define the neck, or during separation of functionally important vascular branches and perforators and identification of the proximal and distal branches of the parent vessel. In a few cases, IOR was noted during reaching of the aneurysm following the parent artery and may have been related to overstretching of this vessel, excessive pressure on the aneurysm, anatomical miscalculation of its location, or inaccurate suction of surrounding blood clots.

Finally, IOR of the aneurysm during clipping itself also contributes significantly to the rate of this complication and may be related to various technical factors, such as the size, configuration, type, placement, and readjustment of the clip; the clarity of the operative field during the clipping process; and the size, shape, and smoothness of the clip applier [1, 13]. In our experience, IOR at this stage of surgery was noted in 12 cases (24%; Figs. 12 and 13). In five of them (mostly involving big ICA aneurysms with wide necks), it happened during application of the clip, and we suspected that the clip that was selected was not of the appropriate length and configuration, leading to tearing of the neck. This complication was managed by parallel application of a longer clip. In 4 cases, IOR was noted during readjustment of the clip, which was deemed necessary for various reasons (e.g., partial neck obliteration, inclusion of the vessel, or a desire to perform more distal application of the clip on the neck). In such cases, the complication was rather easy to manage: we applied a temporary clip on the parent vessel and readjusted the clip on the aneurysm. In two of our cases, IOR during clipping was caused by improper release of the clip applier, with tearing of the aneurysm neck. This caused difficulty in controlling the bleeding; we applied a temporary clip on the parent vessel, and a new clip was placed on the neck, taking part of the parent vessel wall within the clip. In one case, because of improper selection of the clip applier, the hand of the surgeon blocked the view during clipping and the blade of the clip cut the aneurysm neck.

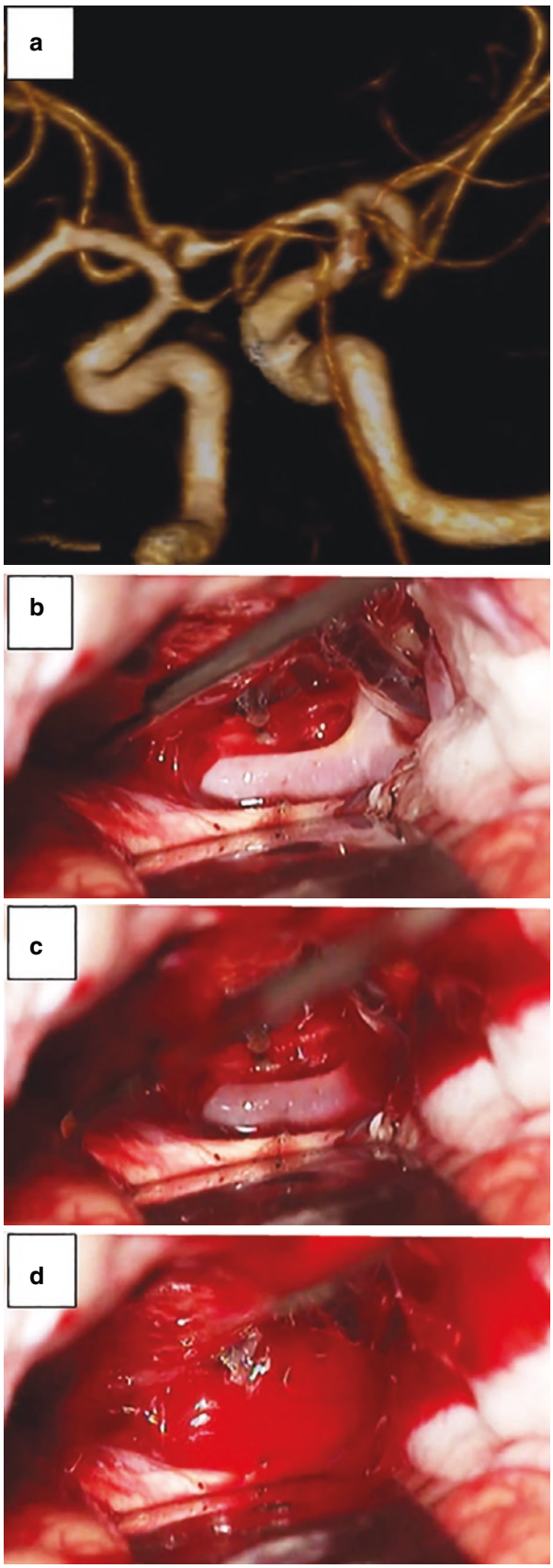

Fig. 6 Three-dimensional computed tomography angiography (**a**) and intraoperative visualization (**b**–**d**) of an anterior communicating artery aneurysm, which ruptured during its dissection

Prevention of Intraoperative Rupture

Most neurosurgeons agree that IOR of an aneurysm leads to a poor outcome and associated suffering of the patient and his or her family; thus, it is always better to avoid this complication than to have to treat it. Detailed planning of the surgical procedure, application of meticulous microdissection techniques, and anticipation of possible intraoperative incidents during intervention for intracranial aneurysms can reduce the risk of IOR and the associated morbidity and mortality. Surgical clipping of intracranial aneurysms should at least be supervised—or, in the most difficult cases, executed—by well-trained neurosurgeons with extensive experience in cerebrovascular microsurgical procedures, assisted by less experienced colleagues, with the aim of training them.

Measures directed at avoidance and prevention of IOR of intracranial aneurysms start with initiation of anesthesia; proper positioning of the patient on the operating table; infiltration of the skin with a local anesthetic at pin fixation sites and along the surgical incision; appropriate sedation, analgesia, and muscle relaxation; and prevention of intraoperative surges in the arterial blood pressure and heart rate. Insertion of lumbar CSF drain is advantageous in cases of early surgery, large amounts of subarachnoid blood, associated communicating hydrocephalus, and a tight edematous brain. Insertion of intraventricular drain is of great help in cases of associated ventriculomegaly and intraventricular hemorrhage [1, 13, 16, 27, 48].

During craniotomy, full attention should be given to optimal placement of the bone flap and appropriate resection of bony structures as required by the selected surgical approach (e.g., drilling of the greater or lesser wings of the sphenoid bone and the anterior and posterior clinoid processes) to gain wider access to the skull base and the circle of Willis, and to reduce the amount of brain retraction required. In our practice, use of intraoperative neuronavigation for planning the surgical access to an aneurysm has been rather helpful in some cases.

During access to the aneurysm, brain retraction should be avoided or minimized, and it is preferable to just support the cerebral lobe instead of forcibly displacing it with a spatula. If one prefers to use retractors, they should be applied with low force, slowly and gently, with intermittent release and careful coverage of the brain under the retractor blade with a cottonoid and/or a small piece of a cut surgical glove.

Since the circle of Willis is positioned within the subarachnoid space, opening of the arachnoid is the first step in safe and smooth dissection of the aneurysm complex [28, 29]. We prefer to widely open all related basal cisterns (depending on the location of the aneurysm—e.g., the Sylvian and carotid cisterns, chiasmatic cistern, and perimesencepahalic cisterns, in cases of ICA, AComA, and BA aneurysms, respectively) at the very beginning of the microsurgical

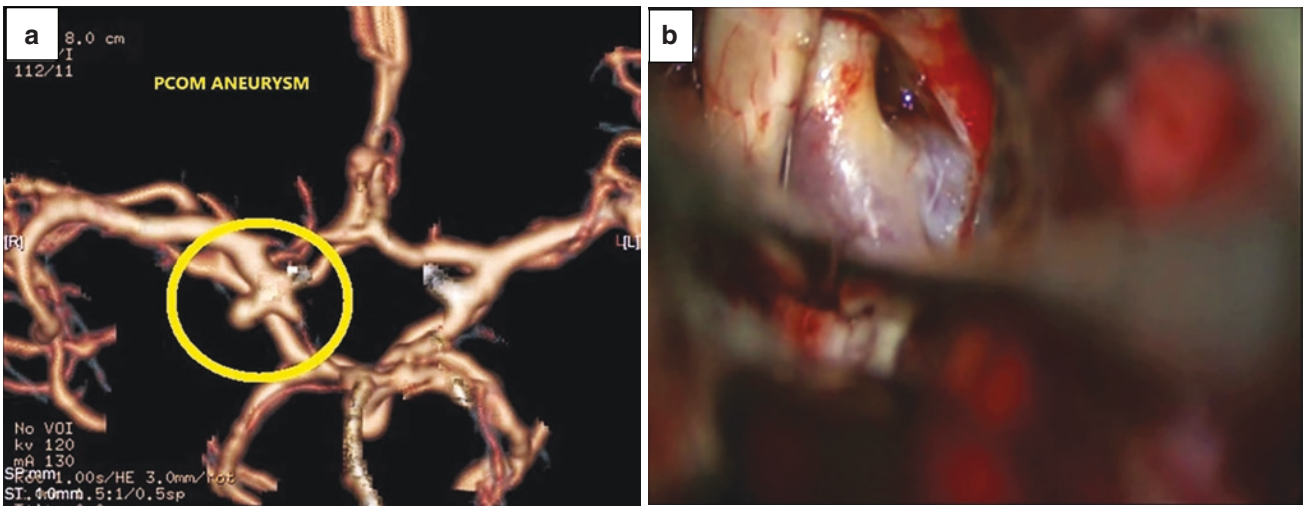

Fig. 7 Three-dimensional computed tomography angiography (**a**) and intraoperative visualization (**b**) of a right-side posterior communicating artery aneurysm, which ruptured during its dissection. *PCOM* Posterior communicating artery

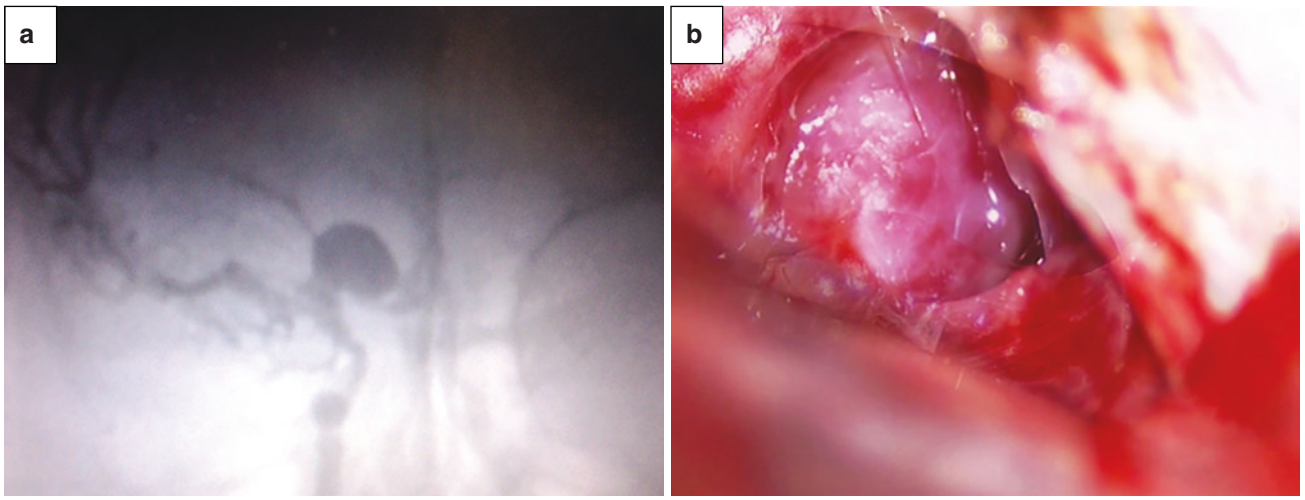

Fig. 8 Digital subtraction angiography (**a**) and intraoperative visualization (**b**) of a big right-side internal carotid artery aneurysm, which ruptured during its dissection

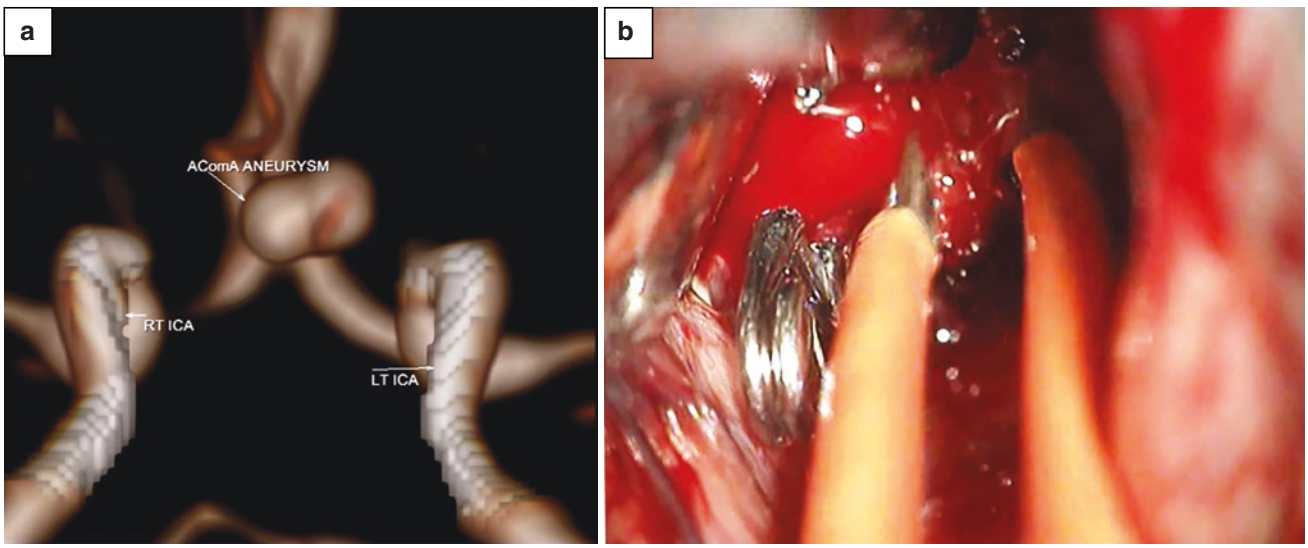

Fig. 9 High-resolution three-dimensional computed tomography angiography (**a**) and intraoperative visualization (**b**) of an anterior communicating artery aneurysm, which ruptured during its dissection. *AComA* Anterior communicating artery, *ICA* Internal carotid artery, *LT* Left, *RT* Right

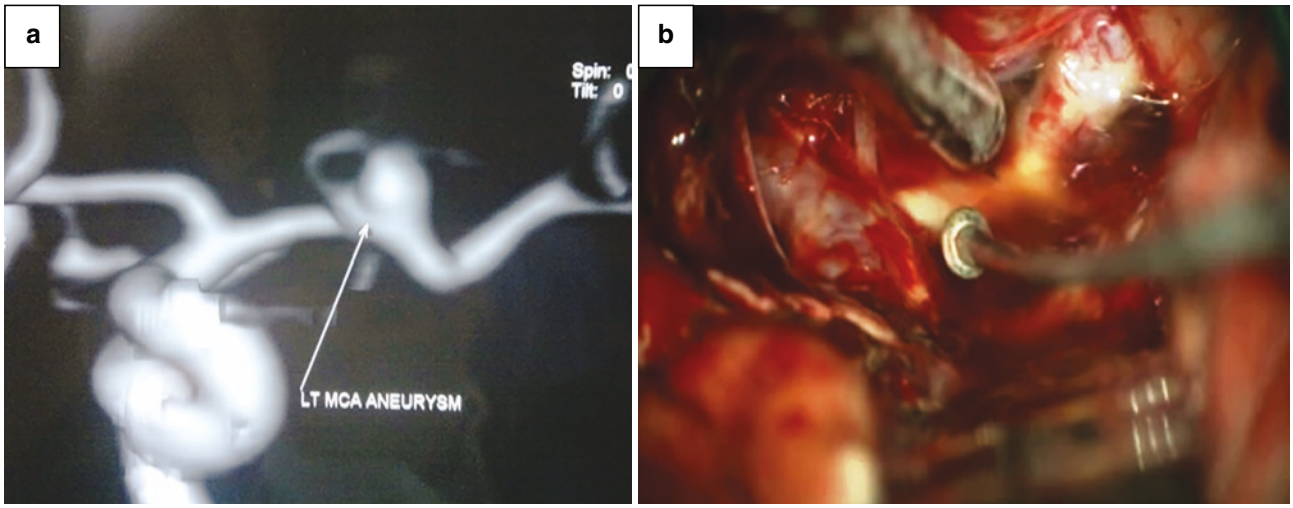

Fig. 10 Three-dimensional computed tomography angiography (**a**) and intraoperative visualization (**b**) of a left-side middle cerebral artery aneurysm, which ruptured during its dissection. *LT* Left, *MCA* Middle cerebral artery

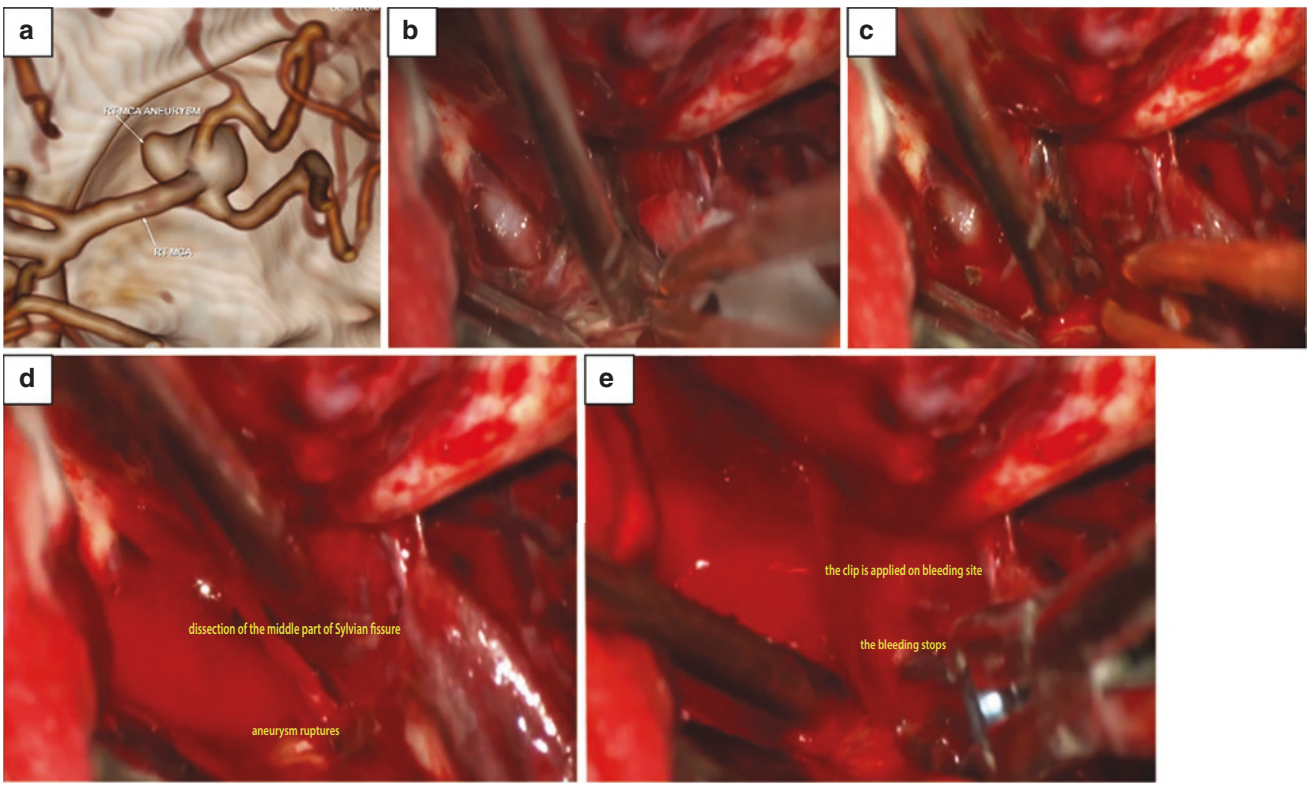

Fig. 11 Three-dimensional computed tomography angiography (**a**) of a right-side middle cerebral artery aneurysm, which ruptured during its dissection (**b**–**e**). *MCA* Middle cerebral artery, *RT* Right

part of the procedure. Particularly in cases of MCA aneurysms, we prefer to open the Sylvian fissure starting from its medial part to the lateral direction. Opening of basal subarachnoid cisterns is of great help in achieving good relaxation of the brain with removal of subarachnoid blood and release of CSF, facilitating handling of the circle of Willis, its branches, and perforators. It also allows effective aneurysm dissection and exposure, provides good access to proximal vessels for application of temporary clips if deemed necessary, and significantly reduces the risk of subsequent cerebral vasospasm [1–4, 10, 13, 24, 28, 29, 43].

For safe and comfortable dissection of the aneurysm complex, appropriate illumination of the operative field and high magnification by means of an operating microscope

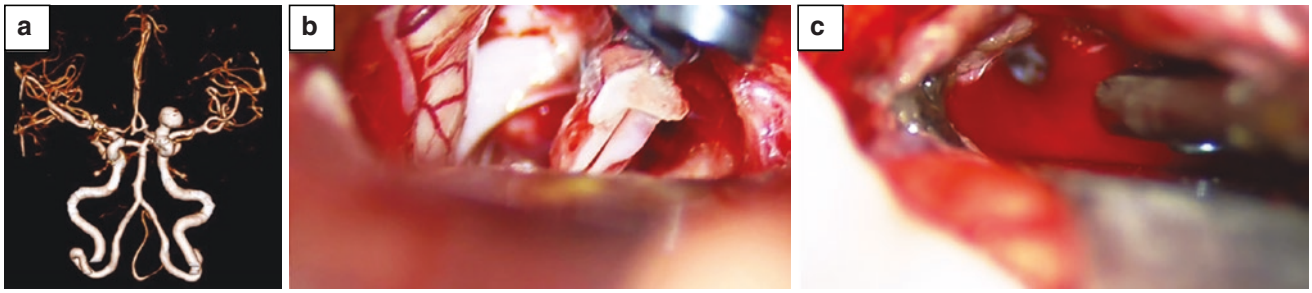

Fig. 12 Three-dimensional computed tomography angiography (**a**) of a giant multilobulated left-side internal carotid artery aneurysm, which ruptured during clip application (**b**, **c**)

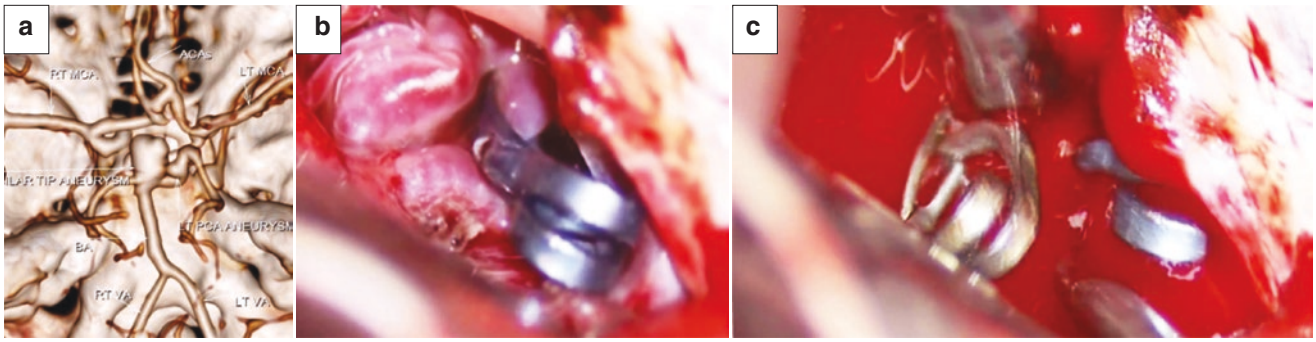

Fig. 13 Three-dimensional computed tomography angiography (**a**) of a big basilar artery (BA) tip aneurysm, which ruptured during clip application (**b**, **c**). Of note, there is a second aneurysm arising from the left proximal posterior cerebral artery (PCA). *ACA* Anterior cerebral artery, *LT* Left, *MCA* Middle cerebral artery, *RT* Right

are very important [28, 29]. During the dissection, the most important issues are early exposure of the proximal vessel and identification and exposure of the neck of the aneurysm. At this stage, we prefer to use high magnification and execute sharp, smooth, and slow bimanual dissection, keeping both the suction force and the bipolar power low. In particular, if there is an associated hematoma, the dissection needs to be very slow and smooth, with low suction power and removal of the hematoma layer by layer. Once the proximal vessel and the neck of the aneurysm are exposed, we proceed to dissect the aneurysm complex all around and confirm all of the vessels, the perforators on both sides of the dome, the distal vessels, and the adjacent cranial nerves before applying the clip. At the end stage of the dissection and clipping, to keep the vision constant, we use retractors with low applied force. We prefer not to use a temporary clip for routine aneurysm dissections. If the aneurysm is complex and the dissection will be difficult, we use a temporary clip nearer the aneurysm to prevent injury and compromise of perforators.

Once the neck is fully exposed, several important steps need to be taken to avoid IOR during clip application. First of all, the length, size, and shape of the clip, as well as the type of clip applier, should be selected appropriately. In particular, the optimal clip applier should not obstruct the view of the operative field and should allow smooth application and release of the clip. When the clip position is being readjusted on the neck, the whole clip should be opened and readjusted; it should not be pulled or pushed without the blades being completely opened.

Management of Intraoperative Rupture

If IOR of an aneurysm occurs, achieving a safe outcome is crucial for the entire surgical procedure. Fortunately, in the majority of cases, this complication can be overcome effectively, but it clearly requires well-developed microsurgical skills, patience, and strong intraoperative teamwork. The management options vary with regard to the stage of surgery and the extent and severity of bleeding.

If IOR is detected during induction of anesthesia, we prefer to stop at that stage, correct the vital signs (blood pressure and heart rate), and transfer the patient for emergency CT. If there is a small SAH or a big hematoma causing a mass effect, we proceed with the surgery, but if there is an extensive diffuse SAH, intraventricular hemorrhage, brain stem hemorrhage, or evidence of prominent brain swelling, we prefer to abandon the procedure and take appropriate conservative measures (e.g., ventricular drainage, sedation, and ventilation) for stabilization of the patient's condition in the intensive care unit.

If IOR of an aneurysm occurs during craniotomy, we proceed with the surgery and enhance the anesthesia using high doses of propofol and thiopentone, hyperventilation, and hypothermia. Although there are concerns that hyperventilation can result in cerebral vasoconstriction and an associated risk of brain ischemia, its brief use may help to reduce intracranial pressure, which may be augmented by administration of osmotic diuretics and a small reduction (by approximately 20%) in the mean arterial blood pressure [1, 47, 48]. It should be acknowledged that hypothermia is difficult to apply in the acute phase of IOR of an intracranial aneurysm, and its role in neuroprotection is yet to be confirmed [49–52].

If IOR occurs after opening of the dura mater but before dissection of the aneurysm, it is most important not to panic and not to lose control of the situation. At present, there are no standardized effective management options for such an intraoperative complication, and its outcomes may be very disappointing. The teamwork of the neurosurgeon and his or her assistants, the anesthetist, and the operating nurse plays a vital role in tackling the situation. First of all (as mentioned above), deep sedation with infusion of high doses of propofol and thiopentone, analgesia, hyperventilation, administration of osmotic diuretics (we prefer to administer 40 mg of furosemide and/or a 350-mL bolus dose of 20% mannitol), and a reduction in the mean arterial pressure by 20% should be considered. Still, unlike IOR of an aneurysm in a closed skull, IOR after opening of the dura mater allows the blood to leak out, which may reduce its compressive effect on the brain tissue. Thus, the ruptured aneurysm should be localized quickly; for that, one needs to clear the blood, for which two suctions are frequently used, one by the surgeon and one by an assistant (we prefer that the assistant holds the suction at a distance from the rupture site). We gently elevate the frontal lobe or any other relevant part of the brain to have wider access for dissection of the parent vessel and the aneurysm complex for control of bleeding. Possible resection of brain tissue and fast evacuation of a hematoma under deep hypotension may occasionally be effective. Thereafter, we perform wide opening of the arachnoid and evacuation of the subarachnoid blood for identification of the major and minor vessels and for application of temporary clips on the parent artery. Obtaining proximal control with a temporary clip allows dissection of the aneurysm complex and is considered the most definitive step in preventing devastating neurological consequences of IOR.

Of note, IOR may occur during dissection of an aneurysm even after application of a temporary clip on the proximal vessel and is caused by patent cross-circulation or blood backflow; in such cases, we also prefer to use temporary clips to control the situation, but we try to avoid bipolar coagulation because it may be rather difficult to identify what is really coagulated within a pool of blood, and functionally important vessels could end up being damaged permanently, resulting in extensive ischemic neurological deficits. Another important factor is the utility of suction; we prefer low power or a multichannel thumb-controlled suction-irrigation tube, where the force of suction can be controlled according to the situation. High-pressure suction could further damage the parent vessel, the aneurysm, other surrounding vessels, or small perforators, leading to extensive neurological deficits. It is much safer to perform suctioning through a small wet cottonoid with marking thread.

Nevertheless, in some cases of complex aneurysms, routine techniques for management of IOR may fail. This may necessitate use of more advanced treatment, such as reversible transient complete flow arrest with adenosine-induced asystole, the effectiveness and safety of which have been demonstrated in several studies [11, 48, 53, 54]. The recommended starting dose of adenosine is 0.3–0.4 mg/kg of ideal body weight to achieve approximately 45 s of profound systemic hypotension during remifentanil low-dose volatile anesthesia and propofol-induced burst suppression. This may allow achievement of circumferential visualization of the aneurysm neck, but larger clinical trials are warranted to provide further information on long-term outcomes after application of this technique. Another advanced method is transient flow arrest via rapid ventricular pacing, which can also facilitate surgical management of IOR of an intracranial aneurysm. Rapid ventricular pacing (a technique developed in interventional cardiology) can be used to induce flow arrest lasting a few seconds, which may be an effective and safe adjunct for dissection and clipping of an aneurysm [55]. Still, this method also requires additional clinical evaluation. So far, we do not have personal experience with either of these techniques.

The most important step during dissection of the aneurysm complex is visualization of the rupture site, fundus, body, and neck so that appropriate clip shapes and sizes can be selected and applied properly without compromising any surrounding vessels, perforators, or neuronal structures (e.g., an adjacent cranial nerve). Another important infrastructural need is availability of a tray containing all types of clips of different sizes, shapes, and configurations, as well as multiple clip appliers of various functional designs. Having a wide variety of clips readily available allows optimal clip selection for the most effective reconstruction of the vessel and clipping of the aneurysm, preventing possible complications (primarily, ischemic neurological deficits).

In the most complex situations, when IOR requires permanent parent vessel occlusion, the neurosurgeon should have sufficient knowledge and skills to accomplish the intracranial vascular bypass procedures needed to revascularize the vascular territory affected by the compromised vessels. The related surgical decision-making may be significantly facilitated by use of intraoperative microvascular Doppler, indocyanine green fluorescence angiography, or digital subtraction angiography, allowing selection of the optimal strategy for a safe and effective procedure.

Consequences of Intraoperative Rupture

What are the end results of a surgical catastrophe such as IOR of an intracranial aneurysm? In fact, the outcomes vary, but they are clearly less favorable than those of uncomplicated clipping procedures. In a series described by Batjer and Samson [13], the incidence rates of favorable outcomes at long-term (more than 6 months) follow-up were 88% after uncomplicated clipping of an aneurysm but only 66% in cases complicated by IOR.

Multiple factors have important impacts on the overall result of treatment. They include the stage of surgery at which the complication happens, the location of the aneurysm (in a major vessel, the circle of Willis, or a distal vessel), its size and angioarchitecture. If a premature rupture develops before it is possible to secure the parent artery or clip the aneurysm, the outcome is generally much grimmer. It is also generally worse in cases where major arteries (the ICA, BA, or vertebral artery) or dominant arteries are involved. The outcome also depends on the patient's preoperative neurological status and Glasgow Coma Scale score, and on the timing of the surgery (the worst results occur in cases of early surgery within 3 days after SAH) [13, 18]. IOR of an intracranial aneurysm is strongly associated with such devastating complications as extensive ischemia of deep and superficial functionally important brain structures, intraparenchymal and intraventricular hemorrhage, vasospasm, cranial nerve injuries, hydrocephalus, and multiple postoperative systemic complications, which lead to a prolonged hospital stay, a high rate of disability, and significant social and financial burdens. The reported morbidity and mortality rates range between 34% and 65%, and between 18% and 27%, respectively, but they may be even higher under specific conditions [1, 6, 7, 9, 10, 12–14, 18, 22, 24, 30, 47]. In our experience of 49 cases of IOR of an intracranial aneurysm, 22 patients (45%) demonstrated good postoperative outcome, 18 (37%) recovered with some deficits, and 9 (18%) died; in all of the latter cases, the surgery was done for big or multilobulated ICA aneurysms.

Conclusion

Since the introduction of operating microscopes and routine use of microsurgical techniques during surgery for intracranial aneurysms, the incidence and severity of their IOR have been reduced significantly. Nevertheless, this undesired, unavoidable, and infrequent event may happen during treatment of any aneurysm and at the hands of any surgeon, and it can result in variable neurological consequences ranging from relatively mild to devastating ones. Therefore, neurosurgeons practicing microsurgical techniques for management of intracranial aneurysms need to keep in mind that every aneurysm could rupture at any time; thus, it is vital to plan an appropriate strategy to manage this possible complication right from the outset of the surgical procedure. This requires well-coordinated teamwork in the operating room. Surgical clipping of intracranial aneurysms should preferably be performed by well-trained neurosurgeons with extensive experience in cerebrovascular microsurgical procedures, assisted by less experienced colleagues, with the aim of their training and transferring knowledge and skills to them. Preoperative discussions with and counseling of the patient and his or her family about the incidence and outcomes of IOR of the aneurysm—along with other aspects of the surgery and their possible outcomes—are very important and also give a good psychological boost to the surgeon and help him or her perform better during the procedure. If an IOR of the aneurysm occurs, the most important things are to maintain equanimity and not panic. Quick organization, prompt reaction, planning, and control of the situation, both mental and physical, will help greatly to overcome the crisis with good results. Every case of IOR of an intracranial aneurysm is a combination of the agony of its management and the ecstasy of successful salvage of the patient's life.

Conflict of Interest Statement The author has no conflict of interest concerning the reported materials or methods.

References

1. Barrow DL. Intraoperative misadventures: complication avoidance and management in aneurysm surgery. Clin Neurosurg. 2011;58:93–109.
2. Leipzig TJ, Morgan J, Horner TG, Payner T, Redelman K, Johnson CS. Analysis of intraoperative rupture in the surgical treatment of 1694 saccular aneurysms. Neurosurgery. 2005;56:455–68.
3. Awad IA, editor. Current management of cerebral aneurysms. Park Ridge: AANS Publication Committee; 1993.
4. Kassell NF, Boarini DJ, Adams HP Jr, Sahs AL, Graf CJ, Torner JC, Gerk MK. Overall management of ruptured aneurysm: comparison of early and late operation. Neurosurgery. 1981;9:120–8.
5. Kheĭreddin AS, Filatov IM, Belousova OB, Pilipenko IV, Zolotukhin SP, Sazonov IA, Zarzur KK. Intraoperative rupture of cerebral aneurysm—incidence and risk factors [in Russian]. Zh Vopr Neirokhir Im N N Burdenko. 2007;71(4):33–8.
6. Lakićević N, Prstojević B, Rasulić L, Vujotić L, Vukašinović I, Miličić B, Savić A, Živković B, Rotim K, Samardžić M. Intraoperative aneurysmal rupture: clinical outcome following open surgery or endovascular treatment. Acta Clin Croat. 2015;54:285–94.
7. Le Roux PD, Elliot JP, Newell DW, Grady MS, Winn HR. The incidence of surgical complications is similar in good and poor grade patients undergoing repair of ruptured anterior circulation aneurysms: a retrospective review of 355 patients. Neurosurgery. 1996;38:887–95.
8. Levy E, Koebbe CJ, Horowitz MB, Jungreis CA, Pride GL, Dutton K, Kassam A, Purdy PD. Rupture of intracranial aneurysms during endovascular coiling: management and outcomes. Neurosurgery. 2001;49:807–13.
9. Sandalcioglu IE, Schoch B, Regel JP, Wanke I, Gasser T, Forsting M, Stolke D, Wiedemayer H. Does intraoperative aneurysm rupture influence outcome? Analysis of 169 patients. Clin Neurol Neurosurg. 2004;106:88–92.

10. Schramm J, Cedzich C. Outcome and management of intraoperative aneurysm rupture. Surg Neurol. 1993;40:26–30.
11. Sluzewski M, Bosch JA, van Rooij WJ, Nijssen PC, Wijnalda D. Rupture of intracranial aneurysms during treatment with Guglielmi detachable coils: incidence, outcome, and risk factors. J Neurosurg. 2001;94:238–40.
12. Tummala RP, Chu RM, Madison MT, Myers M, Tubman D, Nussbaum ES. Outcomes after aneurysm rupture during endovascular coil embolization. Neurosurgery. 2001;49:1059–67.
13. Batjer H, Samson D. Intraoperative aneurysmal rupture: incidence, outcome, and suggestions for surgical management. Neurosurgery. 1986;18:701–7.
14. Lakićević N, Vujotić L, Radulović D, Cvrkota I, Samardžić M. Factors influencing intraoperative rupture of intracranial aneurysms. Turk Neurosurg. 2015;25:858–85.
15. Giannotta SL, Oppenheimer JH, Levy ML, Zelman V. Management of intraoperative rupture of aneurysm without hypotension. Neurosurgery. 1991;28:531–6.
16. Batjer H, Samson D. Management of intraoperative aneurysm rupture. Clin Neurosurg. 1990;36:275–88.
17. Greenberg IM. Cerebral aneurysm rupture during neurosurgery. Neurosurgery. 1984;15:243–5.
18. Ljunggren B, Säveland H, Brandt L. Causes of unfavorable outcome after early aneurysm operation. Neurosurgery. 1983;13:629–33.
19. Ljunggren B, Säveland H, Brandt L. Tolerance of temporary arterial occlusion in early aneurysm surgery. In: Voth D, Glees P, Betz E, Schürmann K, editors. Cerebral vascular spasm. Berlin: Walter de Gruyter; 1985. p. 421–37.
20. Ljunggren B, Brandt L. Timing of aneurysm surgery. Clin Neurosurg. 1986;33:159–75.
21. Ljunggren B, Fodstad H, Romner B. Advances in the management of victims struck by ruptured intracranial aneurysms. Neurol Res. 1990;12:3–11.
22. Paul RL, Arnold JG Jr. Operative factors influencing mortality in intracranial aneurysm surgery: analysis of 186 consecutive cases. J Neurosurg. 1970;32:289–94.
23. Pertuiset B. Intraoperative aneurysmal rupture and reduction by coagulation of the sac. In: Pia HW, Langmaid C, Zierski J, editors. Cerebral aneurysms: advances in diagnosis and therapy. Berlin: Springer; 1979. p. 398–401.
24. Seifert V, Stolke D, Trost HA, Brüning A, Schäffer J. Incidence, management, and outcome of patients with premature rupture of cerebral aneurysms during surgery. In: Frowein RA, Brock M, Klinger M, editors. Head injuries. Advances in neurosurgery, vol. 17. Berlin: Springer; 1989. p. 203–7.
25. Sengupta RP, Chiu JS, Brierley H. Quality of survival following direct surgery for anterior communicating artery aneurysms. J Neurosurg. 1975;43:58–64.
26. Snyckers FD, Drake CG. Aneurysms of the distal anterior cerebral artery. A report on 24 verified cases. S Afr Med J. 1973;47:1787–91.
27. Yaşargil MG, Fox JL, Ray MW. The operative approach to aneurysms of the anterior communicating artery. Adv Tech Stand Neurosurg. 1975;2:113–70.
28. Yaşargil MG, Smith RD. Management of aneurysms of anterior circulation by intracranial procedures. In: Youmans JR, editor. Neurological surgery, vol. 3. 2nd ed. Philadelphia: Saunders; 1982. p. 1663–714.
29. Yasui N, Suzuki A, Ohta H, Kamiyama H, Kitami K. Pitfalls in aneurysm surgery—management of aneurysm rupture. In: Auer LM, editor. Timing of aneurysm surgery. Berlin: Walter de Gruyter; 1985. p. 349–55.
30. Rinne J, Hernesniemi J, Niskanen M, Vapalahti M. Management outcome for multiple intracranial aneurysms. Neurosurgery. 1995;36:31–8.
31. Sheth SA, Hausrath D, Numis AL, Lawton MT, Josephson SA. Intraoperative rerupture during surgical treatment of aneurysmal subarachnoid hemorrhage is not associated with an increased risk of vasospasm. J Neurosurg. 2014;120:409–14.
32. Houkin K, Kuroda S, Takahashi A, Takikawa S, Ishikawa T, Yoshimoto T, Itamato K. Intra-operative premature rupture of the cerebral aneurysms. Analysis of the causes and management. Acta Neurochir (Wien). 1999;141:1255–63.
33. Chandler JP, Getch CC, Batjer HH. Intraoperative aneurysm rupture and complication avoidance. Neurosurg Clin N Am. 1998;9:861–8.
34. Awad IA, Little JR. Perioperative management and outcome after surgical treatment of anterior cerebral artery aneurysms. Can J Neurol Sci. 1991;18:120–5.
35. Lawton MT, Du R. Effect of the neurosurgeon's surgical experience on outcomes from intraoperative aneurysmal rupture. Neurosurgery. 2005;57:9–15.
36. Whittle IR, Viswanathan R. Acute intraoperative brain herniation during elective neurosurgery: pathophysiology and management considerations. J Neurol Neurosurg Psychiatry. 1996;61:584–90.
37. Graf CJ, Nibbelink DW. Cooperative study of intracranial aneurysms and subarachnoid hemorrhage. Report on a randomized treatment study. 3. Intracranial surgery. Stroke. 1974;5:557–601.
38. Güresir E, Schuss P, Berkefeld J, Vatter H, Seifert V. Treatment results for complex middle cerebral artery aneurysms. A prospective single-center series. Acta Neurochir (Wien). 2011;153:1247–52.
39. Lindgren AE, Koivisto T, Björkman J, von Und Z, Fraunberg M, Helin K, Jääskeläinen JE, Frösen J. Irregular shape of intracranial aneurysm indicates rupture risk irrespective of size in a population-based cohort. Stroke. 2016;47:1219–26.
40. Peerless SJ, Hernesniemi JA, Gutman FB, Drake CG. Early surgery for ruptured vertebrobasilar aneurysms. J Neurosurg. 1994;80:643–9.
41. van Dijk JM, Groen RJ, Ter Laan M, Jeltema JR, Mooij JJ, Metzemaekers JD. Surgical clipping as the preferred treatment for aneurysms of the middle cerebral artery. Acta Neurochir (Wien). 2011;153:2111–7.
42. Sundt TM Jr, Kobayashi S, Fode NC, Whisnant JP. Results and complications of surgical management of 809 intracranial aneurysms in 722 cases. Related and unrelated to grade of patient, type of aneurysm, and timing of surgery. J Neurosurg. 1982;56:753–65.
43. Hunt WE, Hess RM. Surgical risk as related to time of intervention in the repair of intracranial aneurysms. J Neurosurg. 1968;28:14–20.
44. Bederson JB, Connolly ES Jr, Batjer HH, Dacey RG, Dion JE, Diringer MN, Duldner JE Jr, Harbaugh RE, Patel AB, Rosenwasser RH. Guidelines for the management of aneurysmal subarachnoid hemorrhage: a statement for healthcare professionals from a special writing group of the Stroke Council, American Heart Association. Stroke. 2009;40:994–1025.
45. Chowdhury T, Cappellani RB, Sandu N, Schaller B, Daya J. Perioperative variables contributing to the rupture of intracranial aneurysm: an update. ScientificWorldJournal. 2013;2013:396404.
46. Guy J, McGrath BJ, Borel CO, Friedman AH, Warner DS. Perioperative management of aneurysmal subarachnoid hemorrhage: part 1. Operative management. Anesth Analg. 1995;81:1060–72.
47. Tsementzis SA, Hitchcock ER. Outcome from "rescue clipping" of ruptured intracranial aneurysms during induction anaesthesia and endotracheal intubation. J Neurol Neurosurg Psychiatry. 1985;48:160–3.
48. Chowdhury T, Petropolis A, Wilkinson M, Schaller B, Sandu N, Cappellani RB. Controversies in the anesthetic management of intraoperative rupture of intracranial aneurysm. Anesthesiol Res Pract. 2014;2014:595837.
49. Li LR, You C, Chaudhary B. Intraoperative mild hypothermia for postoperative neurological deficits in intracranial aneurysm patients. Cochrane Database Syst Rev. 2012;N2:CD008445.
50. Mackensen GB, McDonagh DL, Warner DS. Perioperative hypothermia: use and therapeutic implications. J Neurotrauma. 2009;26:342–58.
51. Seule MA, Muroi C, Mink S, Yonekawa Y, Keller E. Therapeutic hypothermia in patients with aneurysmal subarachnoid hemor-

rhage, refractory intracranial hypertension, or cerebral vasospasm. Neurosurgery. 2009;64:86–93.
52. Zhao ZX, Wu C, He M. A systematic review of clinical outcomes, perioperative data and selective adverse events related to mild hypothermia in intracranial aneurysm surgery. Clin Neurol Neurosurg. 2012;114:827–32.
53. Bendok BR, Gupta DK, Rahme RJ, Eddleman CS, Adel JG, Sherma AK, Surdell DL, Bebawy JF, Koht A, Batjer HH. Adenosine for temporary flow arrest during intracranial aneurysm surgery: a single-center retrospective review. Neurosurgery. 2011;69:815–21.
54. Luostarinen T, Takala RS, Niemi TT, Katila AJ, Niemelä M, Hernesniemi J, Randell T. Adenosine-induced cardiac arrest during intraoperative cerebral aneurysm rupture. World Neurosurg. 2010;73:79–83, e9.
55. Saldien V, Menovsky T, Rommens M, Van der Steen G, Van Loock K, Vermeersch G, Mott C, Bosmans J, De Ridder D, Maas AI. Rapid ventricular pacing for flow arrest during cerebrovascular surgery: revival of an old concept. Neurosurgery. 2012;70(2 Suppl Operative):270–5.

Complication of Middle Cerebral Artery Aneurysm Surgery: An M2 Tear at the Neck, Managed with a Salvage M2-to-M2 In Situ Bypass

Krunal Patel, Leonardo Desessards Olijnyk, Peter Khong, and Ivan Radovanovic

Abstract

An unexpected rupture at the aneurysm neck, with or without adjacent arterial injury or compromise of distal branches during microsurgical clipping, can be a challenging surgical problem to resolve. In this presented case of a neurologically intact 65-year-old woman, elective clipping of an unruptured right middle cerebral artery bifurcation aneurysm was complicated by an unexpected M2 tear at the neck, involving the origin of the frontal M2. Attempts to seal the tear directly, using various techniques, failed; therefore, it was ultimately managed with sacrifice of the vessel and a salvage side-to-side M2-to-M2 *in situ* bypass. Six months after surgery, the patient demonstrated moderate disability but was able to ambulate with a cane.

Keywords

Anastomosis · Aneurysm clipping · Aneurysm neck rupture · Complication · Cotton-clipping technique · In situ bypass · Management · Surgery

Introduction

Unless a rupture is anticipated in cases of complex or giant aneurysms requiring distal arterial branch occlusion and revascularization, an unexpected rupture at the aneurysm neck, with or without adjacent arterial injury or compromise of distal branches during microsurgical clipping, can be a challenging intraoperative complication to manage. In such cases, attempts to occlude the tear with a clip or other measures may lead to narrowing or sacrifice of the parent or distal arterial branches, or worsening of the vascular injury. In the case presented herein, clipping of an unruptured right middle cerebral artery (MCA) bifurcation aneurysm was complicated by an unexpected M2 tear at the neck, involving the origin of the frontal M2, which was ultimately managed with a salvage side-to-side M2-to-M2 *in situ* anastomosis (See Supplementary Video 1).

Case Report

A 65-year-old woman with Charcot–Marie–Tooth disease, a past medical history of atrial fibrillation, and a family history of aneurysms presented with a 3-year history of headaches. A neurological examination was normal. Three-dimensional computed tomography angiography (CTA) revealed a right MCA bifurcation aneurysm 8 mm in size, with a neck of 5 mm (Fig. 1). Following a case review at a multidisciplinary neurovascular conference and discussions with the patient, microsurgical clipping was offered to her. Informed consent was obtained.

Surgery

Surgery was done under general anesthesia in the supine position with the head turned 15° to the left. Motor evoked potentials (MEP) and somatosensory evoked potentials (SEP) were monitored throughout the procedure. Following a standard

Supplementary Information The online version contains supplementary material available at [https://doi.org/10.1007/978-3-030-12887-6_10].

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_10

right-side lateral supraorbital craniotomy and Sylvian fissure dissection, the M1 segment, aneurysm, and both M2 segments were identified (Fig. 2a). The aneurysm neck involved the origin of the frontal M2, which was adherent to it, and during blunt dissection of this vessel, an inadvertent tear occurred at the site of its origin (Fig. 2b). Clipping low on the neck was therefore done with the aims of occluding the aneurysm and controlling the tear (Fig. 2c). Indocyanine green (ICG) videoangiography confirmed occlusion of the aneurysm and patency of both M2 segments.

While the fundus was being coagulated, the previously encountered tear at the frontal M2 origin became apparent as the rupture site and started to bleed. Initially, short bursts of low-power bipolar coagulation were attempted to occlude the rupture site. This was unsuccessful and even made the defect in the vessel wall larger. Direct suturing was then tried, but the vessel was too fragile and the suture tore through its wall. Thereafter, multiple attempts were made to clip the rupture site, but the adventitia of the vessel did not appose sufficiently to enable the tear to close. A small piece of cotton was then wrapped around the frontal M2 origin at the neck, and attempts were made to fix it with a clip (the so-called cotton-clipping technique [1–3]), but this strategy also failed to control the bleeding from the vessel tear.

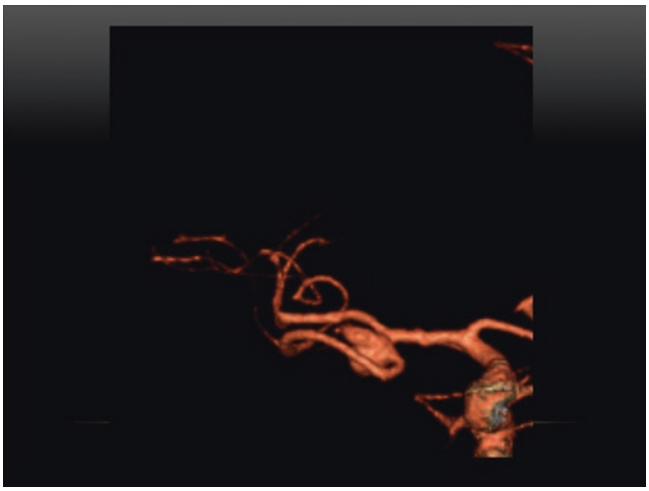

Fig. 1 Three-dimensional computed tomography angiography in a 65-year-old woman demonstrates a right middle cerebral artery bifurcation aneurysm

Once it was apparent that attempts at direct reconstruction of the aneurysm neck/frontal M2 origin were futile, temporary clips were placed on both M2 segments and the permanent clip at the aneurysm neck was readjusted to incorporate the frontal M2 origin, with additional use of a piece of cotton to wrap-clip the frontal M2 origin, in order to sacrifice the vessel. As was previously described by Steiger et al. [4], both M2 segments ran over the insular cistern in proximity (of approximately 5 mm) to each other (Fig. 3a). Both the temporal M2 and the occluded frontal M2 were isolated between temporary aneurysm clips. Corresponding 5-mm longitudinal arteriotomies were then made in adjacent M2 segments, and a side-to-side M2-to-M2 *in situ* anastomosis was done using a 10-0 Nylon (Ethilon BV75-3, Ethicon Inc., Somerville, NJ, USA) running suture (Fig. 3b). The total ischemic time during creation of the bypass was 31 min. Immediately following completion of the anastomosis, microvascular Doppler sonography and ICG videoangiography (Fig. 3c) confirmed blood flow in both M2 segments and complete occlusion of the aneurysm.

Postoperative Course

In the immediate postoperative period, the patient had left-side hemiplegia but no sensory deficits. Within 2 h after the surgery, the motor function in the left limbs started to recover. Magnetic resonance imaging (MRI) demonstrated brain infarcts (Fig. 4a)

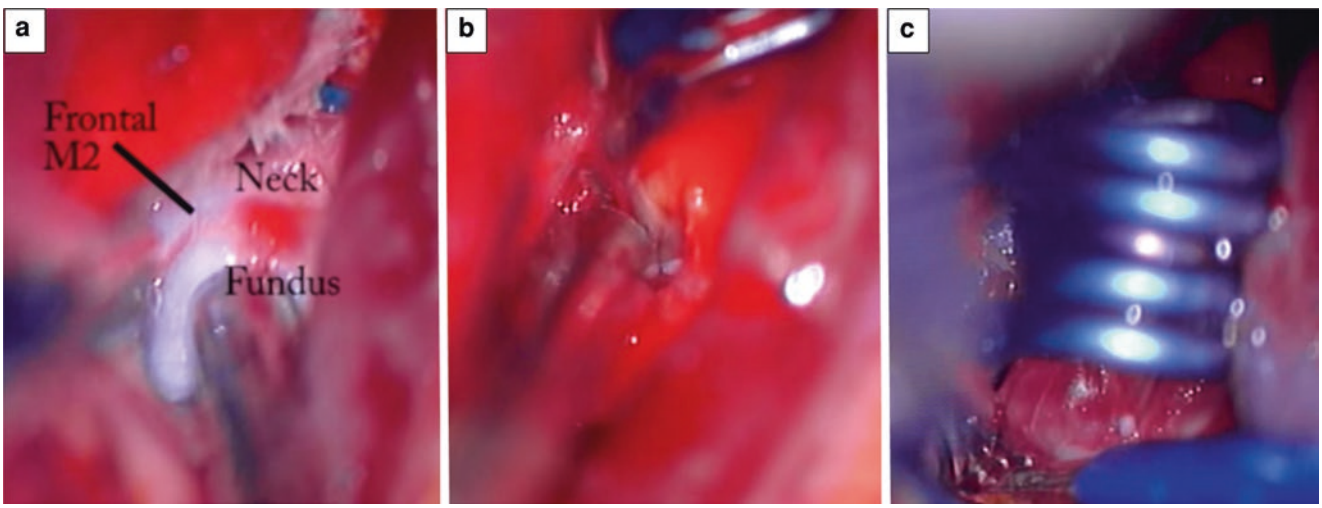

Fig. 2 Clipping of the right middle cerebral artery bifurcation aneurysm through the lateral supraorbital approach. After Sylvian fissure dissection, the frontal M2 segment, adherent to the aneurysm neck, is identified (**a**) and inadvertently torn (**b**). Clipping low on the neck is therefore done with the aims of occluding the aneurysm and controlling the tear (**c**)

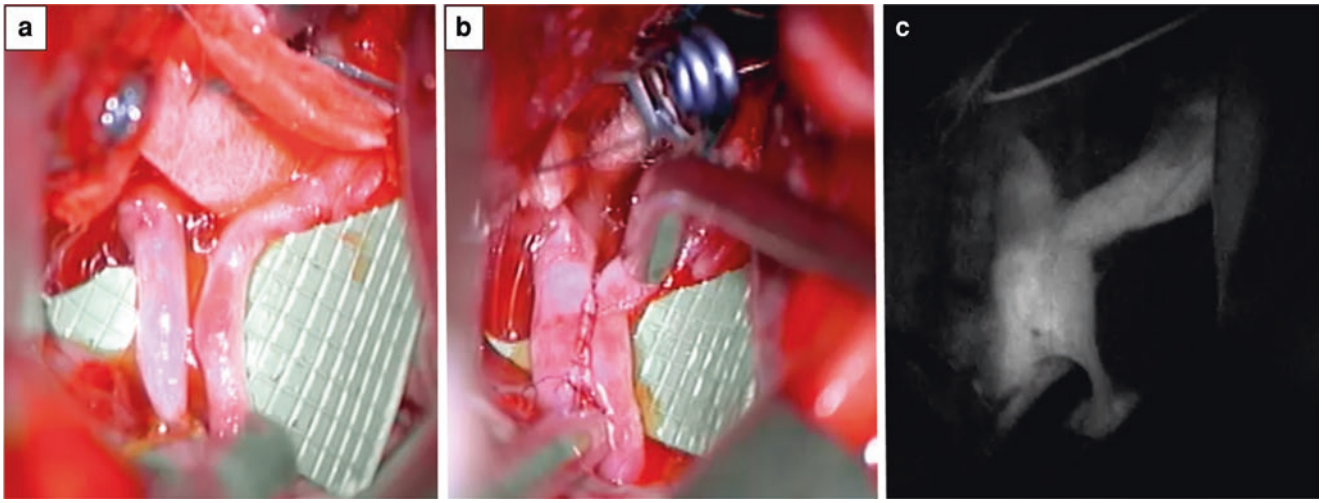

Fig. 3 Creation of the M2-to-M2 *in situ* bypass. Both M2 segments run over the insular cistern in proximity to each other (**a**), allowing creation of a side-to-side anastomosis (**b**). Its patency is confirmed by intraoperative indocyanine green videoangiography (**c**)

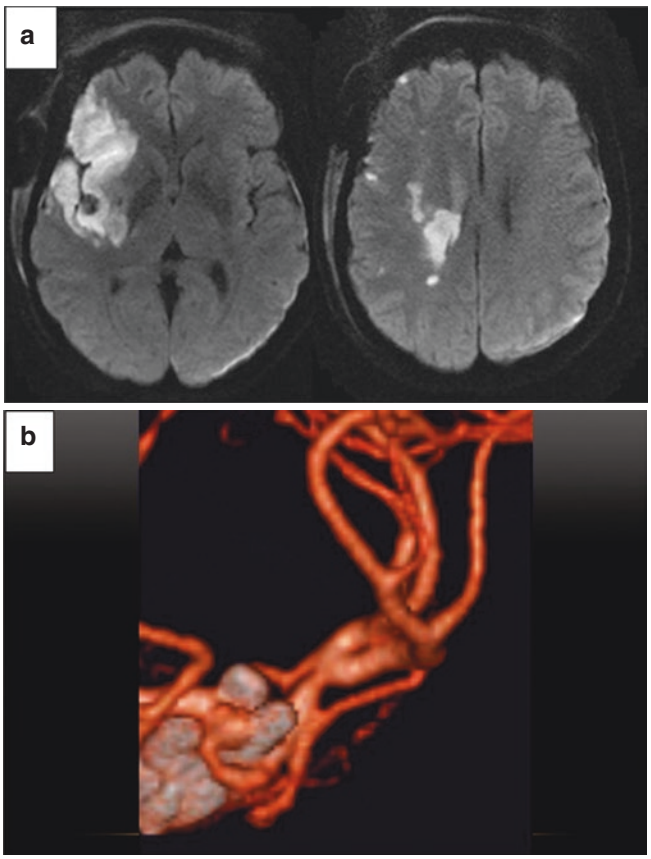

Fig. 4 Postoperative magnetic resonance imaging (**a**) demonstrates brain infarcts in the frontal M2 territory and perforator region. Three-dimensional computed tomography angiography (**b**) shows complete occlusion of the aneurysm and a patent M2-to-M2 bypass

in the right frontal M2 territory and perforator region (resulting from the temporary M1 clipping). CTA showed complete occlusion of the aneurysm and a patent M2-to-M2 bypass (Fig. 4b).

The patient was given aspirin (325 mg per day) for 1 year and entered a neurorehabilitation program. Six months after surgery, she had residual weakness in the left upper limb, ranging from 3/5 (proximally) to 1/5 (distally), and in the left lower limb, ranging from 4+/5 (proximally) to 2/5 (distally), but she was able to ambulate with a quadripod cane. Follow-up CTA at that time demonstrated a patent M2-to-M2 bypass.

Discussion

An aneurysm rupture at the neck or close to the origin of a distal vessel presents a uniquely challenging intraoperative complication. In the presented case, the frontal M2 tear at its origin occurred during blunt dissection, which, reportedly, is associated with a greater risk of rupture than sharp dissection [5]. Various strategies have been suggested to manage this situation, including use of short bursts of low-power bipolar coagulation, direct suturing of the tear, or direct clipping of the rupture site, as well as the cotton-clipping technique [1–3] or an alternative method using a piece of crushed muscle [6]. Their success in sealing the tear, however, will ultimately depend on the size of the rupture, the fragility of the aneurysm neck and/or the parent artery, and the exact location of the vessel origin. In the presented case, nearly all of these methods were tried but failed, mainly because the frontal M2 was too fragile. Ultimately, in such a difficult situation, one must be prepared to create a salvage anastomosis, as was done in our patient.

Conclusion

Use of a salvage side-to-side M2-to-M2 *in situ* anastomosis should be reserved as a reliable management option in cases of a complex intraoperative rupture of the MCA bifurcation

aneurysm neck with or without involvement of the parent vessel, if more simple techniques to occlude the tear fail or result in alteration of blood flow.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Lanzino G, Spetzler RF. Clip wrapping for partial avulsion of the aneurysm neck. Technical note. J Neurosurg. 2003;99:931–2.
2. Barrow DL, Spetzler RF. Cotton-clipping technique to repair intraoperative aneurysm neck tear: a technical note. Neurosurgery. 2011;68(2 Suppl Operative):294–9.
3. Safavi-Abbasi S, Sun H, Oppenlander ME, Nakaji P, Kalani MY, Zabramski JM, Spetzler RF. Repair of intraoperative aneurysm neck tear utilizing the cotton-clipping technique. Neurosurg Focus. 2015;38(Video Suppl 1).:Video 14.
4. Steiger HJ, Ito S, Schmid-Elsässer R, Uhl E. M2/M2 side-to-side rescue anastomosis for accidental M2 trunk occlusion during middle cerebral artery aneurysm clipping: technical note. Neurosurgery. 2001;49:743–8.
5. Batjer H, Samson D. Intraoperative aneurysmal rupture: incidence, outcome, and suggestions for surgical management. Neurosurgery. 1986;18:701–7.
6. Menovsky T, de Vries J, Grotenhuis JA. Cotton-clipping technique: piece of smashed muscle as an alternative [letter]. Neurosurgery 2011;69(5):E1183–E1185.

Complications of Endovascular and Open Aneurysm Surgery in the Era of Flow Diversion

Yair M. Gozal, Hussam Abou-Al-Shaar, Gmaan Alzhrani, Philipp Taussky, and William T. Couldwell

Abstract

The techniques used for treatment of intracranial aneurysms have progressed dramatically over the decades. The introduction of modern endovascular techniques and the continued refinement of progressively less invasive neurosurgical approaches have contributed to steadily improving clinical outcomes. Moreover, innovations such as flow-diverting stents have achieved dramatic success and have gained rapid widespread adoption. Particularly in lesions for which the application of conventional treatment techniques is difficult, flow diversion technology has revolutionized aneurysm management. This review provides a discussion on the morbidity and mortality encountered in the treatment of intracranial aneurysms in the modern era. Common adverse events faced in the management of these lesions with open surgery and various endovascular techniques are highlighted.

Keywords

Clipping · Coil embolization · Complication · Flow diverter · Intracranial aneurysm · Morbidity · Mortality · Stent-assisted coiling

Introduction

The initiation of surgical clipping of intracranial aneurysms in the 1930s [1] and the subsequent introduction of microneurosurgical techniques by Yaşargil 30 years later ushered in a new era of cerebrovascular neurosurgery [2]. Proper visualization and the evolution of surgical corridors finally rendered accessible various vascular lesions deemed inoperable for decades. The field thereafter underwent further refinement and advancements, with the realization of many innovations, including bypass surgery for the management of complex intracranial aneurysms and the routine utilization of the intraoperative indocyanine green videoangiography [3]. However, despite wide adoption of surgical clipping for the treatment of intracranial aneurysms, cerebrovascular surgery remained a high-risk endeavor.

Over the past decades, analysis of periprocedural morbidity for surgical clipping of aneurysms was challenging, in part because of the complexity of apportioning the contribution related to the presence of subarachnoid hemorrhage (SAH). With developments in neuroimaging and increased treatment of patients with unruptured aneurysms, the ability to assess surgical risks improved. In fact, the estimated morbidity and mortality of surgical clipping of unruptured intracranial aneurysms were reported to be 4.1–10.9% and 1.0–2.6%, respectively, in several published meta-analyses [4–6]. However, many of the data used in these meta-analyses were of poor quality, having been extracted almost entirely from nonrandomized retrospective studies performed largely in a period during which clipping was the sole treatment option. Interestingly, the emergence of alternative management strategies, such as minimally invasive endovascular techniques,

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_11

has challenged neurosurgeons to more rigorously evaluate treatment outcomes in formal prospective clinical trials. This scientific scrutiny has established a precedent for the regulatory approval of modern endovascular modalities, such as flow diversion, improving our understanding of the risks associated with aneurysm management. Herein, we sought to review the complications and limitations of open surgical and endovascular interventions for intracranial aneurysms in the era of advanced technology and innovations.

Complications of Open Aneurysm Treatment

Prior to the advent of endovascular techniques, surgery was the only established strategy for the treatment of the estimated 30,000 patients who experience aneurysmal SAH in the USA annually [7]. To date, it remains a relevant and effective management option, with open surgical clipping employed in the treatment of 62,820 aneurysms between 2002 and 2007 in the USA alone [7]. Moreover, the cost of endovascular devices is often prohibitive, making surgical clipping the preferred treatment strategy in much of the world [8].

The morbidity and mortality associated with clip ligation and other surgical techniques used in the treatment of aneurysms is dependent, in large part, on patient risk factors, previous rupture, as well as lesion size and location. In recent years, several published studies have attempted to quantify the adverse risks of neurosurgical intervention for both ruptured and unruptured aneurysms, often in the context of comparing open and endovascular techniques to assess the ideal management strategy. In 2005, the International Subarachnoid Aneurysm Trial (ISAT) reported the outcomes of 1070 patients with ruptured aneurysms randomized to undergo surgical clipping [9]. One year after treatment, 30.9% of patients (326 of 1055) were either dead or dependent, with a mortality rate of 9.9%. Of the 450 patients who underwent follow-up angiography, complete aneurysmal occlusion was noted in 82%. The rebleeding rate after treatment was only 1% in the surgical cohort. Finally, the patients randomized to the surgical clipping arm of the study had a higher risk of seizures than patients randomized to receive endovascular therapy [9]. Seizures are a well-described complication of craniotomies and are thought to occur as a result of direct parenchymal injury during surgery. The increased risk of this complication was corroborated in subsequent studies, with reported incidence rates as high as 42% [7, 10, 11].

In a meta-analysis examining the risks of adverse events in patients with unruptured aneurysms, Kotowski et al. [5] reported morbidity and mortality rates of 6.7% and 1.7%, respectively, in 9845 patients from 60 included studies. Similar rates were reported in other meta-analyses [4, 6] and in a study based on the National Inpatient Sample Database, in which the authors identified a composite adverse event rate of 8.35% and a mortality rate of 1.6% in 3738 patients who underwent clip ligation of an unruptured aneurysm [10]. The latter study also reported elevated risks of intracerebral hemorrhage (2.4%), postoperative stroke (6.7%), hydrocephalus (0.9%), and cardiac or pulmonary complications (2.1% and 3.2%, respectively) in patients whose aneurysm was treated surgically [10]. Predictably, the rates of these complications are substantially higher in the setting of SAH [7, 12]. Hydrocephalus, for example, has been reported to occur in up to 16.4% of patients undergoing surgical clipping for treatment of SAH [13], while the incidence of perioperative infarction in such cases may be as high as 40% [14]. Hemorrhage-related hyperglycemia and cerebral salt-wasting syndrome are also quite common postoperatively in cases of aneurysmal SAH, being reported to occur in 27–71% and 34–57% of patients, respectively [7].

Among the complications of open aneurysm treatment is the potential for intraoperative premature aneurysm rupture. Several retrospective studies have reported rates ranging from 7% to 35% [7]. In a retrospective study of 1269 patients with saccular aneurysms treated surgically, Leipzig et al. [15] reported an incidence of intraoperative aneurysm rupture of nearly 9%. This was mirrored in a systematic review of almost 9500 patients, in whom the reported intraoperative rupture rate was 9.2% [8]. In turn, Elijovich et al. [16] found the rate was approximately 19% in the 711 patients who underwent surgical clipping in the Cerebral Aneurysm Rerupture After Treatment (CARAT) study. Notably, the latter investigation also revealed an increased risk of periprocedural death or disability with intraoperative aneurysm rupture (31% versus 18%), although other studies have demonstrated no further risk of adverse outcomes [17].

Other reported morbidity after open aneurysm treatment include new or persistent cranial neuropathies, including oculomotor palsies or optic nerve injury, technical complications such as clip misplacement, cerebrospinal fluid leakage, and positioning- or anesthesia-associated complications.

Complications of Endovascular Aneurysm Repair

Endovascular techniques have revolutionized the field of neurosurgery, offering minimally invasive, effective, and relatively safe routes to address various vascular pathological conditions. Innovative techniques such as coiling, stenting, and flow diversion have evolved to help address lesions with particularly high surgical morbidity, including posterior circulation and paraclinoid aneurysms. Since their introduction, modern endovascular tools have been increasingly used, sometimes in preference to open surgical approaches. According to National Inpatient Survey data, the rate of endovascular interventions for intracranial aneurysm increased from 16,526 cases in 2003 to 35,586 cases in 2007 [18]. Concurrently, clinical outcomes have improved, with

Table 1 Proposed classification of endovascular complications

Mechanical complications	Technical complications	Judgment errors	Critical events
Failure in device deployment Catheter malfunction Wire breakage Closure device failure Coil malfunction Groin hematoma (failure of closure device)	Failure to fully deploy a flow-diverting device Failure to recognize embolization into unintended vessels Asymptomatic air emboli Retroperitoneal hemorrhage from a high femoral artery puncture Vessel dissection Coil misplacement Groin hematoma (poor deployment of a closure device)	Patient selection error Over- or underpacking of an aneurysm Inadequate coiling of an aneurysm, resulting in rerupture Poor selection of adequate equipment	Urinary tract infection Contrast media reactions Groin hematoma Radiation effects Acute coronary syndromes Groin site infections Hemorrhagic complications due to antiplatelet or anticoagulation therapy Thromboembolic complications

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decreased inpatient mortality and increased rates of discharge to home [19]. However, with the emergence of the "endovascular era" and expanded use of these technologies in clinical practice, a set of inherent limitations and complications was soon recognized. As the overall endovascular complication rate is nearly 20% and the 1-month mortality rate is 1.4% [20, 21], it is critical to classify and recognize these limitations and complications, with the goal of improving patient outcomes.

Classification of Complications

The absence of a commonly accepted standardized classification system for complication reporting confounds the recognition and avoidance of perioperative adverse events. This issue is magnified within endovascular practice, where the same adverse event could be caused by multiple types of error, only some of which are avoidable. Moreover, within this relatively new field, complications are often underreported, as not every error results in postoperative morbidity that deviates from the expected patient course [22].

To address these complexities, our group has previously proposed a classification system targeting endovascular complications [22]. It encompasses four major categories that simplify and coalesce the reporting nomenclature for morbidity associated with endovascular interventions. These four categories include mechanical complications, technical complications, judgment errors, and critical events, as outlined in Table 1. More specifically, mechanical complications are related to endovascular equipment failure (e.g., catheters, stents, and flow diverters); technical complications occur because of poor endovascular surgical technique (e.g., injection of air emboli); judgment errors include complications that occur as a result of poor decision-making (e.g., poor patient selection); and critical events are complications encountered during or after procedures that do not directly affect the goals of the procedure but involve a negative outcome (e.g., urinary tract infections). Our complications classification system provides a formal framework to capture and analyze endovascular errors with or without consequent morbidity. Although additional refinement of the system is undoubtedly required, this classification may serve as a cornerstone for future schemes. Importantly, it provides a critical starting point for properly defining surgical complications within endovascular surgery as a subspecialty.

General Complications of Endovascular Procedures

A set of general complications may be encountered during any type of endovascular management of intracranial aneurysms. These complications are related to events that are not specifically correlated with the treatment of the aneurysms and are often categorized as "critical events" in the endovascular complications classification system described above. For example, exposure of both the patient and the physician to radiation is an important risk during endovascular procedures. Exposure to radiation may result in acute radiation dermatitis/skin necrosis, the development of cataracts [18, 23], and increased risks of developing various tumors, including intracranial meningiomas [23]. Thus, the use of radiation should be minimized during endovascular procedures. Other general complications include anesthetic complications or those associated with the administration of contrast media [18]. In the latter example, patients should be prepared preoperatively for the procedure with intravenous hydration and steroids to help mitigate adverse events. Endovascular surgeons should be aware of these potential complications and be prepared to manage them in a timely fashion should they occur.

Complications of Coil Embolization

Endovascular coiling of intracranial aneurysms has revolutionized the management of these lesions since the approval of the first coils by the US Food and Drug Administration in 1995 [24]. Depending on the clinical status of the patient and the aneurysm size, location, and morphology, the treatment with coil embolization has proven to be safe, efficacious,

and, in most cases, durable. In fact, several randomized controlled trials, including ISAT [9], have demonstrated greater benefits from coiling of ruptured aneurysms than from surgical clipping in patients in whom either treatment is feasible [25]. Nevertheless, the increased use of coil embolization has uncovered various limitations of this technology and complications associated with it.

Among the primary limitations of endovascular coiling is its use for the treatment of wide-neck, fusiform, and multilobulated aneurysms. Chalouhi et al. [26] reported that coiling of large and giant wide-necked aneurysms was associated with high aneurysmal recurrence rates (40–60%) and a rebleeding rate of 1.9% per year. Although modern technology capable of complex coil shapes has been developed, many of these aneurysms are now treated surgically or with adjunctive techniques, such as stent-assisted coiling [27].

The complications of coil embolization have been well described. In a French series of 217 aneurysms, the authors reported a permanent neurological deficit rate of 3.8% and a mortality rate of 1.2% among patients who underwent aneurysm coil embolization [28]. The permanent neurological deficits encountered in this series, as well as those reported by others, were most often associated with ischemic complications [29]. Similarly, in a meta-analysis of 29,388 patients who underwent coil embolization, Phan et al. [29] found an overall complication rate of 12.0% (122 of 1017 cases), with permanent deficits in 3.5% (62 of 1763 cases), in the studies that reported these statistics. The pooled immediate aneurysm occlusion rate was 48.7% (777 of 1597 cases), and the aneurysm recurrence rate was 27.9% (446 of 1599 cases). Additionally, thrombotic complications were common, occurring in 4.1% of patients, and 0.2% of patients (63 of 28,712) died [29]. In a separate meta-analysis, Ruan et al. [30] demonstrated pooled rates of bleeding, ischemia, and death of 2%, 8%, and 1%, respectively, after endovascular coiling. Interestingly, while the rates of incomplete occlusion or posttreatment aneurysm remnants are significantly higher with endovascular coiling than with surgical clipping, the rebleeding rate with either procedure is not dramatically high [31] and was reported to have affected 0.7% of patients in the ISAT cohort within 1 year after intervention [9]. More concerning is the potential for intraprocedural rupture of the lesion, which reportedly occurs at a frequency of 2–8% and results in significant morbidity or mortality in half of the affected patients [24]. Finally, intraprocedural coil migration is also a potentially serious complication, with reported rates ranging from 2% to 6% [32]. The exposed thrombogenic intraluminal coil fragment subsequently predisposes patients to potentially severe thromboembolic complications.

Complications of Endovascular Stenting

Recognition of the limitations and complications of coil embolization for the management of intracranial aneurysms, particularly in lesions with a fundus-to-neck ratio of <2, prompted the technical development of stent-assisted and balloon-assisted coiling. These techniques offer superior efficacy in the treatment of morphologically complex aneurysms, and numerous studies have reported lower rates of aneurysm recurrence after stent-assisted coiling than after coiling alone [29].

This effect is often attributed to the improved neck coverage and coil packing density achieved with stenting, but it may also be related to stent-induced endothelialization of the parent vessel [33]. Moreover, the stent may divert the blood flow away from the aneurysm, promoting stasis and thrombosis within the lesion. Yet, the rates of recanalization after stent- and balloon-assisted coiling remain high (12% and 10%, respectively), especially in the settings of large and giant aneurysms (20–57%) [28, 29, 34].

Despite offering multiple advantages in the management of complex aneurysms, stent-assisted coiling has been associated with higher morbidity and mortality rates than coiling alone [33]. After treating 49 wide-necked aneurysms with stent-assisted coiling, Benitez et al. [35] reported a 10.7% overall complication rate, driven primarily by a 7% incidence of thromboembolism. Similarly, Piotin et al. [28] noted a 7.4% rate of permanent neurological deficits. In a large meta-analysis, Phan et al. [29] defined a pooled rate of overall complications of 12.2% (92 of 752 cases), with 4.5% of patients experiencing thrombotic complications. In their study, the pooled immediate occlusion rate in patients undergoing stent-assisted coiling was 57.7% (1228 of 2133 cases), with a recurrence rate of 12.7% (89 of 703 cases). The mortality rate was 1.4% (31 of 2241 patients) [29]. Other reported complications of stenting include iatrogenic dissection, intraprocedural rupture, stent malposition, and catheter-induced vasospasm [18, 28, 29, 34, 36]. Overall, despite higher obliteration rates with stent-assisted coiling, the risk of thromboembolic events, particularly with concurrent prophylactic use of antiplatelet medications, is not insignificant [24].

Complications of Flow Diversion

Endovascular flow diversion represents a paradigm shift in the treatment of cerebral aneurysms [37]. Flow diversion is accomplished by the use of low-porosity stents (flow-diverting stents [FDS]) placed within the parent artery adjacent to the aneurysm, rather than by direct occlusion of the aneurysm. The devices induce changes in the transmural pressure gradient between the parent artery and the aneurysm, creating progressive intra-aneurysmal thrombosis and promoting remodeling of the parent artery around the stent [38, 39]. Flow diversion was primarily designed to address large aneurysms of the internal carotid artery (ICA) located from the petrous to the paraclinoid regions, which were traditionally treated with extracranial-to-intracranial carotid

bypass and aneurysm trapping [40]. The indications for flow diversion subsequently expanded to include the treatment of fusiform, dissecting, wide-necked, and bifurcation aneurysms, in which coil embolization, stenting, and clipping carry higher risks of morbidity. Moreover, because of a favorable safety profile, the off-label use of FDS has flourished. Such uses include treatment of posterior circulation aneurysms, previously treated recurrent aneurysms, and even acutely ruptured aneurysms, in which the need for concurrent dual antiplatelet therapy imparts an additional risk [40].

The results of flow diversion have been encouraging in multiple trials and meta-analyses. In a systematic review, Briganti et al. [41] reported that the rate of aneurysm occlusion progressively increased during follow-up, rising from 10% immediately postoperatively to 60%, 74.5%, and 89.6% at 3-, 6-, and 12-month follow-up, respectively. Moreover, the reported morbidity rates ranged between 0% and 15%, with a mean mortality rate of 3.4%. The primary causes of morbidity included ischemic complications (mean 4.1%, range 1–14.2%) and hemorrhagic complications (mean 2.9%, range 2.2–7.5%), with many leading to permanent neurological deterioration (mean 3.5%, range 1–15%) [41].

In the landmark multicenter prospective single-arm Pipeline for Uncoilable or Failed Aneurysms (PUFS) clinical trial of treatment of large and giant wide-necked aneurysms of the ICA, Becske et al. [42] found that 73.6% of patients (78 of 106) achieved complete aneurysmal occlusion by 180 days. The occlusion rate increased to 86.8% (79 of 91 cases) at 1-year follow-up and to 95.2% (60 of 63 cases) at 5 years [43]. Only six patients required retreatment, corresponding to a 5.7% recurrence rate. The safety profile was also favorable, with only 5.6% of patients (6 of 107) having a major ipsilateral stroke or neurological death [42]. Overall, five patients experienced hemorrhagic complications, all of which occurred within the first month postprocedurally. Of these, neurological sequelae were transient in three patients, resulting in a permanent morbidity and mortality rate of 1.9% after hemorrhagic complications, even in the face of long-term antiplatelet therapy. The rate of parent artery occlusion at 5 years was 5.5% (6 of 109 cases), with only one patient experiencing neurological morbidity secondary to an ischemic stroke [43]. At 180 days, the modified Rankin scale (mRS) score had improved in 19.6% of patients (21 of 107), remained unchanged in 65.4% (70 of 107), and had deteriorated in 9.3% (10 of 107). Ultimately, 87.9% of patients had an mRS score of $\leq$1 at this time [42]. Although additional less common complications were reported (including headaches, diplopia, and systemic thrombophilic events), the authors concluded that flow diverters were both safe and effective for the management of large, wide-necked ICA aneurysms [42, 43].

Following the encouraging results of the PUFS trial, data from the International Retrospective Study of Pipeline Embolization Device (IntrePED) were released [44]. This landmark global multicenter study retrospectively examined neurological complications in 906 aneurysms treated with the Pipeline flow diversion device. The study included a much broader range of lesion sizes, locations, and morphologies, and comprised significant numbers of large and giant (47%), posterior circulation (6.6%), and ruptured (8.2%) aneurysms. In IntrePED, the overall rates of neurological morbidity and mortality were 7.4% and 3.8%, respectively. In line with the findings in numerous other reports [45, 46], patients with posterior circulation aneurysms demonstrated the highest rates of complications (16.4%; 9 of 55 cases), with a stroke rate of 7.3%, thought to be related to a high perforator infarction incidence. Moreover, giant aneurysms were associated with significantly higher morbidity and mortality than smaller ones. Ischemic complications were encountered in 4.7% of all cases (37 of 796 patients), while hemorrhagic complications were noted in 2.4% (19 of 796 patients). Other reported complications included permanent cranial neuropathy (0.3%), in-stent stenosis (0.3%), and late aneurysmal rupture (0.6%), with three of five events occurring in patients with giant aneurysms.

The safety profile of flow diversion devices appears to be more favorable than those of other reconstructive techniques (coil embolization, stent-assisted coiling) and deconstructive techniques (parent artery occlusion and trapping). In a meta-analysis comparing reconstructive and deconstructive techniques in 265 procedures for ruptured blister aneurysms, Rouchaud et al. [47] found that patients who received flow diversion had a significantly higher rate of complete aneurysm occlusion than those treated with coil embolization or stent-assisted coiling (90.8% versus 69.7%). The authors also found that patients treated with flow diverters demonstrated a lower rate of retreatment (6.6% versus 27.1%), with similar perioperative morbidity rates (12.6% versus 13.2%) and mortality rates (8.7% versus 7.2%) [47]. Similarly, Kallmes et al. [48] performed a pooled analysis of three large multicenter studies of 1092 patients with 1221 intracranial aneurysms treated with flow diverters, and defined a 3.7% major ipsilateral ischemic stroke rate, a 2% major ipsilateral intracranial hemorrhage rate, and a 7.1% combined major morbidity and neurological mortality rate (3.3% neurological mortality).

However, the recent publication of the Canadian Flow Diversion in the Treatment of Intracranial Aneurysm Trial (FIAT) has challenged the assertion of safety and efficacy espoused in numerous previous studies [49]. Specifically, FIAT, which was halted because of safety concerns, identified significantly higher than expected risks of death or dependence in patients undergoing flow diversion for a diverse range of complex intracranial aneurysms, some of which were ruptured. Only 58% of patients undergoing flow diversion experienced no complications. Notably, 6% of treated individuals experienced a stroke, while 16% demonstrated angiographically confirmed immediate device failure. Although the study was relatively small, encompassing 112 cases across all

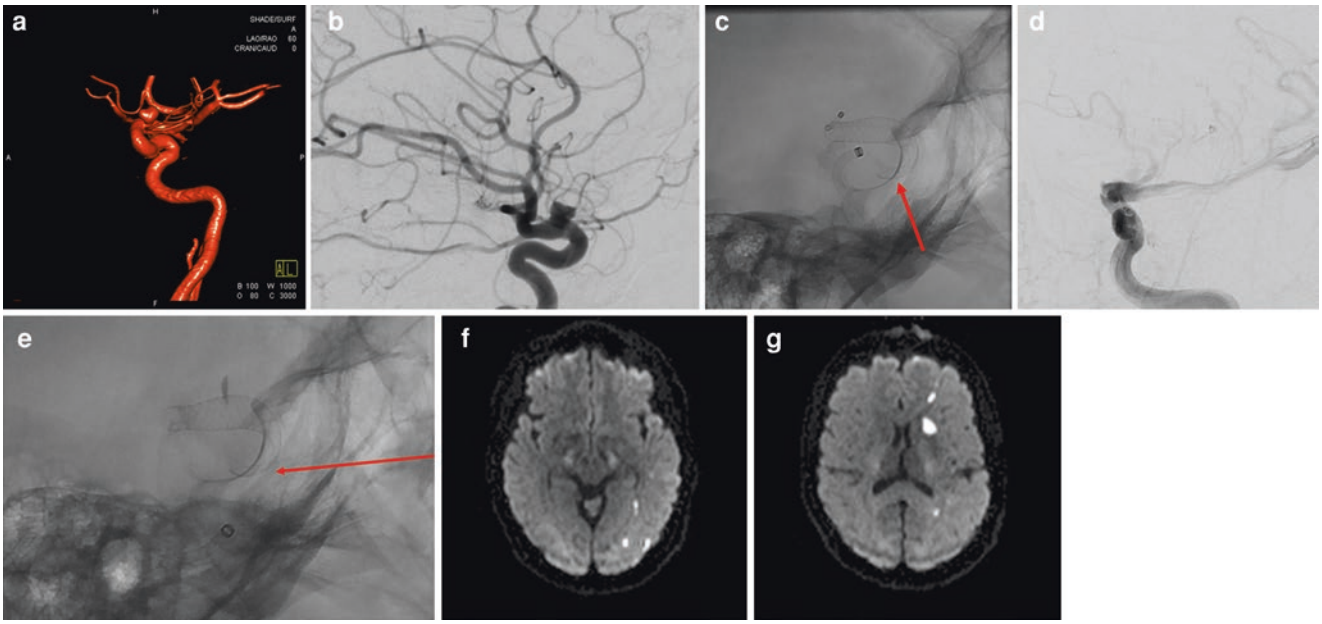

Fig. 1 Imaging in a 42-year-old woman with an incidentally identified dysplastic left ophthalmic artery aneurysm 7 × 4 mm in size (**a**, **b**). Placement of a flow-diverting stent showed failure of proximal wall apposition, resulting in a "comma-shaped" pattern of contrast enhancement (*arrow*) and creating an endoleak and a source of distal embolization (**c**). After aberrant deployment of the stent, angiography demonstrated delayed flow into the left middle cerebral artery and no flow into the anterior cerebral artery (**d**). The "comma-shaped" contrast pattern (*arrow*) persisted despite efforts to correct the defect (**e**). Although the patient remained asymptomatic, immediate postinterventional axial diffusion-weighted magnetic resonance imaging revealed multiple emboli, resulting from the stent malapposition (**f**, **g**)

study groups, the reported 10.7% mortality rate highlights the importance of identifying the specific patient populations most likely to benefit from flow diversion technologies.

Other reported complications of flow diversion that require attention and early intervention include iatrogenic dissection, intraprocedural rupture, catheter-induced vasospasm, stent malposition or migration (Figs. 1 and 2), carotid–cavernous fistula formation, delayed rupture, and contralateral hemorrhagic stroke [34, 36, 38, 39, 41, 47, 48, 51, 52]. Moreover, the rate of occlusion or significant stenosis of the parent artery during the procedure is not negligible (mean 3.8%, range 0–8.3%) [34, 36, 38, 39, 41, 47, 48, 51, 52].

Finally, as also observed in coil embolization and stenting studies, the complication rate in flow diversion decreases significantly with operator experience. Jabbour et al. [53] reported significant reductions in procedural complications (from 16.2% to 5.6%) and major perioperative complications (from 10.8% to 0%) with increasing experience. These results were reproduced in a separate study [51], which showed reductions in intraprocedural technical difficulties (from 13.3% to 2.7%), procedure-related combined major morbidity and neurological mortality (from 14.7% to 2.7%), and overall combined major morbidity and neurological mortality (from 14.7% to 4.0%) with increasing experience. Certainly, it is clear that the use of flow diverters is subject to a significant learning curve.

Complications of Antiplatelet Therapy

Patients undergoing endovascular stenting and flow diverter treatment routinely receive dual antiplatelet therapy, typically with aspirin and clopidogrel. Balancing the risks of hemorrhage associated with long-term antiplatelet therapy and the thrombotic risks of early termination of such treatment remains an area of debate among endovascular specialists [38, 54]. In addition, the initiation of antiplatelet therapy in cases of aneurysmal SAH is of significant concern, particularly in the setting of flow diversion, where aneurysm occlusion occurs in a delayed fashion [37].

Routine assessment of platelet function using pharmacologically specific testing (e.g., for aspirin or P2Y12) prior to the initiation of dual antiplatelet therapy is controversial [37, 38, 54, 55]. Although some oppose such testing on the basis of cost ineffectiveness, many others cite the increased incidence of thrombotic complications associated with platelet resistance to antiplatelet therapy and the potential to decrease that rate with early recognition and timely replacement of prescribed agents (e.g., replacement of clopidogrel

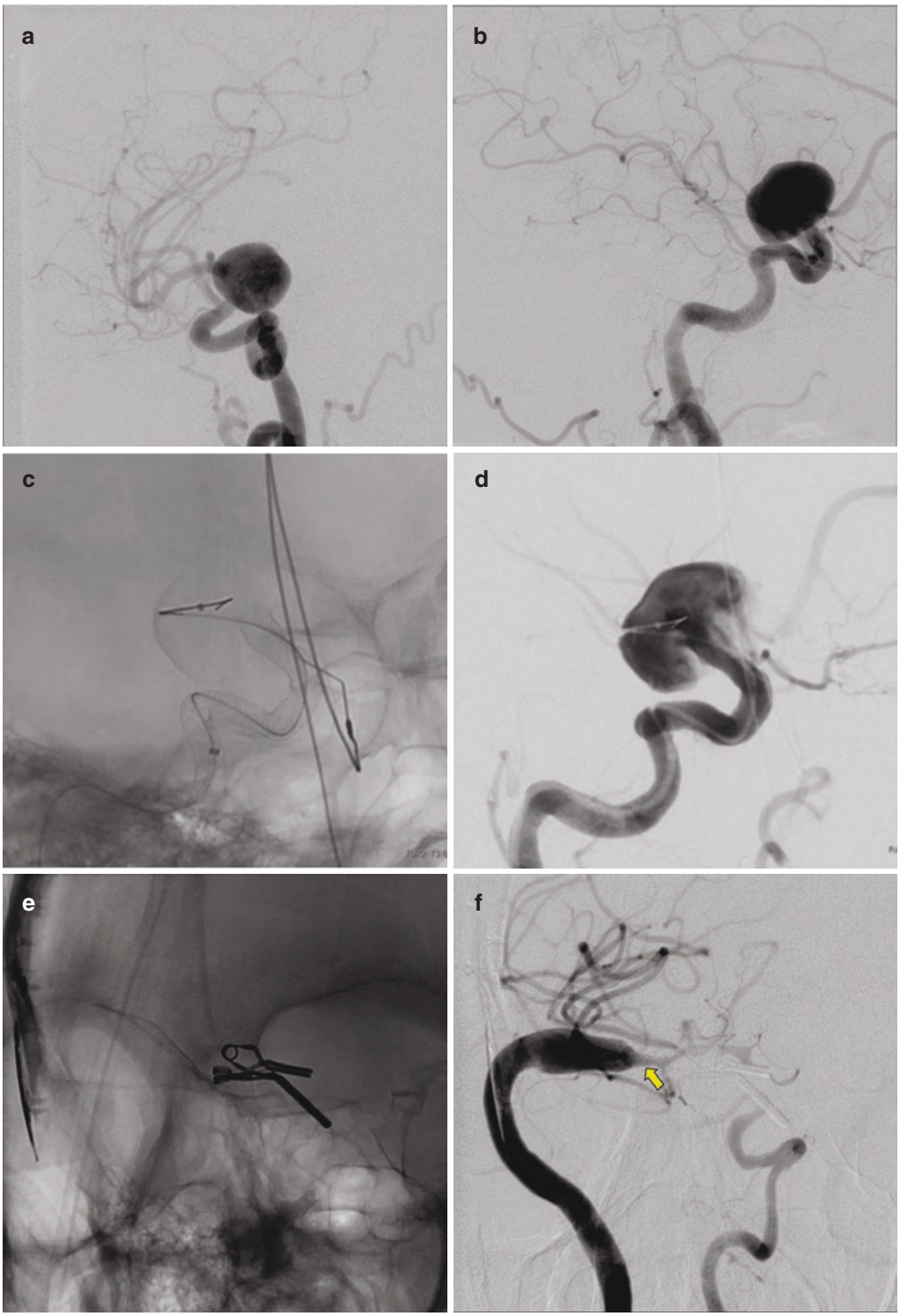

Fig. 2 A giant unruptured aneurysm, 3 × 2.2 cm in size, of the right internal carotid artery (ICA) (**a**, **b**). Placement of a flow-diverting stent spanning from the distal middle cerebral artery to the proximal ICA was attempted; however, during stent placement, the device migrated, with the distal end positioned within the aneurysm sac. An angiogram demonstrated persistent aneurysm filling after stent deployment (**c**, **d**). The patient was treated with aneurysm trapping and bypass (**e**, **f**). The ICA aneurysmal segment was trapped with aneurysm clips, the aneurysm sac was opened, and the flow-diverting stent was removed. A saphenous vein graft was used to create an end-to-end anastomosis between the external carotid artery and the right M2 segment (*arrow*). The proximal ICA supplied the ophthalmic artery. (Panels **a**–**d** and **f** reproduced from Bowers et al. [50], with permission; panel **e** reproduced from Mazur et al. [37], with permission)

with prasugrel) [37, 56]. Further studies are therefore needed to determine the cost effectiveness of routine platelet function testing and to establish treatment guidelines.

Conclusion

In recent decades, the treatment paradigm for intracranial aneurysms has shifted dramatically to accommodate the introduction and rapid advancements of endovascular techniques. However, regardless of the approach used, and in spite of improving clinical outcomes [19], the risks of periprocedural complications and mortality remain significant. In particular, giant aneurysms, aneurysms involving the posterior circulation, and recurrent aneurysms have proven challenging to treat with conventional techniques. The emergence of flow diversion technology has shown great promise in the management of these complex cerebrovascular lesions and may slowly supplant the need for radical surgical interventions, such as extracranial-to-intracranial bypass with trapping or carotid occlusion, in most cases. Nevertheless, neurosurgeons should remain prepared to address lesions that are not amenable to endovascular treatment, a feat that is becoming progressively more difficult in the era of flow diversion as neurosurgical trainees are faced with declining exposure to aneurysm surgery.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Maurice-Williams RS, Lafuente J. Intracranial aneurysm surgery and its future. J R Soc Med. 2003;96:540–3.
2. Lai LT, O'Neill AH. History, evolution, and continuing innovations of intracranial aneurysm surgery. World Neurosurg. 2017;102:673–81.
3. Sharma M, Ambekar S, Ahmed O, Nixon M, Sharma A, Nanda A, Guthikonda B. The utility and limitations of intraoperative near-infrared indocyanine green videoangiography in aneurysm surgery. World Neurosurg. 2014;82:e607–13.
4. King JT Jr, Berlin JA, Flamm ES. Morbidity and mortality from elective surgery for asymptomatic, unruptured, intracranial aneurysms: a meta-analysis. J Neurosurg. 1994;81:837–42.
5. Kotowski M, Naggara O, Darsaut TE, Nolet S, Gevry G, Kouznetsov E, Raymond J. Safety and occlusion rates of surgical treatment of unruptured intracranial aneurysms: a systematic review and meta-analysis of the literature from 1990 to 2011. J Neurol Neurosurg Psychiatry. 2013;84:42–8.
6. Raaymakers TW, Rinkel GJ, Limburg M, Algra A. Mortality and morbidity of surgery for unruptured intracranial aneurysms: a meta-analysis. Stroke. 1998;29:1531–8.
7. Wong JM, Ziewacz JE, Ho AL, Panchmatia JR, Kim AH, Bader AM, Thompson BG, Du R, Gawande AA. Patterns in neurosurgical adverse events: open cerebrovascular neurosurgery. Neurosurg Focus. 2012;33(5):E15.
8. Madhugiri VS, Ambekar S, Pandey P, Guthikonda B, Bollam P, Brown B, Ahmed O, Sonig A, Sharma M, Nanda A. The pterional and suprabrow approaches for aneurysm surgery: a systematic review of intraoperative rupture rates in 9488 aneurysms. World Neurosurg. 2013;80:836–44.
9. Molyneux AJ, Kerr RS, Yu LM, Clarke M, Sneade M, Yarnold JA, Sandercock P. International Subarachnoid Aneurysm Trial Collaborative Group. International Subarachnoid Aneurysm Trial (ISAT) of neurosurgical clipping versus endovascular coiling in 2143 patients with ruptured intracranial aneurysms: a randomised comparison of effects on survival, dependency, seizures, rebleeding, subgroups, and aneurysm occlusion. Lancet. 2005;366:809–17.
10. Alshekhlee A, Mehta S, Edgell RC, Vora N, Feen E, Mohammadi A, Kale SP, Cruz-Flores S. Hospital mortality and complications of electively clipped or coiled unruptured intracranial aneurysm. Stroke. 2010;41:1471–6.
11. Lai LT, O'Donnell J, Morgan MK. The risk of seizures during the in-hospital admission for surgical or endovascular treatment of unruptured intracranial aneurysms. J Clin Neurosci. 2013;20:1498–502.
12. Zhao J, Lin H, Summers R, Yang M, Cousins BG, Tsui J. Current treatment strategies for intracranial aneurysms: an overview. Angiology. 2018;69:17–30.
13. Li H, Pan R, Wang H, Rong X, Yin Z, Milgrom DP, Shi X, Tang Y, Peng Y. Clipping versus coiling for ruptured intracranial aneurysms: a systematic review and meta-analysis. Stroke. 2013;44:29–37.
14. Umredkar A, Gupta SK, Khandelwal N, Chhabra R, Mathuriya SN, Pathak A, Tiwari MK, Mukherjee KK, Mohindra S, Singla N, Salunke P. Intracerebral infarcts following clipping of intracranial aneurysms: incidence, clinical correlation and outcome. Br J Neurosurg. 2010;24:156–62.
15. Leipzig TJ, Morgan J, Horner TG, Payner T, Redelman K, Johnson CS. Analysis of intraoperative rupture in the surgical treatment of 1694 saccular aneurysms. Neurosurgery. 2005;56:455–68.
16. Elijovich L, Higashida RT, Lawton MT, Duckwiler G, Giannotta S, Johnston SC. Predictors and outcomes of intraprocedural rupture in patients treated for ruptured intracranial aneurysms: the CARAT study. Stroke. 2008;39:1501–6.
17. Sandalcioglu IE, Schoch B, Regel JP, Wanke I, Gasser T, Forsting M, Stolke D, Wiedemayer H. Does intraoperative aneurysm rupture influence outcome? Analysis of 169 patients. Clin Neurol Neurosurg. 2004;106:88–92.
18. Wong JM, Ziewacz JE, Panchmatia JR, Bader AM, Pandey AS, Thompson BG, Frerichs K, Gawande AA. Patterns in neurosurgical adverse events: endovascular neurosurgery. Neurosurg Focus. 2012;33(5):E14.
19. Pandey AS, Gemmete JJ, Wilson TJ, Chaudhary N, Thompson BG, Morgenstern LB, Burke JF. High subarachnoid hemorrhage patient volume associated with lower mortality and better outcomes. Neurosurgery. 2015;77:462–70.
20. Pierot L, Spelle L, Vitry F, Investigators ATENA. Immediate clinical outcome of patients harboring unruptured intracranial aneurysms treated by endovascular approach: results of the ATENA study. Stroke. 2008;39:2497–504.
21. Ross IB, Dhillon GS. Complications of endovascular treatment of cerebral aneurysms. Surg Neurol. 2005;64:12–9.
22. Ravindra VM, Mazur MD, Park MS, Kilburg C, Moran CJ, Hardman RL, Couldwell WT, Taussky P. Complications in endovascular neurosurgery: critical analysis and classification. World Neurosurg. 2016;95:1–8.
23. Peterson EC, Kanal KM, Dickinson RL, Stewart BK, Kim LJ. Radiation-induced complications in endovascular neurosurgery: incidence of skin effects and the feasibility of estimating risk of future tumor formation. Neurosurgery. 2013;72:566–72.
24. Koebbe CJ, Veznedaroglu E, Jabbour P, Rosenwasser RH. Endovascular management of intracranial aneurysms: current experience and future advances. Neurosurgery. 2006;59:S93–102.

25. Yoon W. Current update on the randomized controlled trials of intracranial aneurysms. Neurointervention. 2011;6:1–5.
26. Chalouhi N, Tjoumakaris S, Gonzalez LF, Dumont AS, Starke RM, Hasan D, Wu C, Singhal S, Moukarzel LA, Rosenwasser R, Jabbour P. Coiling of large and giant aneurysms: complications and long-term results of 334 cases. AJNR Am J Neuroradiol. 2014;35:546–52.
27. Brinjikji W, Cloft HJ, Kallmes DF. Difficult aneurysms for endovascular treatment: overwide or undertall? AJNR Am J Neuroradiol. 2009;30:1513–7.
28. Piotin M, Blanc R, Spelle L, Mounayer C, Piantino R, Schmidt PJ, Moret J. Stent-assisted coiling of intracranial aneurysms: clinical and angiographic results in 216 consecutive aneurysms. Stroke. 2010;41:110–5.
29. Phan K, Huo YR, Jia F, Phan S, Rao PJ, Mobbs RJ, Mortimer AM. Meta-analysis of stent-assisted coiling versus coiling-only for the treatment of intracranial aneurysms. J Clin Neurosci. 2016;31:15–22.
30. Ruan C, Long H, Sun H, He M, Yang K, Zhang H, Mao B. Endovascular coiling vs. surgical clipping for unruptured intracranial aneurysm: a meta-analysis. Br J Neurosurg. 2015;29:485–92.
31. Campi A, Ramzi N, Molyneux AJ, Summers PE, Kerr RS, Sneade M, Yarnold JA, Rischmiller J, Byrne JV. Retreatment of ruptured cerebral aneurysms in patients randomized by coiling or clipping in the International Subarachnoid Aneurysm Trial (ISAT). Stroke. 2007;38:1538–44.
32. Ding D, Liu KC. Management strategies for intraprocedural coil migration during endovascular treatment of intracranial aneurysms. J Neurointerv Surg. 2014;6:428–31.
33. Yang H, Sun Y, Jiang Y, Lv X, Zhao Y, Li Y, Liu A. Comparison of stent-assisted coiling vs coiling alone in 563 intracranial aneurysms: safety and efficacy at a high-volume center. Neurosurgery. 2015;77:241–7.
34. Zhang Y, Zhou Y, Yang P, Liu J, Xu Y, Hong B, Zhao W, Chen Q, Huang QH. Comparison of the flow diverter and stent-assisted coiling in large and giant aneurysms: safety and efficacy based on a propensity score–matched analysis. Eur Radiol. 2016;26:2369–77.
35. Benitez RP, Silva MT, Klem J, Veznedaroglu E, Rosenwasser RH. Endovascular occlusion of wide-necked aneurysms with a new intracranial microstent (Neuroform) and detachable coils. Neurosurgery. 2004;54:1359–68.
36. Kawabata S, Imamura H, Adachi H, Tani S, Tokunaga S, Funatsu T, Suzuki K, Sakai N. Risk factors for and outcomes of intraprocedural rupture during endovascular treatment of unruptured intracranial aneurysms. J Neurointerv Surg. 2018;10:362–6.
37. Mazur MD, Taussky P, Park MS, Couldwell WT. Contemporary endovascular and open aneurysm treatment in the era of flow diversion. J Neurol Neurosurg Psychiatry. 2018;89:277–86.
38. Fiorella D, Lylyk P, Szikora I, Kelly ME, Albuquerque FC, McDougall CG, Nelson PK. Curative cerebrovascular reconstruction with the Pipeline embolization device: the emergence of definitive endovascular therapy for intracranial aneurysms. J Neurointerv Surg. 2009;1:56–65.
39. Rajah G, Narayanan S, Rangel-Castilla L. Update on flow diverters for the endovascular management of cerebral aneurysms. Neurosurg Focus. 2017;42(6):E2.
40. Patel PD, Chalouhi N, Atallah E, Tjoumakaris S, Hasan D, Zarzour H, Rosenwasser R, Jabbour P. Off-label uses of the Pipeline embolization device: a review of the literature. Neurosurg Focus. 2017;42(6):E4.
41. Briganti F, Leone G, Marseglia M, Mariniello G, Caranci F, Brunetti A, Maiuri F. Endovascular treatment of cerebral aneurysms using flow-diverter devices: a systematic review. Neuroradiol J. 2015;28:365–75.
42. Becske T, Kallmes DF, Saatci I, McDougall CG, Szikora I, Lanzino G, Moran CJ, Woo HH, Lopes DK, Berez AL, Cher DJ, Siddiqui AH, Levy EI, Albuquerque FC, Fiorella DJ, Berentei Z, Marosfoi M, Cekirge SH, Nelson PK. Pipeline for uncoilable or failed aneurysms: results from a multicenter clinical trial. Radiology. 2013;267:858–68.
43. Becske T, Brinjikji W, Potts MB, Kallmes DF, Shapiro M, Moran CJ, Levy EI, McDougall CG, Szikora I, Lanzino G, Woo HH, Lopes DK, Siddiqui AH, Albuquerque FC, Fiorella DJ, Saatci I, Cekirge SH, Berez AL, Cher DJ, Berentei Z, Marosfoi M, Nelson PK. Long-term clinical and angiographic outcomes following Pipeline embolization device treatment of complex internal carotid artery aneurysms: five-year results of the Pipeline for Uncoilable or Failed Aneurysms Trial. Neurosurgery. 2017;80:40–8.
44. Kallmes DF, Hanel R, Lopes D, Boccardi E, Bonafe A, Cekirge S, Fiorella D, Jabbour P, Levy E, McDougall C, Siddiqui A, Szikora I, Woo H, Albuquerque F, Bozorgchami H, Dashti SR, Delgado Almandoz JE, Kelly ME, Turner R 4th, Woodward BK, Brinjikji W, Lanzino G, Lylyk P. International retrospective study of the Pipeline embolization device: a multicenter aneurysm treatment study. AJNR Am J Neuroradiol. 2015;36:108–15.
45. Phillips TJ, Wenderoth JD, Phatouros CC, Rice H, Singh TP, Devilliers L, Wycoco V, Meckel S, McAuliffe W. Safety of the Pipeline embolization device in treatment of posterior circulation aneurysms. AJNR Am J Neuroradiol. 2012;33:1225–31.
46. Siddiqui AH, Abla AA, Kan P, Dumont TM, Jahshan S, Britz GW, Hopkins LN, Levy EI. Panacea or problem: flow diverters in the treatment of symptomatic large or giant fusiform vertebrobasilar aneurysms. J Neurosurg. 2012;116:1258–66.
47. Rouchaud A, Brinjikji W, Cloft HJ, Kallmes DF. Endovascular treatment of ruptured blister-like aneurysms: a systematic review and meta-analysis with focus on deconstructive versus reconstructive and flow-diverter treatments. AJNR Am J Neuroradiol. 2015;36:2331–9.
48. Kallmes DF, Brinjikji W, Cekirge S, Fiorella D, Hanel RA, Jabbour P, Lopes D, Lylyk P, McDougall CG, Siddiqui A. Safety and efficacy of the Pipeline embolization device for treatment of intracranial aneurysms: a pooled analysis of 3 large studies. J Neurosurg. 2017;127:775–80.
49. Raymond J, Gentric JC, Darsaut TE, Iancu D, Chagnon M, Weill A, Roy D. Flow diversion in the treatment of aneurysms: a randomized care trial and registry. J Neurosurg. 2017;127:454–62.
50. Bowers CA, Taussky P, Park MS, Neil JA, Couldwell WT. Rescue microsurgery with bypass and stent removal following Pipeline treatment of a giant internal carotid artery terminus aneurysm. Acta Neurochir (Wien). 2015;157:2071–5.
51. Delgado Almandoz JE, Kayan Y, Tenreiro A, Wallace AN, Scholz JM, Fease JL, Milner AM, Mulder M, Uittenbogaard KM, Tenreiro-Picon O. Clinical and angiographic outcomes in patients with intracranial aneurysms treated with the Pipeline embolization device: intra-procedural technical difficulties, major morbidity, and neurological mortality decrease significantly with increased operator experience in device deployment and patient management. Neuroradiology. 2017;59:1291–9.
52. Kiyofuji S, Graffeo CS, Perry A, Murad MH, Flemming KD, Lanzino G, Rangel-Castilla L, Brinjikji W. Meta-analysis of treatment outcomes of posterior circulation non-saccular aneurysms by flow diverters. J Neurointerv Surg. 2018;10:493–9.
53. Jabbour P, Chalouhi N, Tjoumakaris S, Gonzalez LF, Dumont AS, Randazzo C, Starke RM, Hasan D, Chitale R, Singhal S, Moukarzel LA, Rosenwasser R. The Pipeline embolization device: learning curve and predictors of complications and aneurysm obliteration. Neurosurgery. 2013;73:113–20.
54. Skukalek SL, Winkler AM, Kang J, Dion JE, Cawley CM, Webb A, Dannenbaum MJ, Schuette AJ, Asbury B, Tong FC. Effect of antiplatelet therapy and platelet function testing on hemorrhagic and thrombotic complications in patients with cerebral aneurysms treated with the Pipeline embolization device: a review and meta-analysis. J Neurointerv Surg. 2016;8:58–65.

55. Comin J, Kallmes DF. Platelet-function testing in patients undergoing neurovascular procedures: caught between a rock and a hard place. AJNR Am J Neuroradiol. 2013;34:730–4.
56. Delgado Almandoz JE, Kadkhodayan Y, Crandall BM, Scholz JM, Fease JL, Tubman DE. Variability in initial response to standard clopidogrel therapy, delayed conversion to clopidogrel hyper-response, and associated thromboembolic and hemorrhagic complications in patients undergoing endovascular treatment of unruptured cerebral aneurysms. J Neurointerv Surg. 2014;6:767–73.

Endovascular Management of a Basilar Artery Pseudoaneurysm After Iatrogenic Injury During Endoscopic Third Ventriculostomy: Case Report

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Abstract

Endoscopic third ventriculostomy (ETV) is a well-established neurosurgical procedure. However, it carries risks of intraoperative complications, among which major vascular injury is the most dangerous. Reportedly, prominent bleeding during ETV has been noted in <1% of cases. Herein, we describe a case of a 34-year-old woman with occlusive hydrocephalus caused by a quadrigeminal cistern arachnoid cyst, who developed a pseudoaneurysm after injury of the basilar artery apex during ETV. Complete obliteration of the pseudoaneurysm with endovascular balloon-assisted coiling was done on the first postoperative day, and the patient demonstrated gradual recovery, but approximately 4 weeks later, she suffered massive rebleeding, seemingly due to rupture of the weak pseudoaneurysm wall, which resulted in her death. Careful evaluation of sagittal T2-weighted magnetic resonance images before ETV may be invaluable for assessment of the basilar artery position in relation to the third ventricle floor. In addition, use of a blunt surgical instrument (instead of a sharp one or cautery) for fenestration may be safer for prevention of arterial injury. Finally, special care should be applied in cases with an opaque third ventricle floor and inability to visualize the basilar artery during ETV.

Keywords

Aneurysm coiling · Arterial injury · Basilar artery pseudoaneurysm · Complication · Endoscopic third ventriculostomy · Quadrigeminal cistern arachnoid cyst · Vascular injury

Introduction

Endoscopic third ventriculostomy (ETV) is a well-established treatment modality for management of hydrocephalus. Although it is considered a relatively safe procedure, a variety of complications have been reported, mostly related to the surgery itself. Although their incidence is underestimated, major vascular injuries are the most feared type of intraoperative complication. Herein, we report a case of the basilar artery (BA) apex perforation during ETV performed for management of hydrocephalus caused by a quadrigeminal cistern arachnoid cyst. It resulted in development of a pseudoaneurysm, which was coiled but later rebled, leading to the death of the patient.

Case Report

A 34-year-old woman presented with a 3-month history of a headache and vomiting, and papilledema was disclosed during her examination. Magnetic resonance imaging (MRI) revealed a large multilobulated quadrigeminal cistern arachnoid cyst associated with obstructive hydrocephalus (Fig. 1a). ETV, followed by ventriculocystostomy, was planned.

Surgery

A right-side frontal burr hole was created, and a universal Gaab neuroendoscope (Karl Storz, Tuttlingen, Germany) was introduced into the third ventricle, the floor of which

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_12

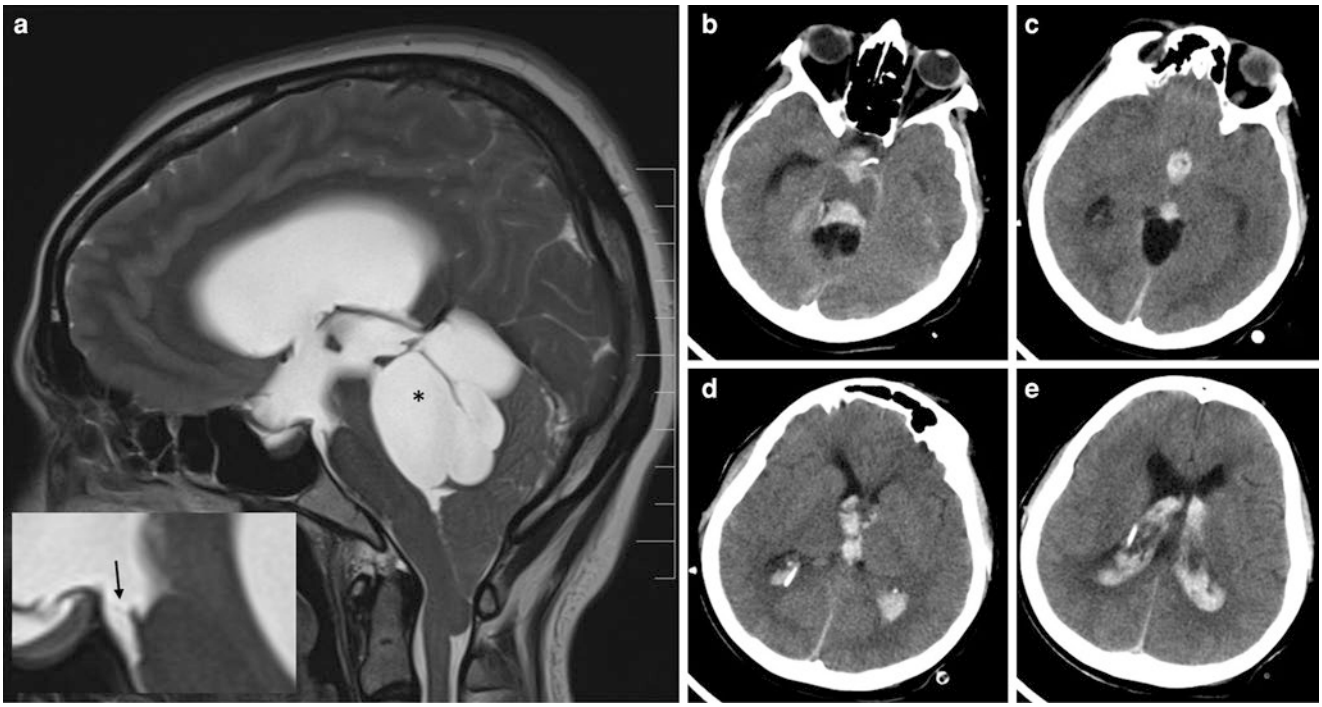

Fig. 1 Neuroimaging findings in a 34-year-old woman who underwent endoscopic third ventriculostomy complicated by injury of the basilar artery (BA) and pseudoaneurysm formation. Sagittal T2-weighted magnetic resonance imaging before surgery (**a**) demonstrated a large multilobulated quadrigeminal cistern arachnoid cyst (*asterisked*) along with a narrow prepontine cistern, and the BA apex was positioned immediately beneath the Liliequist membrane (*arrowed on the insert*). Postoperative computed tomography (**b**–**e**) showed extensive prepontine and intraventricular hemorrhage, with external ventricular drainage in the right lateral ventricle

seemed relatively opaque. It was perforated posterior to the dorsum sellae with an endoscopic bipolar lead without use of electrical energy. After perforation of the third ventricle floor, the thick but transparent Liliequist membrane was found to be intact. The prebasilar space was very narrow. During perforation of the Liliequist membrane, there was brisk bleeding obscuring any further visualization of the operative field despite continuing saline irrigation. Therefore, the endoscope was withdrawn and an external ventricular drain (EVD) was placed.

Detection and Management of the Pseudoaneurysm

Upon reversal of general anesthesia, the patient was conscious but had right third nerve palsy. Postoperative computed tomography (CT) demonstrated extensive prepontine and intraventricular hemorrhage (Fig. 1b–e). Digital subtraction angiography (DSA) done on the next day revealed a BA tip pseudoaneurysm (Fig. 2a, b), which underwent endovascular balloon-assisted coiling using a 2-mm × 2-cm Helix soft coil (Micro Therapeutics, Irvine, CA, USA). The procedure was uneventful, and control DSA showed complete obliteration of the pseudoaneurysm (Fig. 2c, d).

Subsequent Clinical Course

The patient developed delayed cerebral ischemia (DCI) manifested by aphasia and hemiplegia. Medical therapy was administered. Within 2 weeks after the initial intervention, partial recovery of the muscle power in the affected limbs and regained speech were noted. The patient was transferred for rehabilitation. However, about 4 weeks after the initial procedure, she suddenly lost consciousness and demonstrated decerebrate posturing. CT revealed diffuse prepontine and intraventricular hemorrhage with acute hydrocephalus due to rupture of the pseudoaneurysm (Fig. 3). Despite emergency insertion of an EVD, the patient died on the same day.

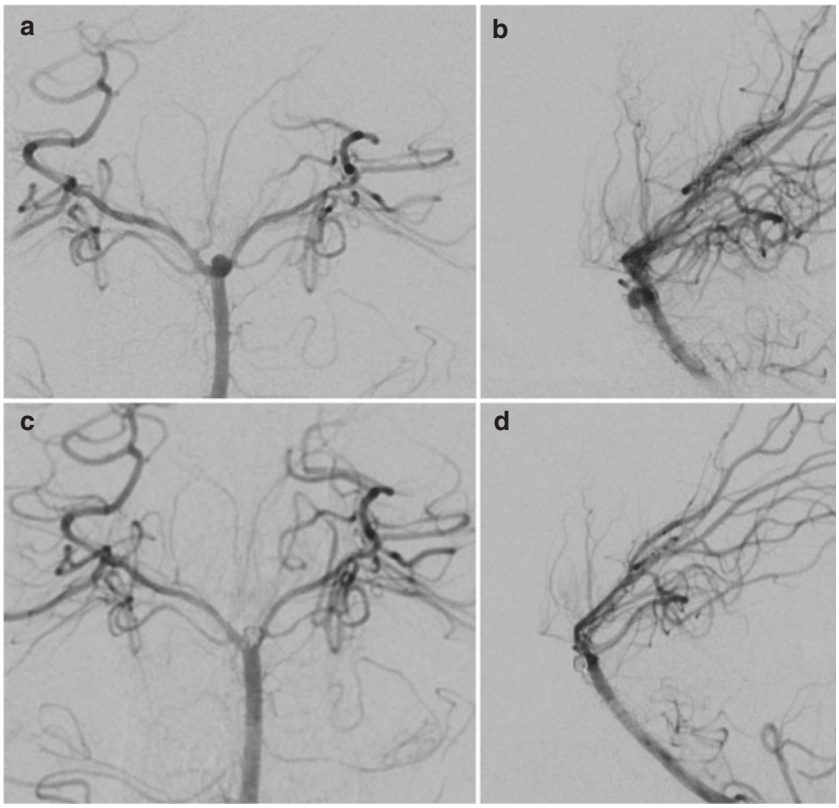

Fig. 2 Digital subtraction angiography, done on the first postoperative day, demonstrated a basilar artery tip pseudoaneurysm (**a**, **b**), which underwent complete obliteration with endovascular balloon-assisted coiling (**c**, **d**)

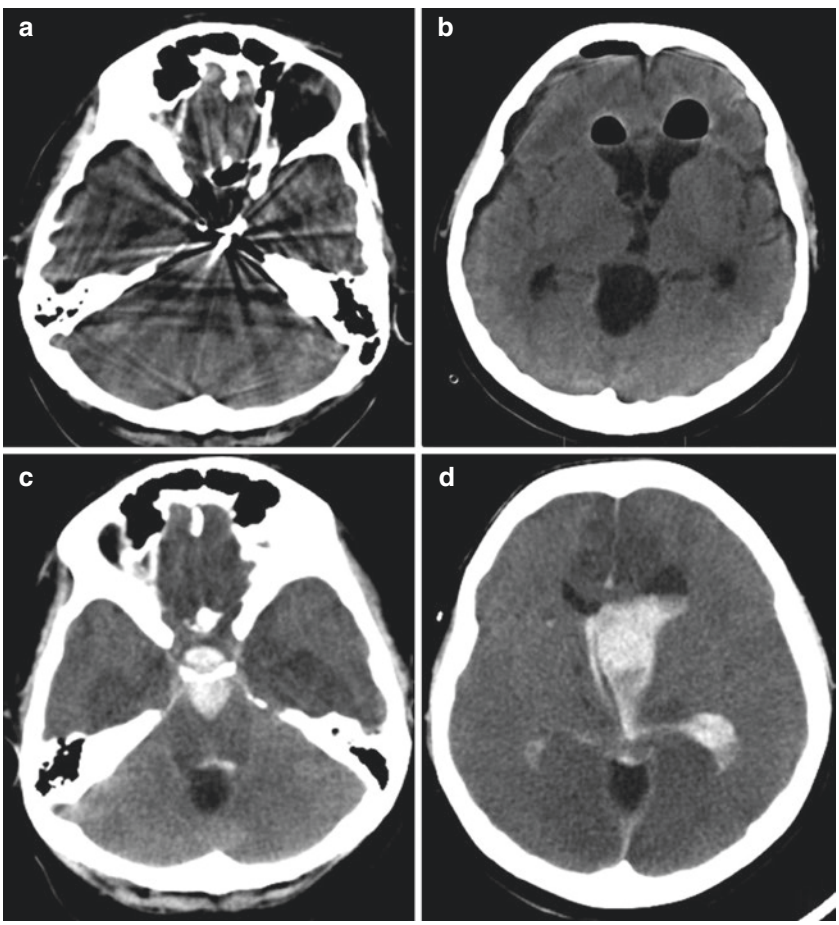

Fig. 3 Neuroimaging findings during the postoperative course. Two weeks after the primary intervention, computed tomography (CT) showed complete resolution of the intraventricular hematoma (**a**, **b**). At the time of clinical deterioration, which resulted from pseudoaneurysm rupture 4 weeks after the primary intervention, CT demonstrated diffuse prepontine and intraventricular hemorrhage with acute hydrocephalus (**c**, **d**)

Discussion

Although, over the years, ETV has become a standard procedure for management of occlusive hydrocephalus, it is certainly not without risks of complications [1]. In fact, the reported rates of associated morbidity range from 0% to 31.2%, with permanent morbidity in approximately 2% of cases [2–4]. Various types of complications have been reported, including cerebral herniation syndromes, cardiac arrhythmias, injury of the hypothalamic–pituitary axis and/or neurovascular structures in proximity to the floor of the third ventricle (e.g., cranial nerves and the BA complex), injury of the large ependymal veins, meningitis, sepsis, and cognitive dysfunction [2, 3, 5–7]. Nevertheless, ETV-related mortality is very low, and in one of the largest relevant reviews, performed by Bouras and Sgouros [2], its incidence was noted to be 0.28%.

Major intraoperative bleeding is clearly one of the most devastating complications of ETV and has a reported incidence of 0.49%. It mainly results from laceration of the septal or thalamostriate veins, or injury of the branches or the main trunk of the BA. Damage of the latter is extremely dangerous; it occurs in 0.2–0.3% of cases and carries significant risks of major morbidity and mortality [2, 6]. Occurrence of such a complication has been linked to the proximity of the BA apex to the floor of the third ventricle. Careful preoperative assessment of thin-section sagittal T2-weighted MRI may provide indispensable information on such anatomical details and allow estimation of the size of the prepontine cistern and the prebasilar space, as well as the tortuosity and herniation of the BA complex with regard to the floor of the third ventricle and the Liliequist membrane, giving a clue to their safe perforation [8]. Use of a blunt probe for fenestration of the third ventricle floor has been considered safer for prevention of arterial injury than use of a sharp instrument or application of cautery or coagulation [9]. However, forceful pressure on the third ventricle floor (especially if it is rubbery and not tense) with a blunt instrument may result in a shear injury of adjacent major vascular structures or perforating arteries supplying the brain stem [9]; in such cases, use of a semiblunt surgical instrument for fenestration may be preferable. Finally, it should be noted that similar to our patient reported herein, arterial injury during ETV has previously occurred in other cases of an opaque third ventricle floor and inability to visualize the BA during fenestration [9–13]. In such cases, one should consider gradual coring ("cookie cutting") of the neuronal tissue (tuber cinereum) to expose the thin membrane of the floor, allowing one to see the silhouette of the BA complex [11, 14].

In our case, the BA injury happened not during fenestration of the opaque third ventricle floor but during a subsequent attempt to perforate the thick Liliequist membrane with a bipolar lead without application of electrical energy. It is debatable whether the latter manipulation would have been safer if a softer surgical device (e.g., a Fogarty balloon catheter) had been used. It can also be argued that fenestration of quadrigeminal cistern arachnoid cyst could be done before ETV. Indeed, theoretically, this might relieve the pressure on the brain stem and increase the prepontine cistern and prebasilar space somewhat, providing greater safety during perforation of the third ventricle floor and the Liliequist membrane.

Pseudoaneurysm Formation After Arterial Injury During Endoscopic Third Ventriculostomy

Iatrogenic or traumatic pseudoaneurysms are rare. They represent fewer than 1% of all intracranial aneurysms [15, 16] and occur as a result of direct injury of the arterial wall or damage of it by acceleration-induced shearing [13]. Pathologically, pseudoaneurysms do not have the normal layers of a typical arterial wall and usually do not have a definable neck. In 21% of cases, they demonstrate gradual enlargement, which is usually observed within the first 3 weeks after formation and is associated with a high (roughly 40%) bleeding rate [13].

Pseudoaneurysms resulting from intraoperative injury of the BA complex during ETV have been described previously (Table 1) [9, 12, 13, 17].

In 1997, McLaughlin et al. [12] reported the first such case, caused either by cautery with a potassium titanyl phosphate (KTP) laser used for perforation of the third ventricle floor or by traction during passage of an endoscope through the fenestration. Bleeding was controlled with thorough irrigation, with subsequent insertion of an EVD. Although DSA performed 2 days later showed no vascular abnormality, the patient deteriorated acutely on the 35th postoperative day as a result of subarachnoid hemorrhage (SAH) and a subdural hematoma (SDH) caused by rupture of the BA aneurysm. Urgent removal of the SDH and subsequent clipping of the aneurysm via the subtemporal approach resulted in a turbulent postoperative course, but at 1-year follow-up, the patient had recovered completely [12].

In 1998, Abtin et al. [9] described a similar case of injury of the right P1 segment during attempted fenestration of the third ventricle floor with the tip of an endoscope. DSA on the third postoperative day revealed a right P1 pseudoaneurysm, which was clipped via pterional craniotomy. However, control DSA 1 month later showed recurrence of the aneurysm; thus, trapping of the right P1 was done, which was possible because the right posterior cerebral artery (PCA) had a fetal origin. The patient demonstrated complete recovery at 1-year follow-up [9].

Table 1 Previous reports on the basilar artery pseudoaneurysm formation as a complication of endoscopic third ventriculostomy (ETV)

Report	Age (years)	Sex	Primary diagnosis	Intraoperative findings	ETV location	Fenestration technique	Timing of bleeding	Immediate management	Aneurysm detection	Management of the pseudoaneurysm	Outcome
McLaughlin et al. (1997) [12]	46	Male	Aqueductal stenosis	Opaque third ventricle floor	Just posterior to the infundibular recess	Cautery with a KTP laser	During endoscope passage through the fenestration	Thorough irrigation through the sheath, followed by EVD insertion	Normal DSA on the third postoperative day; acute deterioration due to SAH and an SDH on the 35th postoperative day; surgery for removal of a right-side SDH; DSA on the next day showed a 6-mm basilar apex aneurysm	Clipping of the aneurysm via the subtemporal approach	No deficits at 1-year follow-up
Abtin et al. (1998) [9]	18	Female	Aqueductal stenosis	Opaque and rubbery third ventricle floor with increased elasticity	Midline, anterior to the mammillary bodies, posterior to the infundibular recess	Perforation with an endoscope tip	During attempted fenestration by pressure on the third ventricle floor against the dorsum sellae	Endoscope removal and EVD insertion thorough the sheath, with copious irrigation; subsequent visualization of the blood clot in the third ventricle	DSA on the third postoperative day showed a right P1 segment pseudoaneurysm	Clipping of the aneurysm via pterional craniotomy; DSA at 1 month after surgery showed recurrence of the aneurysm; thus, trapping of P1 was done, since the right PCA had a fetal origin	No deficits at 1-year follow-up
Horowitz et al. (2001) [17]	30	Male	Chiari type 1 malformation with hydrocephalus	Not mentioned	Immediately posterior to the infundibular recess	Cautery with a Bugbee wire	During fenestration	Endoscope removal and EVD insertion through the sheath, with irrigation until cessation of bleeding	DSA on the first postoperative day showed a 6- to 7-mm basilar trunk pseudoaneurysm originating below the SCA, along with fetal origin of the left PCA	Endovascular trapping of the pseudoaneurysm and basilar trunk with detachable coils; collateral blood flow was noted within the right PCA and both SCA from the right ICA; the midbasilar perforating arteries were spared	Left hemiparesis improved within several days; no data on long-term follow-up findings

(continued)

Table 1 (continued)

Report	Age (years)	Sex	Primary diagnosis	Intraoperative findings	ETV location	Fenestration technique	Timing of bleeding	Immediate management	Aneurysm detection	Management of the pseudoaneurysm	Outcome
Rezende et al. (2008) [13]	4	Female	Aqueductal stenosis	Opaque third ventricle floor	Between the mammillary bodies and the infundibular recess	Coagulation with a Bugbee wire	After deflation of a Fogarty balloon, during an attempt to enlarge the fenestration	Endoscope removal and EVD insertion	DSA on the first postoperative day showed a 2-mm upper basilar trunk aneurysm with a well-defined neck, along with spasm of the left P1 segment and distal basilar artery; fetal origin of the right PCA was revealed	Coiling of the aneurysm, resulting in its total occlusion; nimodipine was given before balloon angioplasty to relieve vasospasm	Decrease in pre-existing mental changes at 6-month follow-up
Present case	34	Female	Quadrigeminal cistern arachnoid cyst	Opaque third ventricle floor and thick Liliequist membrane	Posterior to the dorsum sellae	Perforation with a bipolar lead without use of an energy source	During perforation of the Liliequist membrane	Thorough irrigation through the sheath, followed by EVD insertion	DSA on the first postoperative day showed a basilar trunk pseudoaneurysm	Coiling of the aneurysm	Rerupture of the aneurysm 4 weeks later, resulting in death of the patient

DSA Digital subtraction angiography, *EVD* External ventricular drain, *ICA* Internal carotid artery, *KTP* Potassium titanyl phosphate, *PCA* Posterior cerebral artery, *SAH* Subarachnoid hemorrhage, *SCA* Superior cerebellar artery, *SDH* Subdural hematoma

In 2001, Horowitz et al. [17] reported a BA trunk pseudoaneurysm caused by fenestration of the third ventricle floor with Bugbee wire cautery. The patient was treated with endovascular trapping of the aneurysm and part of the BA trunk with detachable coils, while the small midbasilar perforating arteries were spared since the trapping was done distally to their origin. There was good collateral blood flow from the right internal carotid artery to both superior cerebellar arteries and the right PCA [17].

Finally, in 2008, Rezende et al. [13] described a case of BA trunk injury, which occurred during dilatation of a fenestration of the third ventricle floor with a Fogarty balloon. Total endovascular occlusion of the formed aneurysm was done using three soft coils. At 6-month follow-up, this pediatric patient was well [13].

These cases demonstrate that management of a pseudoaneurysm caused by BA/PCA injury during ETV may be effectively achieved by endovascular coiling. However, the main risk of such a procedure is related to the inability of a very weak pseudoaneurysm wall to support the coils permanently. In our patient, coiling of the BA apex pseudoaneurysm was done successfully, sparing all arterial branches. Despite DCI, she demonstrated gradual recovery. However, rebleeding with massive SAH and intraventricular hemorrhage happened 4 weeks after the procedure, seemingly as a result of rupture of the weak pseudoaneurysm wall, which resulted in the fatal outcome.

Other open and endovascular treatment options for management of the pseudoaneurysm in our patient were also considered but deemed unsuitable. Surgical clipping would have been an ideal choice, but this procedure is risky and does not fully prevent recurrence of a pseudoaneurysm [9], with the possibility of rupture. Endovascular trapping has previously been done successfully in cases of P1 and BA trunk pseudoaneurysms with sparing of perforating arteries to the brain stem [9, 17], but such a procedure, especially in cases of BA apex pseudoaneurysms, presumes that the PCA has a fetal origin, which was not the case in our patient.

Conclusion

Major arterial injury during ETV is an infrequently reported cause of perioperative morbidity and mortality. In such cases, possible pseudoaneurysm formation at the injury site may significantly complicate the subsequent clinical course and necessitate definitive treatment for prevention of rupture. While endovascular coiling of a BA/PCA pseudoaneurysm may be quite effective, it does not fully prevent subsequent rebleeding and its grave consequences, as was shown in the case presented herein. The paramount importance of prevention of major arterial injury during the ETV procedure cannot be overemphasized.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Jallo GI, Kothbauer KF, Abbott IR. Endoscopic third ventriculostomy. Neurosurg Focus. 2005;19(6):E11.
2. Bouras T, Sgouros S. Complications of endoscopic third ventriculostomy. J Neurosurg Pediatr. 2011;7:643–9.
3. Bouras T, Sgouros S. Complications of endoscopic third ventriculostomy. World Neurosurg. 2013;79(2 Suppl):S22.e9–12.
4. Kawsar KA, Haque MR, Chowdhury FH. Avoidance and management of perioperative complications of endoscopic third ventriculostomy: the Dhaka experience. J Neurosurg. 2015;123:1414–9.
5. Bouras T, Sgouros S. Complications of endoscopic third ventriculostomy: a systematic review. Acta Neurochir Suppl. 2012;113:149–53.
6. Kulkarni AV, Riva-Cambrin J, Holubkov R, Browd SR, Cochrane DD, Drake JM, Limbrick DD, Rozzelle CJ, Simon TD, Tamber MS, Wellons JC 3rd, Whitehead WE, Kestle JR. Endoscopic third ventriculostomy in children: prospective, multicenter results from the Hydrocephalus Clinical Research Network. J Neurosurg Pediatr. 2016;18:423–9.
7. Schroeder HW, Niendorf WR, Gaab MR. Complications of endoscopic third ventriculostomy. J Neurosurg. 2002;96:1032–40.
8. Fabiano AJ, Leonardo J, Grand W. Posterior cerebral artery P1 segment at the stoma during endoscopic third ventriculostomy in adults. J Neurol Neurosurg Psychiatry. 2010;81:374–8.
9. Abtin K, Thompson BG, Walker ML. Basilar artery perforation as a complication of endoscopic third ventriculostomy. Pediatr Neurosurg. 1998;28:35–41.
10. Grand W, Leonardo J, Chamczuk AJ, Korus AJ. Endoscopic third ventriculostomy in 250 adults with hydrocephalus: patient selection, outcomes, and complications. Neurosurgery. 2016;78:109–19.
11. Iannitelli A, Grande R, Di Stefano A, Di Giulio M, Sozio P, Bessa LJ, Laserra S, Paolini C, Protasi F, Cellini L. Potential antibacterial activity of carvacrol-loaded poly(DL-lactide-*co*-glycolide) (PLGA) nanoparticles against microbial biofilm. Int J Mol Sci. 2011;12:5039–51.
12. McLaughlin MR, Wahlig JB, Kaufmann AM, Albright AL. Traumatic basilar aneurysm after endoscopic third ventriculostomy: case report. Neurosurgery. 1997;41:1400–4.
13. Rezende MT, Spelle L, Piotin M, Mounayer C, Lucas Cde P, Abud DG, Moret J. Selective endovascular treatment of a traumatic basilar aneurysm after endoscopic third ventriculostomy. Neuroradiology. 2008;50:443–6.
14. Grand W, Leonardo J. Endoscopic third ventriculostomy in adults: a technique for dealing with the neural (opaque) floor. J Neurosurg. 2011;114:446–53.
15. Ciceri EF, Regna-Gladin C, Erbetta A, Chiapparini L, Nappini S, Savoiardo M, Di Meco F. Iatrogenic intracranial pseudoaneurysms: neuroradiological and therapeutical considerations, including endovascular options. Neurol Sci. 2006;27:317–22.
16. Yokota H, Tazaki H, Murayama K, Shimura T, Higuchi H, Yajima K, Nakazawa S. Traumatic cerebral aneurysm: 94 cases from the literature and 5 cases observed by the authors [in Japanese]. No Shinkei Geka. 1983;11:521–8.
17. Horowitz M, Albright AL, Jungreis C, Levy EI, Stevenson K. Endovascular management of a basilar artery false aneurysm secondary to endoscopic third ventriculostomy: case report. Neurosurgery. 2001;49:1461–5.

Minimally Invasive Neuroendoscopic Surgery for Spontaneous Intracerebral Hemorrhage: A Review of the Rationale and Associated Complications

Arie Ibrahim, Muhammad Reza Arifianto, and Asra Al Fauzi

Abstract

Spontaneous intracerebral hemorrhage (ICH) is associated with a poor prognosis. Its mortality rate exceeds 40%, and 10–15% of survivors remain fully dependent. Considering the limited number of effective therapeutic options in such cases, the possibilities for surgical interventions aimed at removal of a hematoma should always be borne in mind. Although conventional surgery for deep-seated ICH has failed to show an improvement in outcomes, use of minimally invasive techniques—in particular, neuroendoscopic procedures—may be more effective and has demonstrated promising results. Although there are certain risks of morbidities (including rebleeding, epilepsy, meningitis, infection, pneumonia, and digestive tract disorders) and a nonnegligible risk of mortality, their incidence rates after neuroendoscopic evacuation of ICH compare favorably with those after conventional surgery. Prevention of complications requires careful postoperative surveillance of the patient and, preferably, treatment in a neurointensive care unit, as well as early detection and appropriate management of associated comorbidities.

Keywords

Complication · Endoscopic neurosurgery · Minimally invasive neurosurgery · Spontaneous intracerebral hemorrhage

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Introduction

Spontaneous intracerebral hemorrhage (ICH) accounts for 30–60% of all stroke hospitalizations and is associated with a poor prognosis [1]. Indeed, the mortality rate for this devastating disease exceeds 40%, and 10–15% of survivors remain fully dependent [2]. The incidence of spontaneous ICH has distinctly risen by 18% over the past decade, partly because of the increased life expectancy in the general population [3, 4]. Primary spontaneous ICH accounts for 80–85% of all ICH cases and most commonly results from degenerative changes of the cerebral vasculature caused by arterial hypertension and/or cerebral amyloid angiopathy [5, 6], use of anticoagulant therapy (in particular, an international normalized ratio [INR] >3.5 is recognized as a potential risk factor for ICH [7]), and prior ictus.

Pathogenesis of Spontaneous Intracerebral Hemorrhage and Associated Complications

The pathogenesis of spontaneous ICH includes three dynamic phases: (1) initial hemorrhage, (2) hematoma expansion, and (3) development of perihematomal edema (PHE) of the brain tissue [8]. In the first phase, lasting around 24 h, there is immediate cellular injury in the hemorrhage core as a result of acute bleeding and early enlargement of the hematoma. The second phase is characterized by further expansion of the hematoma volume (the rate of which may be variable) and progressive alteration of the adjacent brain tissue, caused by various interrelated pathophysiological processes, such as the mass effect and excitotoxicity, and increasing neurotoxicity caused by blood breakdown products, thrombin, free radical formation, protease activation and inflammation, iron deposition, and local hyperglycolysis [9–14]. The cascade of these events leads to secondary brain damage with development of PHE, the growth of which may continue for up to 2 weeks after the onset of spontaneous ICH [11, 13, 15].

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_13

The damaging effect of PHE is related to two main mechanisms. First, it results in an increase in the brain shift and development of brain herniation, a recognizable factor directly influencing mortality, particularly in patients with a large ICH [16, 17]. Second, PHE augments the affected brain injury through alteration of the blood–brain barrier, hypoperfusion, and induction of inflammatory and proapoptotic pathways, further augmenting excitotoxicity (particularly as a result of glutamate release) and neurotoxicity, and leading to neuronal damage and death [18, 19].

Complications

The outcome in patients with spontaneous ICH depends on multiple factors, including the initial hemorrhage location and volume, expansion of the hematoma and its final volume, and development and growth of PHE, as well as associated neurological and systemic complications [8, 20]. The latter may be divided into primary ones, which are hardly predictable (e.g., rebleeding, hematoma expansion, development and growth of PHE, and gastrointestinal tract bleeding), and secondary ones, which may be predicted and prevented (e.g., increased intracranial pressure [ICP] caused by the mass effect of ICH and PHE, hydrocephalus due to intraventricular extension of the hemorrhage, seizures, deep venous thrombosis, hyperglycemia, arterial hypertension, fever, and infections) [1]. The most common unpredictable event is early rebleeding, which occurs in 10–14% of patients [1, 15, 20–26]. Of note, the risks of those complications that may be preventable decrease with time.

Almost one-third of patients with ICH develop pulmonary complications, mostly pneumonia (which occurs in 20% of cases) and pulmonary edema (which occurs in 8% of cases) [27]. The latter is particularly caused by the effects of stroke-related central sympathetic activation on systemic and pulmonary vascular resistance and vessel capacitance. Pulmonary complications in patients with spontaneous ICH increase mortality, morbidity, the duration of hospitalization, and overall treatment costs; therefore, they require aggressive management and active preventive measures. In particular, in patients with a Glasgow Coma Scale (GCS) score <8 at admission, endotracheal intubation is usually performed, which can reduce the risks of aspiration and related pneumonia (although these complications are also frequently noted in patients with a GCS score of 8–14 [27]).

Minimally Invasive Neurosurgical Management of Spontaneous Intracerebral Hemorrhage

Early attempts at surgical removal of spontaneous ICH, using simple aspiration or other methods for mechanical clot evacuation, frequently failed to accomplish satisfactory reduction of the hematoma volume. In 1998, in a prospective randomized controlled trial (RCT) evaluating surgical treatment for intracerebral hemorrhage (STICH), Morgenstern et al. [28] revealed a trend toward improved outcomes in patients with a lobar hematoma but not in those affected by a deep-seated one. Worse results in the latter cases might have been related to more profound intraoperative damage of the brain. Indeed, during conventional removal of ICH through craniotomy, effective visualization of the entire hematoma cavity frequently requires significant retraction and inadvertent compression of the viable neuronal tissue, augmenting its injury.

In contrast, minimally invasive interventions drastically reduce manipulation of the affected brain and allow prevention of additional damage during the approach to and evacuation of the hematoma, especially if it is located in a deep-seated area (e.g., in the putamen or thalamus). Furthermore, use of these procedures has been facilitated by advances in intraoperative neuronavigation, which effectively allows one to plan a surgical trajectory through noneloquent brain regions [29, 30]. Another advantage of minimally invasive surgeries is that they take significantly less time, which may be highly important in cases of large space-occupying hematomas accompanied by increased ICP and brain herniation [28, 31].

The effectiveness of minimally invasive neurosurgical management of spontaneous ICH, using various techniques, has been tested in multiple studies [1, 4, 5, 10, 15, 25, 26, 32–36]. In addition, to provide more effective evacuation of the hematoma, local use of thrombolytic agents has been also applied [26, 33, 34, 36–38]. In particular, Zhou et al. [36] introduced the concept of minimally invasive stereotactic puncture and thrombolytic therapy (MISPT). Several studies have tested this strategy in the acute phase of spontaneous ICH, but its impacts on the short- and long-term neurological and functional outcomes of survivors still remain uncertain [36, 38]. Similarly, other researchers have reported promising results of a treatment strategy based on a combination of minimally invasive surgery and administration of recombinant tissue-type plasminogen activator (rt-PA) for intracerebral hemorrhage evacuation (MISTIE), which entails stereotactic infusion of the fibrinolytic agent into the hematoma cavity, with subsequent active evacuation of the lysed and liquefied blood clot [37] or closed-system drainage of it [34].

Overall, the currently available data suggest that indications for surgical intervention in cases of spontaneous ICH and choice of the most appropriate operative strategy and technique should take into account multiple parameters—including the hematoma location (superficial versus deep-seated) and volume, the age of the patient, and the presence of comorbidities—as well as estimating the expected neurological outcome on the basis of several prognostic and predictive factors, including the characteristics of the hematoma

(particularly its location) and the general and neurological status of the patient.

Role of Neuroendoscopy in Management of Spontaneous Intracerebral Hemorrhage

About two centuries ago, a German doctor, Philipp Bozzini, introduced endoscopy, a method using a dedicated device to visualize internal organs. This technique steadily gained widespread acceptance in the field of medicine, especially in surgical disciplines. Neuroendoscopy started to develop at the beginning of the twentieth century, when Victor D. Lespinasse applied this tool, for the first time, in children with hydrocephalus. Later on, Walter E. Dandy introduced third ventriculostomy, making a hole in the third ventricle floor for bypass of blocked cerebrospinal fluid (CSF) into the basal subarachnoid cisterns. However, use of endoscopy in neurosurgery developed slowly, mainly because of the insufficient quality of the available devices. It was only in the 1970s that advances in technology resulted in increasing interest in application of this technique in clinical practice [38]. At present, this tool is applied routinely for variable indications, allowing several surgical options that are not possible with a conventional technique (e.g., visual observation and manipulation of structures obscured from direct view through an operating microscope). The perfect optical quality and small size of modern endoscopes, both rigid and flexible ones, have made their application highly effective and safe.

In particular, neuroendoscopy is frequently utilized for minimally invasive removal of spontaneous ICH. The interest in such treatment has increased since the late 1980s, when Auer et al. [32] published the results of their RCT and demonstrated that in comparison with medically treated patients, those who underwent endoscopic evacuation of spontaneous ICH had significantly better functional recovery (in cases of relatively small hematomas) and significantly lower mortality (in cases of large hematomas). Promising results of such treatment and its superiority to conservative therapy and surgical management using craniotomy have since been further demonstrated [1, 15, 33, 39]. In particular, Cai et al. [33] retrospectively compared three surgical techniques for treatment of spontaneous supratentorial ICH—namely, conventional craniotomy, burr hole catheter drainage after urokinase infusion, and endoscopic evacuation—and considered the latter option most promising because of its minimal invasiveness, direct visualization of the operative field, effective hematoma removal, and relatively good results. In our own series, the rate of evacuation of spontaneous ICH using a rigid endoscope with a transparent sheath was around 80% [1]. In addition, endoscopic techniques allow effective manipulations using long surgical trajectories, which may significantly facilitate management of deep-seated hematomas. It is noticeable that the vast majority of the relevant studies have originated from Asian countries, which may reflect higher incidence rates of this disease in their populations, caused by specific predisposing and pathophysiological factors [40, 41].

Complications of Neuroendoscopic Surgery for Spontaneous Intracerebral Hemorrhage

The most devastating complication of neuroendoscopic surgery, as well as other interventions for removal of spontaneous ICH, is rebleeding. It is reportedly encountered in up to 20% of cases [10, 15, 25, 33, 42, 43]—a rate comparable to those associated with other minimally invasive procedures, such as stereotactic puncture with local use of urokinase (Table 1). Rebleeding is usually observed during the first 24 h after the initial intervention and is mainly caused by oozing of blood from the walls of the hematoma cavity. It may develop even if there is no evident bleeding point at the end of surgery. To overcome recognizable problems encountered when hemostasis is being secured during neuroendoscopic procedures for removal of spontaneous ICH, a variety of surgical maneuvers are performed in our practice, including simultaneous irrigation–coagulation using a rigid suction tube, filling of the hematoma cavity with fibrin sealant, and a control Valsalva maneuver at the end of the intervention [1]. Still, postoperative rebleeding was noted in 1% of patients in our previously published series and caused the death of one of them [1].

Other common complications after neuroendoscopic removal of spontaneous ICH include epilepsy (in 8% of cases), meningitis (in 2% of cases), infection (in 15% of cases), pneumonia (in 5–11% of cases), and digestive tract disorders (in 12% of cases) [1, 33, 43]. Their prevention requires careful postoperative surveillance of the patient, preferably with treatment in a neurointensive care unit, although this may be difficult to achieve in some small rural hospitals [1, 35, 36, 38, 44]. Early detection and appropriate management of associated comorbidities may also be effective for avoidance of complications.

The postoperative mortality rate after neuroendoscopic removal of spontaneous ICH is not negligible (36.8% in our series) and is profoundly influenced by the criteria applied during surgical candidate selection. According to some reports, pulmonary infection is the most frequent cause of death [1, 36]. Nevertheless, both morbidity rates and mortality rates after neuroendoscopic treatment of spontaneous ICH compare favorably with those associated with conventional surgery for hematoma evacuation using craniotomy [15].

Table 1 Reported rates of postoperative complications in selected series of minimally invasive surgical procedures for evacuation of spontaneous intracerebral hematomas

Study	Number of cases	Study design	Diagnostic modality	Treatment method	Postoperative complication (%)				Outcome
					Rebleeding	Pulmonary infection	Upper gastrointestinal bleeding	Epilepsy	
Nishihara et al., 2007 [25]	27	Prospective/ retrospective	CT	Endoscopic procedure with use of a transparent sheath	5	ND	ND	ND	At 6-month follow-up, 33% of patients in the endoscopy group had a GOS score of 5
Miller et al., 2007 [10]	12	Prospective RCT	CT, frameless neuronavigation	Endoscopic procedure with use of a transparent sheath	20	ND	ND	ND	Mean 72-h NIHSS score 12.6
Umebayashi et al., 2010 [26]	70	Retrospective	CT	Stereotactic aspiration/ urokinase	7.1	27.1	ND	ND	Statistically significant improvement in the JCS score ($P < 0.01$)
Zhou et al., 2011 [36]	168	Prospective RCT	CT	Minimally invasive stereotactic puncture	10	8.9	17.8	5.6	18.9% case fatality rate at 1 year
Nagasaka et al., 2011 [15]	43	Prospective/ retrospective	CT	Endoscopic procedure with use of a transparent sheath	0	ND	ND	ND	4% mortality rate (1 out of 23 patients) in the endoscopy group
Ibrahim, 2016 [1]	43	Prospective RCT	CT	Endoscopic procedure with use of a transparent sheath	1	7	ND	ND	36.8% mortality rate
Cai et al., 2017 [33]	63	Retrospective	CT	Endoscopic procedure with use of a transparent sheath	0	5	ND	ND	5% mortality rate
				Burr hole/urokinase	18.2	9.1	ND	ND	13.6% mortality rate

CT computed tomography, *GOS* Glasgow Outcome Scale, *JCS* Japan Coma Scale, *NIHSS* National Institutes of Health Stroke Scale, *ND* no data, *RCT* randomized controlled trial

Conclusion

Considering the limited number of effective therapeutic options in patients with spontaneous ICH, the possibilities for surgical interventions aimed at removal of a hematoma should be always borne in mind. For such a purpose, especially in cases of deep-seated ICH, minimally invasive neuroendoscopic procedures seems to be an optional technique. While they are associated with nonnegligible postoperative morbidity and mortality, the superiority of neuroendoscopic interventions to conservative therapy and conventional surgical management using craniotomy has been demonstrated. Nevertheless, the majority of the relevant studies have been retrospective, involved relatively small numbers of cases, and had too limited postoperative follow-up for appropriate evaluation of outcomes—in particular, the functional recovery of the patients. Additional large-scale prospective RCT are needed to validate the role of neuroendoscopic surgery in management of spontaneous ICH and to assess the exact incidence rates of associated perioperative complications, along with their impacts on the overall results of such treatment.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Ibrahim A. Comparison between modified neuroendoscopy and craniotomy evacuation of spontaneous intra-cerebral hemorrhages: study of clinical outcome and Glasgow Outcome Score. Bali Med J. 2016;5(1):77–81.
2. Dennis MS. Outcome after brain haemorrhage. Cerebrovasc Dis. 2003;16(Suppl 1):9–13.
3. Feigin VL, Lawes CM, Bennett DA, Anderson CS. Stroke epidemiology: a review of population-based studies of incidence, prevalence, and case-fatality in the late 20th century. Lancet Neurol. 2003;2:43–53.
4. Qureshi AI, Suri MF, Nasar A, Kirmani JF, Ezzeddine MA, Divani AA, Giles WH. Changes in cost and outcome among US patients with stroke hospitalized in 1990 to 1991 and those hospitalized in 2000 to 2001. Stroke. 2007;38:2180–4.
5. Qureshi AI, Tuhrim S, Broderick JP, Batjer HH, Hondo H, Hanley DF. Spontaneous intracerebral hemorrhage. N Engl J Med. 2001;344:1450–60.
6. Woo D, Sauerbeck LR, Kissela BM, Khoury JC, Szaflarski JP, Gebel J, Shukla R, Pancioli AM, Jauch EC, Menon AG, Deka R, Carrozzella JA, Moomaw CJ, Fontaine RN, Broderick JP. Genetic and environmental risk factors for intracerebral hemorrhage: preliminary results of a population-based study. Stroke. 2002;33:1190–5.
7. Fang MC, Chang Y, Hylek EM, Rosand J, Greenberg SM, Go AS, Singer DE. Advanced age, anticoagulation intensity, and risk for intracranial hemorrhage among patients taking warfarin for atrial fibrillation. Ann Intern Med. 2004;141:745–52.
8. Brott T, Broderick J, Kothari R, Barsan W, Tomsick T, Sauerbeck L, Spilker J, Duldner J, Khoury J. Early hemorrhage growth in patients with intracerebral hemorrhage. Stroke. 1997;28:1–5.
9. Gebel JM Jr, Jauch EC, Brott TG, Khoury J, Sauerbeck L, Salisbury S, Spilker J, Tomsick TA, Duldner J, Broderick JP. Natural history of perihematomal edema in patients with hyperacute spontaneous intracerebral hemorrhage. Stroke. 2002;33:2631–5.
10. Miller CM, Vespa PM, McArthur DL, Hirt D, Etchepare M. Frameless stereotactic aspiration and thrombolysis of deep intracerebral hemorrhage is associated with reduced levels of extracellular cerebral glutamate and unchanged lactate pyruvate ratios. Neurocrit Care. 2007;6:22–9.
11. Qureshi AI, Mendelow AD, Hanley DF. Intracerebral haemorrhage. Lancet. 2009;373:1632–44.
12. Wu J, Hua Y, Keep RF, Nakamura T, Hoff JT, Xi G. Iron and iron-handling proteins in the brain after intracerebral hemorrhage. Stroke. 2003;34:2964–9.
13. Xi G, Keep RF, Hoff JT. Mechanisms of brain injury after intracerebral haemorrhage. Lancet Neurol. 2006;5:53–63.
14. Zazulia AR, Videen TO, Powers WJ. Transient focal increase in perihematomal glucose metabolism after acute human intracerebral hemorrhage. Stroke. 2009;40:1638–43.
15. Nagasaka T, Tsugeno M, Ikeda H, Okamoto T, Inao S, Wakabayashi T. Early recovery and better evacuation rate in neuroendoscopic surgery for spontaneous intracerebral hemorrhage using a multifunctional cannula: preliminary study in comparison with craniotomy. J Stroke Cerebrovasc Dis. 2011;20:208–13.
16. Staykov D, Wagner I, Volbers B, Hauer EM, Doerfler A, Schwab S, Bardutzky J. Natural course of perihemorrhagic edema after intracerebral hemorrhage. Stroke. 2011;42:2625–9.
17. Zazulia AR, Diringer MN, Derdeyn CP, Powers WJ. Progression of mass effect after intracerebral hemorrhage. Stroke. 1999;30:1167–73.
18. McCourt R, Gould B, Gioia L, Kate M, Coutts SB, Dowlatshahi D, Asdaghi N, Jeerakathil T, Hill MD, Demchuk AM, Buck B, Emery D, Butcher K. Cerebral perfusion and blood pressure do not affect perihematoma edema growth in acute intracerebral hemorrhage. Stroke. 2014;45:1292–8.
19. Zazulia AR, Diringer MN, Videen TO, Adams RE, Yundt K, Aiyagari V, Grubb RL Jr, Powers WJ. Hypoperfusion without ischemia surrounding acute intracerebral hemorrhage. J Cereb Blood Flow Metab. 2001;21:804–10.
20. Kazui S, Naritomi H, Yamamoto H, Sawada T, Yamaguchi T. Enlargement of spontaneous intracerebral hemorrhage. Incidence and time course. Stroke. 1996;27:1783–7.
21. Broderick JP, Brott TG, Tomsick T, Barsan W, Spilker J. Ultra-early evaluation of intracerebral hemorrhage. J Neurosurg. 1990;72:195–9.
22. Fujii Y, Tanaka R, Takeuchi S, Koike T, Minakawa T, Sasaki O. Hematoma enlargement in spontaneous intracerebral hemorrhage. J Neurosurg. 1994;80:51–7.
23. Fujitsu K, Muramoto M, Ikeda Y, Inada Y, Kim I, Kuwabara T. Indications for surgical treatment of putaminal hemorrhage. Comparative study based on serial CT and time-course analysis. J Neurosurg. 1990;73:518–25.
24. Niizuma H, Suzuki J, Yonemitsu T, Otsuki T. Spontaneous intracerebral hemorrhage and liver dysfunction. Stroke. 1988;19:852–6.
25. Nishihara T, Morita A, Teraoka A, Kirino T. Endoscopy-guided removal of spontaneous intracerebral hemorrhage: comparison with computer tomography–guided stereotactic evacuation. Childs Nerv Syst. 2007;23:677–83.
26. Umebayashi D, Mandai A, Osaka Y, Nakahara Y, Tenjin H. Effects and complications of stereotactic aspiration for spontaneous intracerebral hemorrhage. Neurol Med Chir (Tokyo). 2010;50:538–44.
27. Maramattom BV, Weigand S, Reinalda M, Wijdicks EF, Manno EM. Pulmonary complications after intracerebral hemorrhage. Neurocrit Care. 2006;5:115–9.
28. Morgenstern LB, Frankowski RF, Shedden P, Pasteur W, Grotta JC. Surgical treatment for intracerebral hemorrhage (STICH): a single-center, randomized clinical trial. Neurology. 1998;51:1359–63.

29. Kwon WK, Park DH, Park KJ, Kang SH, Lee JH, Cho TH, Chung YG. Prognostic factors of clinical outcome after neuronavigation-assisted hematoma drainage in patients with spontaneous intracerebral hemorrhage. Clin Neurol Neurosurg. 2014;123:83–9.
30. Upadhyay UM, Golby AJ. Role of pre- and intraoperative imaging and neuronavigation in neurosurgery. Expert Rev Med Devices. 2008;5:65–73.
31. Morgenstern LB, Hemphill JC 3rd, Anderson C, Becker K, Broderick JP, Connolly ES Jr, Greenberg SM, Huang JN, MacDonald RL, Messé SR, Mitchell PH, Selim M, Tamargo RJ. Guidelines for the management of spontaneous intracerebral hemorrhage: a guideline for healthcare professionals from the American Heart Association/American Stroke Association. Stroke. 2010;41:2108–29.
32. Auer LM, Deinsberger W, Niederkorn K, Gell G, Kleinert R, Schneider G, Holzer P, Bone G, Mokry M, Körner E, Kleinert G, Hanusch S. Endoscopic surgery versus medical treatment for spontaneous intracerebral hematoma: a randomized study. J Neurosurg. 1989;70:530–5.
33. Cai Q, Zhang H, Zhao D, Yang Z, Hu K, Wang L, Zhang W, Chen Z, Chen Q. Analysis of three surgical treatments for spontaneous supratentorial intracerebral hemorrhage. Medicine (Baltimore). 2017;96(43):e8435.
34. Schaller C, Rohde V, Meyer B, Hassler W. Stereotactic puncture and lysis of spontaneous intracerebral hemorrhage using recombinant tissue-plasminogen activator. Neurosurgery. 1995;36:328–35.
35. Vespa PM, Martin N, Zuccarello M, Awad I, Hanley DF. Surgical trials in intracerebral hemorrhage. Stroke. 2013;44(6 Suppl 1):S79–82.
36. Zhou H, Zhang Y, Liu L, Han X, Tao Y, Tang Y, Hua W, Xue J, Dong Q. A prospective controlled study: minimally invasive stereotactic puncture therapy versus conventional craniotomy in the treatment of acute intracerebral hemorrhage. BMC Neurol. 2011;11:76.
37. Mould WA, Carhuapoma JR, Muschelli J, Lane K, Morgan TC, McBee NA, Bistran-Hall AJ, Ullman NL, Vespa P, Martin NA, Awad I, Zuccarello M, Hanley DF. Minimally invasive surgery plus recombinant tissue-type plasminogen activator for intracerebral hemorrhage evacuation decreases perihematomal edema. Stroke. 2013;44:627–34.
38. Samadani U, Rohde V. A review of stereotaxy and lysis for intracranial hemorrhage. Neurosurg Rev. 2009;32:15–22.
39. Prasad K, Browman G, Srivastava A, Menon G. Surgery in primary supratentorial intracerebral hematoma: a meta-analysis of randomized trials. Acta Neurol Scand. 1997;95:103–10.
40. Klatsky AL, Friedman GD, Sidney S, Kipp H, Kubo A, Armstrong MA. Risk of hemorrhagic stroke in Asian American ethnic groups. Neuroepidemiology. 2005;25:26–31.
41. Steiner T, Bösel J. Options to restrict hematoma expansion after spontaneous intracerebral hemorrhage. Stroke. 2010;41:402–9.
42. Gebel JM, Broderick JP. Intracerebral hemorrhage. Neurol Clin. 2000;18:419–38.
43. Yao Z, Hu X, You C, He M. Effect and feasibility of endoscopic surgery in spontaneous intracerebral hemorrhage: a systematic review and meta-analysis. World Neurosurg. 2018;113:348–356.e2.
44. Balami JS, Buchan AM. Complications of intracerebral haemorrhage. Lancet Neurol. 2012;11:101–18.

Avoidance of Pitfalls and Complications During Surgery for Temporal Lobe Epilepsy

Arimappamagan Arivazhagan, Sanjib Sinha, and Malla Bhaskara Rao

Abstract

Anterior temporal lobectomy with amygdalohippocampectomy is the most common epilepsy surgery, which, in cases of mesial temporal lobe epilepsy caused by mesial temporal sclerosis, usually leads to improvements in seizure control, cognitive function, and quality of life. Nevertheless, while the primary goal of intervention is achieved in a large majority of patients, a small number of them, unfortunately, encounter complications. Some morbidity is nonspecific and may be noted after any craniotomy (e.g., surgical site infections, meningitis, bone flap osteomyelitis, and operative site or craniotomy-related hematomas). On the other hand, certain complications are specifically associated with surgery for temporal lobe epilepsy and can be discussed from the etiological standpoint: mechanical injuries of the brain; injury of eloquent neuronal structures; arterial and venous injuries; cerebral venous thrombosis; remote cerebellar hemorrhage; and postoperative hydrocephalus, seizures, and psychiatric disorders. In many cases, these complications are manifested in the early postoperative period by alterations of consciousness and a focal neurological deficit, and it may require immediate decisions on their appropriate management.

Keywords

Amygdalohippocampectomy · Anterior temporal lobectomy · Complication · Epilepsy surgery · Mesial temporal sclerosis · Temporal lobe epilepsy · Vascular injury

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Introduction

Mesial temporal lobe epilepsy (MTLE) caused by mesial temporal sclerosis (MTS) is the most common cause of surgically remediable chronic drug-resistant seizures. Anterior temporal lobectomy (ATL) with amygdalohippocampectomy is the most common surgical procedure for epilepsy, which, in cases of MTLE with MTS, usually leads to definite improvements in seizure control, cognitive function, and quality of life. Suitable candidates for ATL can be identified with standardized noninvasive investigational protocols, which typically include video electroencephalography (EEG), computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and, occasionally, magnetoencephalography (MEG). The clinical outcomes after such diagnostic examinations and subsequent surgical treatment are clearly cost effective.

Nevertheless, while the goal of surgery—that is, cure or control of chronic drug-resistant epilepsy—is achieved in a large majority of patients, a small number of them, unfortunately, encounter complications. Strategies for recognition of the possible pitfalls during surgery for MTLE, prevention of various morbidities, and accomplishment of their appropriate management are discussed herein, using descriptions of clinical cases from the experience of the senior author.

Spectrum of Complications

The entire spectrum of epilepsy surgery complications has been generally classified into two main categories: (1) neurological and (2) nonneurological/surgical. The former mostly depend on the pre-existing functional deficit and the extent and location of the resection area, and they are governed largely by the hemispheric dominance, the proximity of the operative field to the eloquent cortex and critical white matter tracts, and variations in the vascular anatomy. On the

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_14

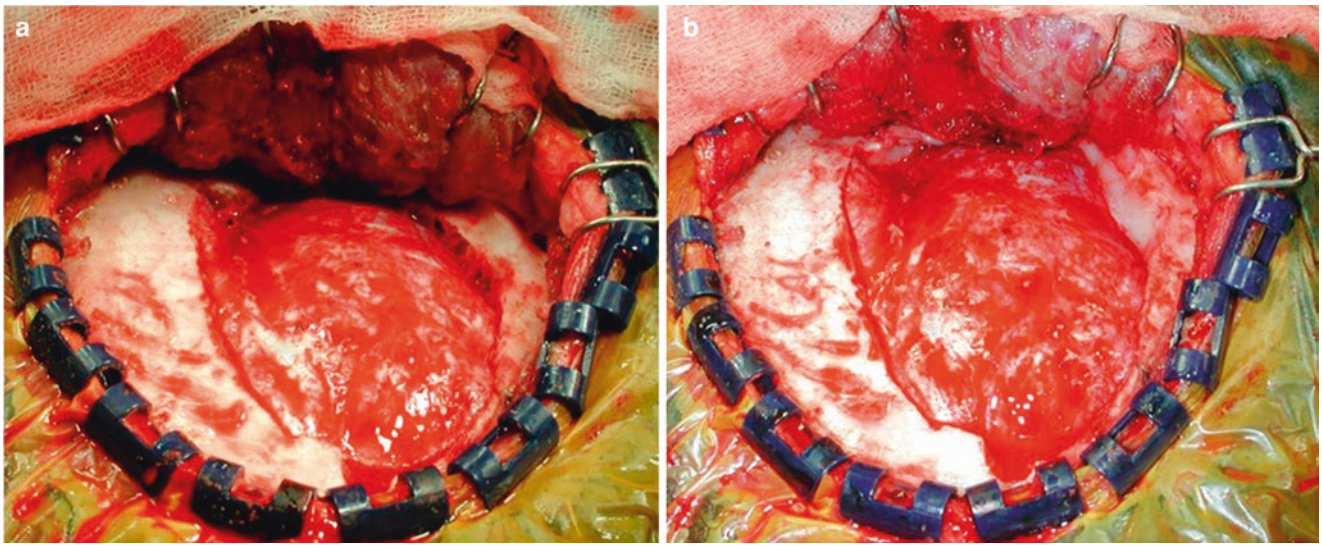

Fig. 1 Intraoperative photography shows mastoid air cells that have been opened following right-side temporal craniotomy (**a**) and properly sealed (**b**) using bone wax to prevent cerebrospinal fluid leakage

other hand, there is always a possibility of nonspecific surgical morbidity.

Correspondingly, ATL with amygdalohippocampectomy may result in complications associated with craniotomy in general (e.g., surgical site infections, meningitis, bone flap osteomyelitis, and operative site or craniotomy-related hematomas). In addition, there are certain challenges and morbidities specifically associated with this surgical procedure, which can be discussed from the etiological standpoint: mechanical injuries of the brain; injury of eloquent neuronal structures; arterial and venous injuries; cerebral venous thrombosis; remote cerebellar hemorrhage; and postoperative hydrocephalus, seizures, and psychiatric disorders. In many cases, these complications are manifested in the early postoperative period by alterations of consciousness and a focal neurological deficit. Finally, surgical treatment failures may be related to false localization or incomplete resection of the epileptogenic focus or lesion, which may happen, in particular, during the learning curve of a comprehensive epilepsy management team.

General Technical Issues

It should be noted that in patients suffering from MTLE with MTS, hippocampal atrophy may be associated with atrophy of the entire temporal lobe. As a result of such chronic changes, bone and mastoid air cells, in particular, can be hypertrophied. Occasional opening of these hypertrophied mastoid air cells during craniotomy is not a problem as long as it is recognized and they are properly sealed at the end of the procedure (Fig. 1) to avoid cerebrospinal fluid (CSF) leakage and meningitis, which can complicate an otherwise good surgical outcome.

ATL includes resection of the neocortex, extending for up to 3.5–4.0 cm on the dominant side and 4.0–4.5 cm on the nondominant side along the Sylvian fissure. Lateral neocortical resection, especially of the superior temporal gyrus (STG), may have to be limited in certain cases, depending on the hemispheric dominance and cortical eloquence, the location of the middle cerebral artery (MCA) branches, and the pattern of venous drainage (Fig. 2). Of note, the vein of Labbé is an inconstant structure and, when it is present, it indicates nothing more than posterior drainage of the Sylvian venous system.

The amygdala and the hippocampus are always removed via the transventricular approach. At this stage, use of an operating microscope is mandatory. Opening of the temporal horn of the lateral ventricle exposes the *pes hippocampi*. *En bloc* resection is limited to the anterior two-thirds of the hippocampus and the lateral two-thirds of the amygdala, along with the uncus and the parahippocampal gyrus, utilizing subpial dissection. The medial part of the amygdala is not removed, as it abuts the striatum, the anterior commissure, and the tail of the caudate nucleus. The hippocampal sulcus contains the Ammon's horn artery (the fundamental landmark for a subependymal, subpial resec-

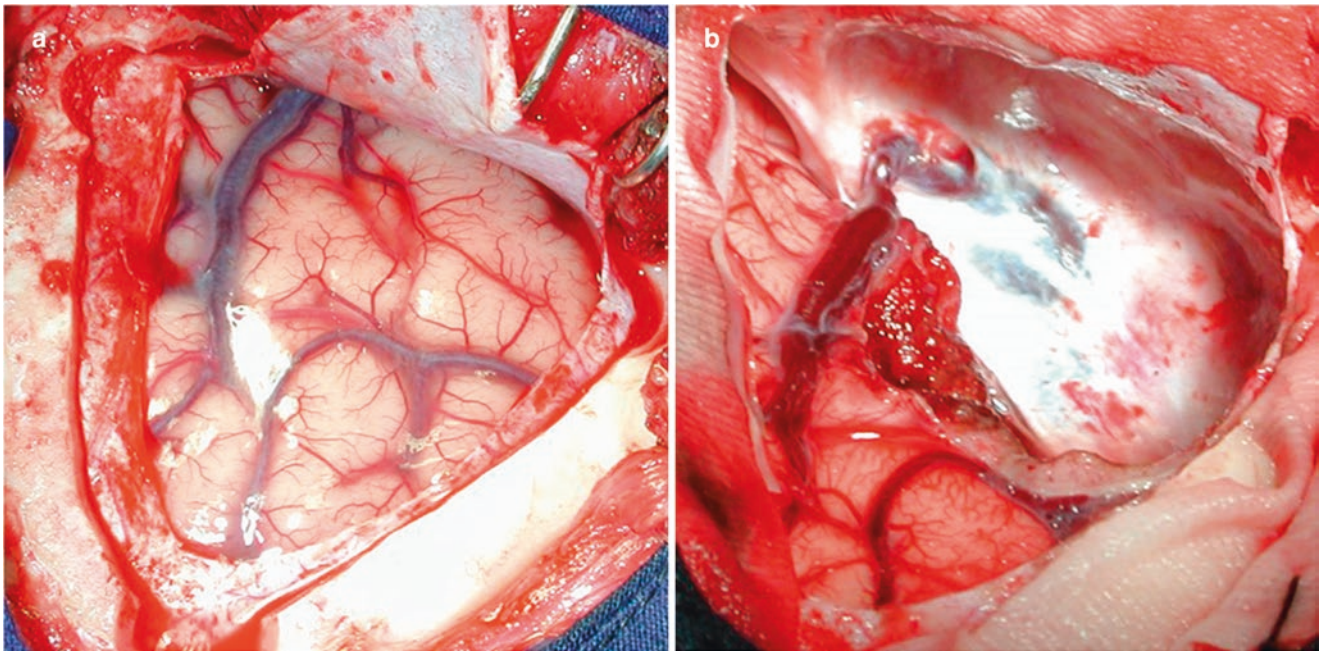

Fig. 2 Intraoperative photography shows a large vein traversing the temporal lobe (**a**), which was preserved during temporal lobectomy (**b**)

tion of the hippocampus). Of note, subpial resection minimizes manipulations of the anterior choroidal artery (AChA) and branches arising from the posterior cerebral artery (PCA), which reduces the risks of vascular injury resulting from occasional division and coagulation of these vessels.

Mechanical Injuries of the Brain

Mechanical injury of the brain during ATL is uncommon. The temporal craniotomy must be located anteriorly to avoid excessive retraction of the temporal lobe, which may lead to a neurological deficit. Retraction of the posterior temporal lobe must be done gently and, preferably, along the long axis of the hippocampus; undue retraction can cause brain edema and/or venous injury, and it may result in a postoperative language deficit if the surgery is performed on the dominant side. Similarly, during hippocampectomy, retraction of the roof of the temporal horn needs to be done carefully, because excessive pressure can cause postoperative hemiparesis. Preferably, the choroid plexus should not be taken under a spatula, since inappropriate traction of it can cause avulsion of arteries in the choroidal fissure. The entire dissection in the medial temporal lobe should be confined to structures below the choroidal fissure. Accidental dissection above the choroidal fissure through the roof of the ventricle can extend to the internal capsule, resulting in permanent hemiparesis or hemiplegia.

Illustrative Case 1: Postoperative Hemiplegia

A 31-year-old man presented with a history of focal seizures, which had started when he was 15 years of age. The clinical semiology consisted of perioral automatism, an aura of seeing stars, and tonic posturing of the left hand, followed by right-side hemifacial twitching with deviation of the angle of the mouth toward the right side, and with subsequent tonic posturing of the right upper limb and then of the right lower limb, and, finally, loss of consciousness. The frequency of the seizures was one per month. He received valproate (valproic acid; 1500 mg per day), levetiracetam (1000 mg per day), and carbamazepine (800 mg per day). Video-EEG revealed that the seizures originated from the right temporal region. The results of brain MRI were suggestive of right-side MTS (Fig. 3a), and PET-MRI showed hypometabolism in the right temporal area. The results of MEG were inconclusive. The patient underwent right-side temporal craniotomy and ATL with amygdalohippocampectomy. During the surgery, inadvertent injury of the right basal ganglia and thalamus occurred (probably because of excessive retraction), which resulted in left-side hemiplegia. Postoperative

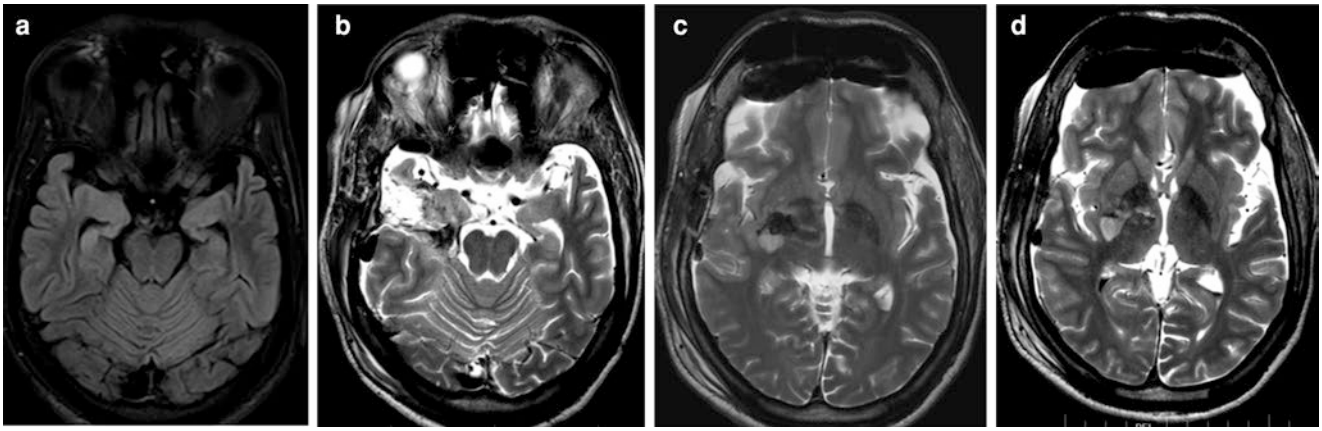

Fig. 3 In a 31-year-old man with a long history of focal seizures, preoperative magnetic resonance imaging (MRI) showed atrophy of the right hippocampus with signal changes suggestive of mesial temporal sclerosis (**a**). Anterior temporal lobectomy with amygdalohippocampectomy was done, but left-side hemiplegia was noted immediately after the surgery. Postoperative MRI (**b**–**d**) demonstrated the results of the temporal lobectomy, along with signal changes in the right basal ganglia, extending into the posterior limb of the internal capsule, suggestive of a hematoma

CT and MRI demonstrated a hematoma in the region of the right internal capsule (Fig. 3b–d). After >3 months of subsequent rehabilitation, his motor function had improved, with the power in the left upper and lower limbs being 2/5 and 4/5, respectively.

Injury of Eloquent Neuronal Structures

When surgery in an eloquent brain region is planned, utilization of specific pre- and intraoperative brain mapping techniques is required for avoidance of injury of the functionally important cortex and white matter tracts.

Illustrative Case 2: Postoperative Naming Difficulty

A 37-year-old man presented with a history of drug-resistant seizures, which had started when he was 14 years of age. The clinical semiology consisted of bilateral ear fullness, *déjà vu* phenomena, motor freezing, and loss of awareness, followed by loss of tone in antigravity muscles and falls. Brain MRI demonstrated a well-defined heterogeneous lesion with perifocal edema, located in the left STG with extension into the posterior part of Sylvian fissure (Fig. 4a–c); the solid component of the lesion demonstrated restricted diffusion. Since the lesion was located in proximity to the temporal language area, the patient underwent functional MRI and received extensive counseling regarding the possibility of a postoperative neurological deficit. Awake surgery was done, involving left-side temporal craniotomy and extended lesionectomy (Fig. 4d) under the control of electrocorticography (ECoG) and direct cortical mapping with electrical stimulation. Nevertheless, postoperatively, he developed a naming difficulty, which partially resolved with speech therapy.

Visual Field Defects

A visual field defect is one of the most common deficits that can appear following ATL. Sometimes, the occurrence of superior quadrantanopia is even considered not as a complication but as an expected consequence of the procedure. Rather often, this side effect is not consistently evaluated during postoperative follow-up; thus, its reported incidence in different series has been rather variable. Superior quadrantanopia has been noted in 4.3–25% of patients but mostly has not led to subjective complaints [1–5]. In contrast, symptomatic hemianopia has been revealed less frequently (occurring in 1.2–1.3% of cases [5, 6]); in particular, in a prospective population-based study performed by Bjellvi et al. [6] the incidence of this complication after ATL with hippocampectomy was 1.2%. For avoidance of injury to Meyer's loop, use of basal approaches has been suggested, but their application requires sufficient expertise and experience. Tractography based on diffusion tensor imaging may depict Meyer's loop and facilitate preoperative planning of the surgical approach. Thudium et al. [3] applied such a technique in their series but still encountered incomplete superior quadrantanopia after surgery in 25% of patients.

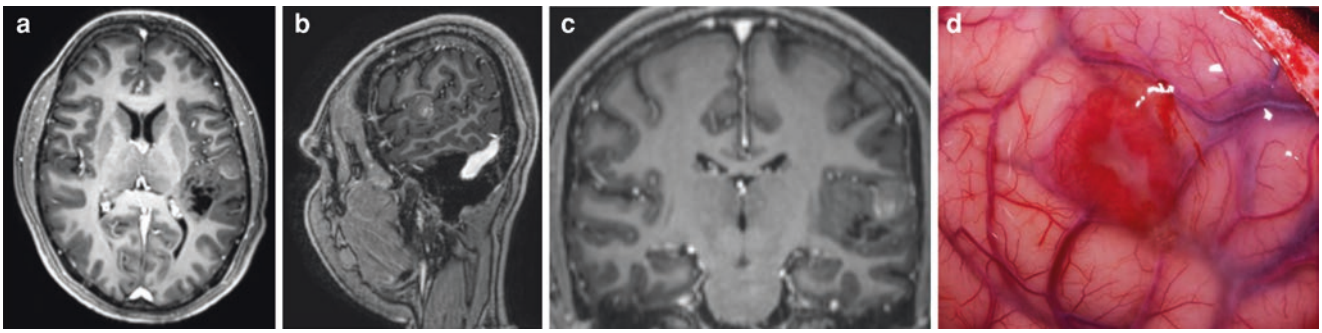

Fig. 4 In a 37-year-old man with a long history of drug-resistant seizures, preoperative postcontrast axial (**a**), sagittal (**b**), and coronal (**c**) magnetic resonance imaging demonstrated a mildly enhanced lesion of heterogeneous intensity, located in the left posterior perisylvian region. Intraoperative photography (**d**) showed a hyperemic lesion on the cortical surface

Arterial Injuries

Vascular injuries (either arterial or venous ones) during ATL with amygdalohippocampectomy are relatively uncommon if the procedure is performed carefully. Nevertheless, because of the close anatomical relationship of the mesial temporal lobe structures with the midbrain and choroidal fissure, the incidence of severe vascular complications, such as postoperative stroke, may be as high as 2.5%. They usually manifest with a motor deficit. Behrens et al. [7] noted transient and permanent hemiparesis in 3.03% and 2.3% of patients, respectively. Upon subgroup analysis of their series, Hader et al. [8] noted occurrence of hemiparesis in 1.8% of cases following temporal lobe resection (in comparison, the incidence of minor hemiparesis after extratemporal resection was 7.9%).

There are two main stages in temporal lobe surgery during which special care should be taken to avoid arterial injury. The first is during subpial dissection of the STG, since the MCA and its branches are located very close to the area of surgical manipulations, requiring a proper dissection technique with preservation of the pia mater and the arachnoid of the Sylvian fissure for avoidance of vascular damage. The second (and most important) stage is during dissection of the hippocampal complex from the choroidal fissure, since the AChA can be injured during removal of the head of the hippocampus, which can cause hemiparesis.

Hippocampal arteries arise from the PCA and should be carefully dissected or coagulated at the hippocampal sulcus to facilitate further subpial dissection of the hippocampal complex. Traction on these vessels should be avoided, since it can lead to their avulsion from the PCA and hemorrhage. Sometimes, an accessory artery from the AChA can be revealed in the most anterior part of the hippocampal sulcus, and this should be preserved. Slight oozing can usually be controlled with local hemostatic agents (e.g., oxidized cellulose), and coagulation should be avoided as much as possible.

Traction injury of perforators can happen during dissection of medial structures, more often if *en bloc* resection of the temporal lobe is attempted. Therefore, it is advisable to separate the procedure into two parts and to perform lateral temporal lobectomy followed by resection of the mesial structures.

Illustrative Case 3: Multiple Postoperative Cerebral Infarcts

A 41-year-old man presented with a history of complex partial seizures, which had started when he was 33 years of age and occurred 5–6 times per month. Video-EEG revealed ictal onset in the left anterior and midtemporal regions. Brain MRI demonstrated volume reduction of the left temporal lobe with hippocampal atrophy (Fig. 5a). MEG did not show definite localization of the epileptic focus. Neuropsychological assessment indicated left frontotemporal impairment. The patient underwent left-side ATL with amygdalohippocampectomy. During subpial dissection of the STG, the pia mater over the Sylvian vessels was breached, but otherwise the surgery was uneventful. Postoperatively, the patient demonstrated a gradual decline of his consciousness level, and within 5 h, his condition corresponded to a Glasgow Coma Scale score of 7 (eye opening: 2; verbal response: 1; motor response: 4) with right-side hemiparesis. Ventilatory support was required. Plain brain CT showed a hypodensity in the left temporal area and specks of hemorrhage in the right cerebellar hemisphere and in the left temporal, left occipital, and right temporal lobes. Brain MRI disclosed infarction in the territory of the inferior branch of the left MCA (Fig. 5b, c). Digital subtraction

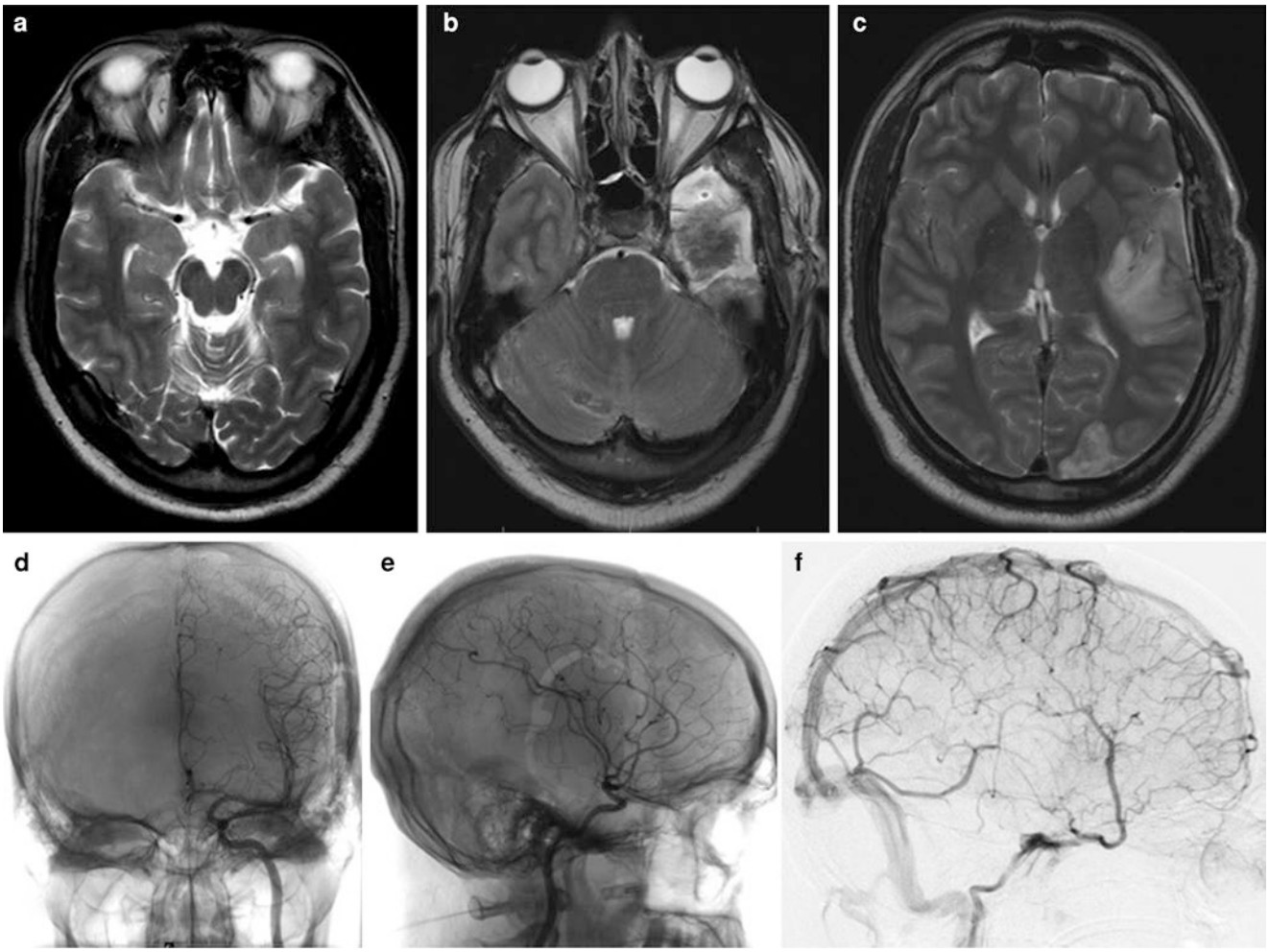

Fig. 5 In a 41-year-old man with complex partial seizures, preoperative magnetic resonance imaging (MRI) showed volume reduction of the left temporal lobe with hippocampal atrophy suggestive of mesial temporal sclerosis (**a**). Anterior temporal lobectomy with amygdalohippocampectomy was done, but, during the early postoperative period, the patient demonstrated a gradual decline of his consciousness level and development of right-side hemiparesis. Postoperative MRI (**b**, **c**) showed the results of the temporal lobectomy, along with signal changes suggestive of infarction in the territory of the inferior branch of the left middle cerebral artery, and specks of hemorrhage in the right cerebellar hemisphere and in the left temporal, left occipital, and right temporal lobes. Digital subtraction angiography (**d**–**f**) did not demonstrate any abnormalities

angiography did not demonstrate significant abnormalities (Fig. 5d–f). With conservative treatment, the condition of the patient gradually improved and he was therefore weaned off ventilatory support and extubated. Thyroid function tests revealed decreased T3 levels; thus, low-dose thyroxine replacement was started. He received speech therapy for dysphasia. Symptomatic treatment during the subsequent 3 months resulted in further improvement of his condition. Although the exact cause of the complication in this case remained unclear, a possibility of vasospasm causing infarction involving multiple cerebral lobes and the right cerebellar hemisphere was considered.

Illustrative Case 4: Postoperative Hemiparesis Caused by Perforator Injury

A 19-year-old woman presented with drug-resistant epilepsy of 10 years' duration. Clinical, EEG, and MRI data were concordant with a diagnosis of right-side MTS; thus, ATL with amygdalohippocampectomy was performed. The temporal lobe and medial temporal structures were resected *in toto* (Fig. 6). Immediately after the surgery, left-side hemiparesis was noted, and brain MRI revealed an internal capsule infarct, most probably due to a perforator injury caused by traction. The patient also demon-

strated adjustment disorder and depression, which improved with psychiatric counseling, antidepressant therapy, and rehabilitation.

Venous Injuries

Venous injuries during temporal lobectomy primarily affect superficial veins of the temporal lobe. However, since the posterior limit of brain resection on the nondominant side is located within 4–5 cm of the temporal pole, it often reaches the proximity of the vein of Labbé. The latter may also be occasionally damaged during retraction of the temporal lobe, if appropriate care is not taken. In addition, a dominant vein draining the Sylvian veins into the transverse sinus may sometimes be found in the anterior temporal lobe. If such a posteriorly directed vessel is present, it should be preserved and the temporal lobe resection should be done anteriorly to it. At the time of hippocampectomy, the basal vein of Rosenthal and its tributaries are encountered in the ambient cistern; thus, a diligent surgical technique is required for avoidance of their injury, which is attained by preservation of the arachnoid of the ambient cistern.

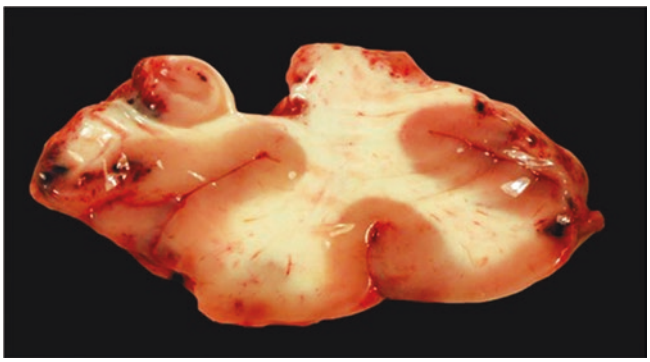

Fig. 6 A surgical specimen from the right lateral temporal lobe and mesial structures resected *in toto* in a 19-year-old woman who presented with a long history of drug-resistant epilepsy. The postoperative period was complicated by left-side hemiparesis, most probably due to a perforator injury caused by traction

Illustrative Case 5: Surgical Limitations Attributable to Vascular Anatomy

A 22-year-old-man presented with a long history of stress-induced complex partial seizures, which occurred 6–7 times per month and were characterized by lip smacking and stiffness of the left limbs. Video-EEG revealed ictal onset in the right mesial temporal region, and brain MRI demonstrated a neocortical lesion in the right posterior temporal lobe (Fig. 7a); a large vein of Labbé draining into the transverse sinus was also noted (Fig. 7b). The patient underwent anterior temporal lobe resection with lesionectomy under the guidance of ECoG. The medial temporal lobe structures were preserved. During the surgery, a large vein of Labbé was noted quite anteriorly (Fig. 7c), which limited the volume of the resection. Temporal lobe tissue was removed on either side of the vein, preserving the vascular continuity. Postoperative MRI showed no residual lesion and demonstrated preservation of the mesial temporal lobe structures. The seizures, however, recurred when the patient abruptly stopped taking his antiepileptic drugs (AED) 9 months after the surgery.

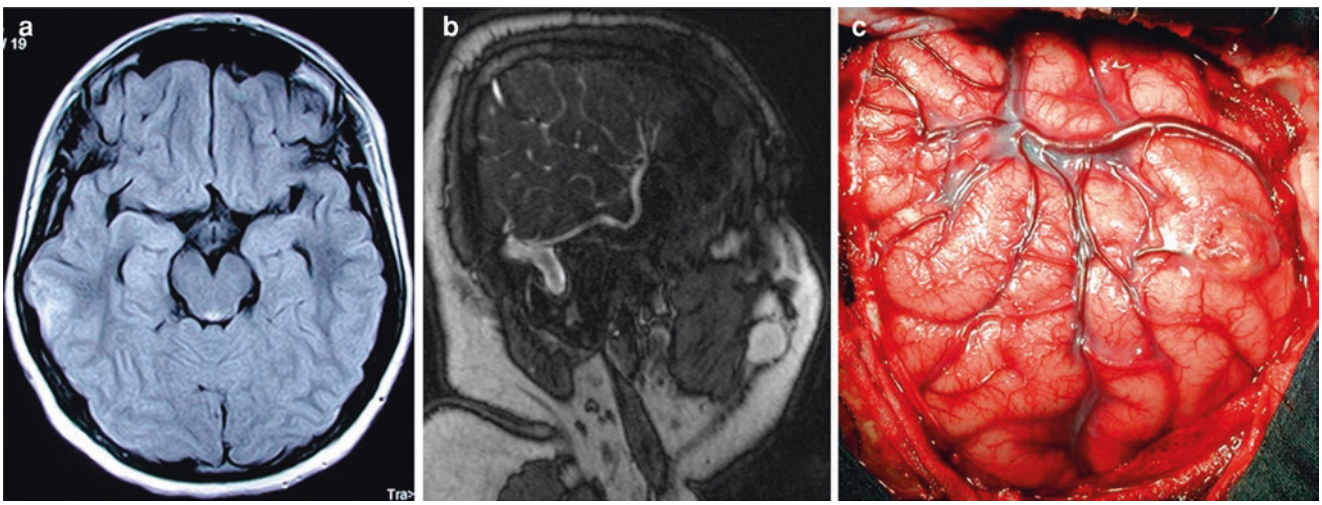

Fig. 7 In a 22-year-old man with a long history of stress-induced complex partial seizures, preoperative magnetic resonance imaging demonstrated a well-defined neocortical lesion in the right posterior temporal lobe (**a**) and a large vein of Labbé draining into the transverse sinus (**b**). Intraoperative photography (**c**) showed a large vein of Labbé located quite anteriorly, which limited the volume of resection

Cortical Venous Thrombosis

Overall, postoperative cortical venous thrombosis (CVT), as a consequence of intraoperative venous injury, is not an uncommon complication and is encountered in 7% of cases. However, spontaneous CVT is extremely rare, and such a diagnosis may be established only after definite exclusion of iatrogenic venous damage during surgery.

Illustrative Case 6: Postoperative Remote Cortical Venous Thrombosis

We have experienced a case of contralateral (left-side) CVT after right-side ATL for MTS. This event has previously been reported elsewhere, with a discussion on various factors that could have resulted in such a unique and previously undescribed complication [9]. The patient developed right-side focal motor seizures and alterations of consciousness on the second postoperative day. Imaging revealed left parietal CVT accompanied by a significant mass effect, which necessitated left-side temporo-parieto-occipital decompressive craniectomy and lax duraplasty. Thereafter, the condition of the patient improved gradually, but mild residual right-side hemiparesis persisted. In this case, development of CVT unrelated to the contralateral temporal lobe surgery might have been linked to existent hyperhomocysteinemia and a probable subclinical hypercoagulable state aggravated by perioperative hemodynamic disturbances [9].

Remote Cerebellar Hemorrhage

Remote cerebellar hemorrhage following supratentorial surgery has been well described in the neurosurgical literature. Its causes are considered to be multifactorial, and the most frequently mentioned risk factors include coagulation disorders, perioperative CSF drainage, arterial hypertension, and seizures. In a review of such cases, Sturiale et al. [10] noted that they were mainly encountered following surgery for intracranial aneurysms, tumor debulking, and lobectomies. Obviously, surgery for MTLE—which entails temporal lobectomy, opening of the cerebral ventricle, and a significant amount of CSF drainage—may occasionally predispose to this complication.

Illustrative Case 7: Remote Cerebellar Hemorrhage

A 39-year-old right-handed man presented with a long history of seizures, which were characterized by vague discomfort and apprehension prior to their onset, followed by lip smacking and automatism in the form of folding of both hands together, with a subsequent staring look and a brief period of unresponsiveness lasting for about 3–5 min. Despite AED administration, the seizures occurred 25–30 times per month. Video-EEG revealed a seizure focus in the right temporal area, and brain MRI demonstrated atrophy of the right hippocampus, suggestive of MTS. The patient underwent right-side ATL with amygdalohippocampectomy. Postoperatively, however, he developed difficulty with breathing, became drowsy (although arousable), and did not obey commands. Neurological examination revealed left-side hemiparesis and poor cough and gag reflexes. He also had bilateral crepitations in the lungs, most probably caused by aspiration. Postoperative CT and MRI examinations, including diffusion-weighted and perfusion-weighted imaging, demonstrated infarction in the posterior limb of the right internal capsule, most likely resulting from a perforator injury. In addition, there were specks of hemorrhage in both cerebellar hemispheres. Antiedema therapy was initiated, but the next day, the patient's condition deteriorated, necessitating intubation and ventilation. Repeat CT showed an increase in the right cerebellar hemorrhage size and obliteration of the fourth ventricle. Urgent posterior fossa decompressive craniectomy with duraplasty was done. After the surgery, he electively remained on a ventilator but was then weaned off it, since his level of consciousness demonstrated gradual improvement. At the time of discharge, the patient was alert and obeyed commands, and the power in his left extremities had improved to 4/5. The reason for the remote cerebellar hemorrhage in this case remained unclear.

Postoperative Hydrocephalus

Hydrocephalus is a very rare complication after epilepsy surgery and is mostly encountered following hemispherotomy or hemispherectomy. In their series of 523 temporal lobe resections, Bjellvi et al. [6] identified only one patient whose postoperative course was complicated by a hematoma and subsequent hydrocephalus. Correspondingly, among 279 patients who underwent temporal lobe surgery, Behrens et al. [7] noted postmeningitic hydrocephalus in only one patient, who underwent implantation of a CSF shunt. On very rare occasions, there may be symptomatic cyst formation at the lobectomy site, resulting in increased intracranial pressure and neurological deterioration; only a few such cases have been reported previously. We have previously described our own experience with such an unusual complication, which required repeat surgery for excision of the cyst, resulting in improvement of the patient's condition [11].

Illustrative Case 8: Postmeningitic Hydrocephalus

A 31-year-old man presented with a 17-year history of multiple episodes of seizures. The clinical semiology consisted of blurring of vision and palpitations, followed by loss of awareness, vocalization, a staring look, orofacial automatism, deviation of the face to the right side, and posturing of the right upper and lower limbs. Despite therapy with multiple AED, including oxcarbazepine and lacosamide, the seizures occurred with a frequency of 10–15 times per month. Video-EEG revealed ictal onset in the left anterior and midtemporal regions, and brain MRI demonstrated atrophy of the left hippocampus (Fig. 8a). Neuropsychological assessment indicated diffuse impairment. The patient underwent left-side ATL with amygdalohippocampectomy. The postoperative course was complicated by fever; thus, a lumbar puncture was done. CSF analysis showed an increased cell count with predominance of polymorphonuclear leukocytes, as well as elevated lactate and protein levels; however, there was no microbial growth from the CSF culture. Treatment with broad-spectrum antibiotics cured the meningitis. Nevertheless, the patient developed fluctuant protrusion of tissues in the area of the craniotomy, and CT demonstrated epidural fluid collection, elevation of the bone flap, and mild hydrocephalus (Fig. 8b, c). There were no contrast-enhanced lesions. In addition, clinical features of normal pressure hydrocephalus were noted (incontinence, ataxia, and disorientation in time and place). Therapy with acetazolamide (750 mg per day) was started, while lumboperitoneal shunting was considered as a reserve option. With medical treatment over the next 3 weeks, the condition of the patient gradually improved and the symptoms decreased; thus, he did not undergo a CSF diversion procedure and was discharged.

Postoperative Seizures

Seizures in the immediate or early postoperative period are often noted following surgery for MTLE, and previous studies have suggested that their occurrence may predict poor seizure control thereafter [12, 13]. A meta-analysis of 17 published studies revealed a 22.58% prevalence of acute postoperative seizures and showed that in comparison with their counterparts, a significantly higher proportion of patients who did not experience seizures within 30 days after the surgery were seizure-free at ≥1 year of follow-up (73.49% versus 38.96%; odds ratio 4.20, 95% confidence interval 2.97–5.93; $P < 0.0001$) [13]. However, patients who had seizures within 24 hours after their surgery (particularly seizures with different semiology from that of their habitual preoperative seizures) were more likely to achieve a seizure-free outcome, although the difference did not reach the level of statistical significance [13].

In fact, if the semiology of postoperative seizures differs from that of the patient's habitual seizures, then their etiology is most often related to perioperative causes. Among the latter, pneumocephalus is frequently noted, since its occurrence is facilitated by the large volume of the resection cavity following temporal lobectomy (this cavity should be filled fully with saline before completion of watertight dural closure). Other possible causes of postoperative seizures include

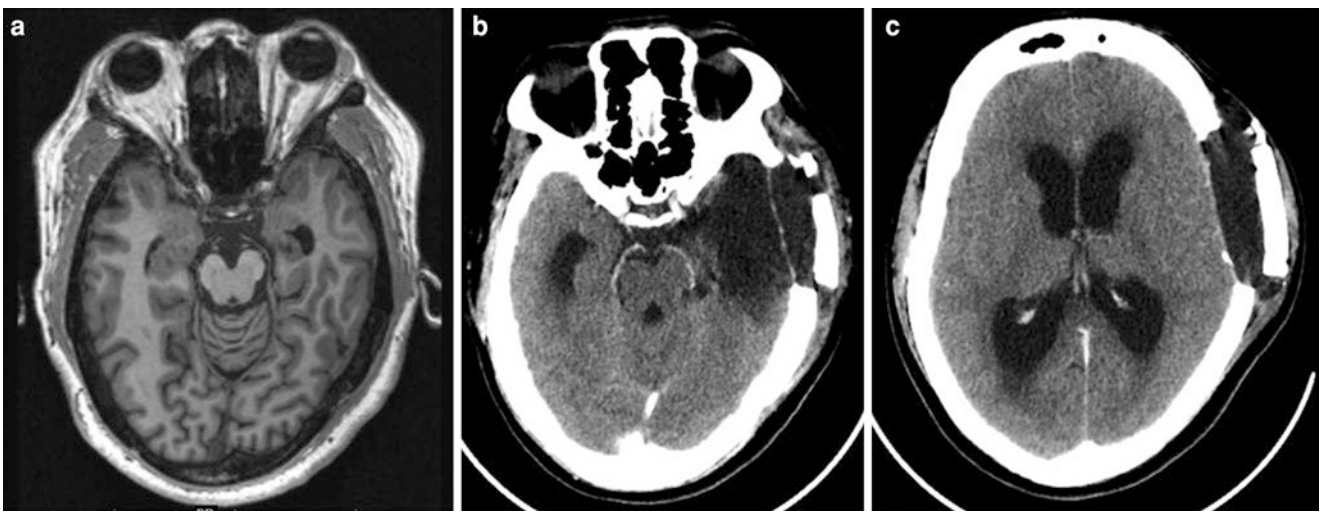

Fig. 8 In a 31-year-old man with a long history of epilepsy, preoperative magnetic resonance imaging demonstrated atrophy of the left hippocampus, suggestive of mesial temporal sclerosis (**a**). Anterior temporal lobectomy with amygdalohippocampectomy was done, but the postoperative course was complicated by meningitis. Subsequent computed tomography (**b**, **c**) demonstrated epidural fluid collection, elevation of the bone flap, and hydrocephalus

cerebral venous infarction, a subdural hematoma, electrolyte disturbances, and decreases in blood AED concentrations caused by perioperative changes in their administration.

Illustrative Case 9: Postoperative Seizures with Different Semiology

A 36-year-old man presented with recurrent seizures, which had started when he was 10 years of age and occurred with a frequency of 2–3 times per month. The clinical semiology consisted of a sensation of fear, followed by rotatory movement of the right wrist, perioral automatism, and postictal confusion lasting approximately 5 min. He received levetiracetam (2000 mg per day), clobazam (20 mg per day), and carbamazepine (1600 mg per day). Ictal EEG revealed that the seizure origin was in the right anterior temporal region. Brain MRI demonstrated atrophy of the right hippocampus, suggestive of MTS (Fig. 9a). PET-MRI showed moderate-to-severe hypometabolism involving the right medial temporal lobe. The patient underwent right-side ATL with amygdalohippocampectomy. In the immediate postoperative period, he had alterations of consciousness. Within 24 h after the surgery, he experienced generalized tonic–clonic seizures (GTCS) twice and a left-side focal motor seizure once. CT demonstrated pneumocephalus (Fig. 9b, c). Therapy with valproate (1500 mg per day) was started. The patient required intubation and ventilatory support for 2 days but demonstrated gradual improvement and was therefore weaned off it. In this case, the occurrence of GTCS after ATL was most likely caused by diffuse pneumocephalus.

Acute Postoperative Psychiatric Disorders

Patients with drug-resistant epilepsy usually have a variety of significant mental disturbances, which can be part of an associated personality disorder and/or the consequences of long-standing seizures. In addition, some AED may cause psychiatric side effects. Therefore, a detailed mental health assessment is essential in all such individuals to identify even subtle psychopathological abnormalities.

Surgery for MTLE with removal of medial temporal lobe structures can have a bearing on pre-existing mental disturbances, which may be exacerbated during the perioperative period. In particular, depression after such interventions has been reported in 4.3–10% of patients [1, 14]. More rarely, new-onset psychopathological problems may appear. Macrodimitris et al. [15] performed a systematic review of studies reporting psychiatric outcomes following epilepsy surgery and noted that the rate of mental disorders occurring *de novo* ranged widely from 1.1% to 18.2%. In such clinical scenarios, collaborative care of the patient with a psychiatrist is mandatory.

Illustrative Case 10: Postoperative Exacerbation of Behavioral Disturbances

A 17-year-old right-handed man presented with a 7-year history of seizures. The clinical semiology included a sudden speech arrest with a vague sensation in the abdomen and head turning to the right side. Behavioral changes with anger outbursts were also noted. Video-EEG revealed seizure onset

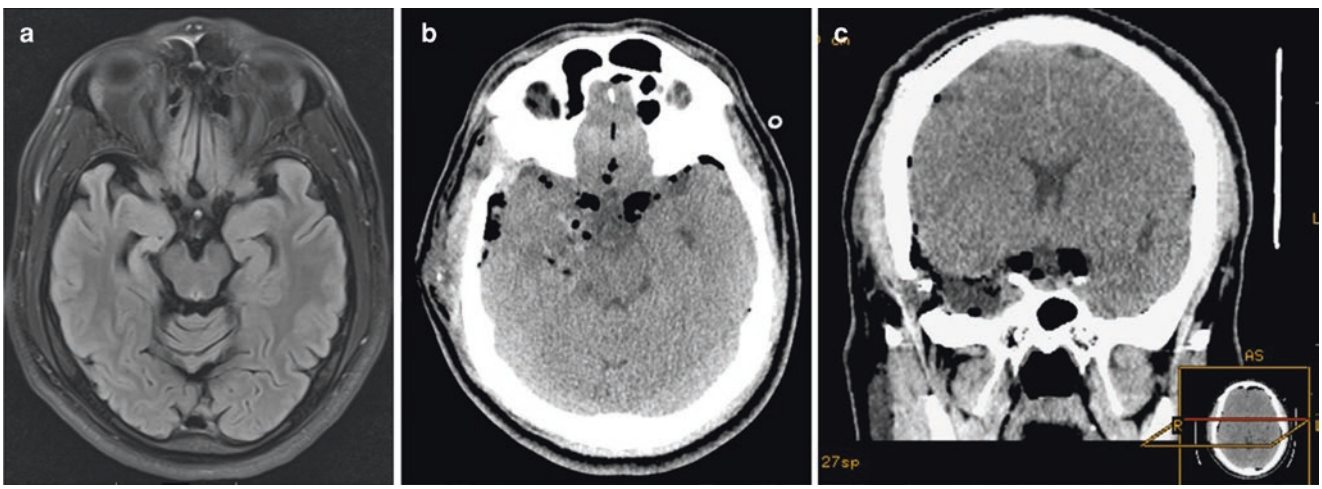

Fig. 9 In a 36-year-old man with a long history of epilepsy, preoperative magnetic resonance imaging showed atrophy of the right hippocampus, suggestive of mesial temporal sclerosis (**a**). Anterior temporal lobectomy with amygdalohippocampectomy was done, but, in the immediate postoperative period, the patient experienced seizures with a semiology different from that of his habitual seizures. They were most likely caused by diffuse pneumocephalus, as postoperative computed tomography (**b**, **c**) demonstrated air in the basal cisterns and along the cerebral convexity

in the left anterior and midtemporal regions. Brain MRI demonstrated loss of gray–white differentiation in the left temporal lobe, along with volume loss suggestive of left temporal lobe focal cortical dysplasia. PET-CT showed decreased metabolism in both hippocampi, more prominent on the left side. The patient underwent left ATL with amygdalohippocampectomy under ECoG monitoring. Postoperatively, he developed a rebound increase in his pre-existing psychiatric disturbance, manifested by frequent outbursts of intense anger, aggressive behavior, and assaults on his parents. Therapy with antipsychotics and AED resulted in gradual stabilization of these mental disorders.

Alternative Surgical Techniques

There are a number of alternative surgical techniques besides standard ATL (e.g., tailored ATL and selective amygdalohippocampectomy), and their different variations have been well described in the literature. However, for a beginner in epilepsy surgery, it is preferable to perform a standard procedure (i.e., ATL with amygdalohippocampectomy), taking into consideration the neurological and neuropsychological status of the patient, the hemispheric dominance, the results of pre- and intraoperative brain mapping, and details of the vascular anatomy. Thereafter, when adequate experience has been obtained, it is possible to apply various types of selective amygdalohippocampectomy based on appropriate indications in each individual case. During such stepwise professional progress, appropriate measures must be taken for attainment of optimal postoperative seizure outcomes, as well as for avoidance of surgical, neurological, and neuropsychological morbidity.

Conclusion

ATL with amygdalohippocampectomy for temporal lobe epilepsy is one of the few neurosurgical procedures that has demonstrated clear class 1 evidence of its superiority to medical treatment with regard to seizure control and improvements in cognitive function and quality of life. However, while the technique of surgical intervention for MTLE is well established and has been safely performed at many centers, one needs to be aware of the possible complications that can occur and must make the best efforts to avoid them for attainment of the best possible outcome with minimal morbidity. The ultimate goal of surgical treatment is restoration of the full functional capacity of patients, giving them freedom from seizures without any neurological deficit and allowing their complete integration into society.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Erba G, Winston KR, Adler JR, Welch K, Ziegler R, Hornig GW. Temporal lobectomy for complex partial seizures that began in childhood. Surg Neurol. 1992;38:424–32.
2. Kim SK, Wang KC, Hwang YS, Kim KJ, Chae JH, Kim IO, Cho BK. Epilepsy surgery in children: outcomes and complications. J Neurosurg Pediatr. 2008;1:277–83.
3. Thudium MO, Campos AR, Urbach H, Clusmann H. The basal temporal approach for mesial temporal surgery: sparing the Meyer loop with navigated diffusion tensor tractography. Neurosurgery. 2010;67(2 Suppl Operative):385–90.
4. Georgiadis I, Kapsalaki EZ, Fountas KN. Temporal lobe resective surgery for medically intractable epilepsy: a review of complications and side effects. Epilepsy Res Treat. 2013;2013:752195.
5. Mathon B, Navarro V, Bielle F, Nguyen-Michel VH, Carpentier A, Baulac M, Cornu P, Adam C, Dupont S, Clemenceau S. Complications after surgery for mesial temporal lobe epilepsy associated with hippocampal sclerosis. World Neurosurg. 2017;102:639–50.e1. –2.
6. Bjellvi J, Flink R, Rydenhag B, Malmgren K. Complications of epilepsy surgery in Sweden 1996–2010: a prospective, population-based study. J Neurosurg. 2015;122:519–25.
7. Behrens E, Schramm J, Zentner J, König R. Surgical and neurological complications in a series of 708 epilepsy surgery procedures. Neurosurgery. 1997;41:1–10.
8. Hader WJ, Tellez-Zenteno J, Metcalfe A, Hernandez-Ronquillo L, Wiebe S, Kwon CS, Jette N. Complications of epilepsy surgery: a systematic review of focal surgical resections and invasive EEG monitoring. Epilepsia. 2013;54:840–7.
9. Arivazhagan A, Mundlamuri RC, Shreedhara AS, Bharath RD, Mahadevan A, Sinha S, Rao MB, Satishchandra P. Remote contralateral side cerebral venous thrombosis following intracranial surgery: a rare complication in an unusual setting. Neurol India. 2018;66:520–2.
10. Sturiale CL, Rossetto M, Ermani M, Volpin F, Baro V, Milanese L, Denaro L, d'Avella D. Remote cerebellar hemorrhage after supratentorial procedures (part 1): a systematic review. Neurosurg Rev. 2016;39:565–73.
11. Rao MB, Radhakrishnan K, Radhakrishnan VV, Gupta AK. Expanding cyst following temporal lobectomy: an unusual complication of epilepsy surgery. Clin Neurol Neurosurg. 1999;101:141–4.
12. Rao MB, O'Brien TJ, Cascino GD, So EL, Radhakrishnan K, Silbert P, Marsh WR. Acute postoperative seizures following anterior temporal lobectomy for intractable partial epilepsy. J Neurosurg. 1998;89:177–82.
13. Giridharan N, Horn PS, Greiner HM, Holland KD, Mangano FT, Arya R. Acute postoperative seizures as predictors of seizure outcomes after epilepsy surgery. Epilepsy Res. 2016;127:119–25.
14. Lopez-Gonzalez MA, Gonzalez-Martinez JA, Jehi L, Kotagal P, Warbel A, Bingaman W. Epilepsy surgery of the temporal lobe in pediatric population: a retrospective analysis. Neurosurgery. 2012;70:684–92.
15. Macrodimitris S, Sherman EM, Forde S, Tellez-Zenteno JF, Metcalfe A, Hernandez-Ronquillo L, Wiebe S, Jetté N. Psychiatric outcomes of epilepsy surgery: a systematic review. Epilepsia. 2011;52:880–90.

Complications of Deep Brain Stimulation for Movement Disorders: Literature Review and Personal Experience

Chingiz Shashkin

Abstract

The contemporary technique of deep brain stimulation (DBS) is very effective for management of movement disorders—including Parkinson's disease, generalized dystonia, and tremors—and has also been successfully applied for novel indications (e.g., intractable epilepsy and chronic pain). As a result, growing numbers of DBS procedures have been performed worldwide; correspondingly, the incidence of associated morbidity has also increased. All complications of DBS can be divided into those associated with (1) the surgical procedure, (2) the device itself, and (3) the applied electrical stimulation. On the basis of an analysis of the available literature and the personal experience of the author, it may be concluded that implantation of a DBS device is a relatively safe procedure accompanied by very low risks of major morbidity or a permanent neurological deficit. Nevertheless, awareness of the possible complications and application of appropriate preventive measures for their avoidance are very important for providing safe and effective treatment.

Keywords

Complication · Deep brain stimulation · Functional neurosurgery · Movement disorders · Outcome · Treatment

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Introduction

At present, deep brain stimulation (DBS) represents the treatment of choice for patients with movement disorders—including Parkinson's disease, generalized dystonia, and tremors—and has consistently demonstrated its high efficacy and safety. More than 150,000 implantations of DBS devices have been done during the 30-year history of this technique. Moreover, the indications for DBS are steadily becoming wider, and it has been applied successfully for treatment of such diseases as intractable epilepsy and chronic pain. Therefore, further increases in the numbers of DBS procedures being performed worldwide may be expected along with a corresponding increase in the incidence of associated morbidity.

Implantation of a DBS lead does not cause significant brain tissue damage (beside development of mild gliosis in proximity to the electrode); thus, the associated risk of a permanent postoperative neurological deficit is minimal. Nevertheless, despite the evidence that this procedure is much safer than ablative surgery for functional brain disorders, certain complications, which can appear at different stages of treatment, have been reported. Although they are mostly mild and transient, some of these events may be rather troublesome; thus, their probability, preventive measures, and optimal management should be clearly recognized. According to a systematic review by Hamani et al. [1], after the DBS procedure, there is a 9% risk of morbidity associated with the device itself (e.g., infection or problems with electrodes or the generator), a 2.8% risk of intracerebral hemorrhage (ICH), a 0.7% risk of development of a permanent neurological deficit, and a mortality rate of approximately 0.4%.

All complications of DBS can be divided into those associated with (1) the surgical procedure, (2) the device itself, and (3) the applied electrical stimulation. Herein, we review their spectrum on the basis of both analysis of the available literature and personal experience of 209 procedures performed at the National Center for Neurosurgery (Astana, Kazakhstan) during the initial 5 years of DBS use.

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_15

Surgery-Related Complications

Surgery-related complications after DBS implantation may be specifically linked to this kind of procedure or may be nonspecific (i.e., associated with any type of surgical intervention).

Intracerebral Hemorrhage

ICH is one of the most typical complications of stereotactic neurosurgery, and its incidence ranges from 1% to 8% [1, 2]. It can result from implantation of a cannula or a microelectrode into the brain. In fact, despite its recognized utility for localizing the target, use of microelectrode recording (MER) may carry a risk of ICH, which is reportedly increased in cases involving a greater number of microelectrode passes [3], particularly in patients with arterial hypertension [4]. Since ICH may be delayed and develop hours after surgery, it is recommended to keep the arterial blood pressure at a level ≤140/100 mmHg during both the intraoperative and early postoperative periods [5]. It is also important to check blood coagulation parameters and to avoid operating on women during menstruation.

From the surgical viewpoint, for avoidance of ICH, it is crucial to determine an appropriate entry point and trajectory to the target, which can be done effectively with reference to postcontrast T1-weighted magnetic resonance imaging (MRI) for identification of the cortical and deep vascular anatomy of the brain and for prevention of inadvertent injury of cerebral vessels during the procedure [6].

There are several obvious intraoperative manifestations of ICH, such as bleeding from the cannula, sudden electric "silence" during MER, an unexpected change in the positions of electrodes detected on a X-ray, or clinical deterioration of the patient's condition, presenting as speech disturbance, a focal neurological deficit (e.g., anisocoria, a sudden stop of a tremor on one side, and development of hemiparesis), or sudden loss of consciousness. In such cases, it is necessary to stop the procedure immediately and to remove the electrode if it has already been implanted. The cannula should be left in situ if outflow bleeding is continuing through it, for maximum discharge of blood and constant irrigation with warm saline through the cannula. In the event of severe deterioration of the patient's condition, the stereotactic frame should be removed to provide free access for the anesthesiologist in the event of emergency intubation, and computed tomography (CT) should be done promptly. The further treatment strategy depends on the results of CT and clinical manifestations, but, in any case, the DBS procedure should be canceled on that day [7]. In our series, there was one case (a 0.5% incidence) of severe ICH with a prominent neurological deficit, which required decompressive craniotomy. Upon recovery and cranioplasty, this patient underwent implantation of the DBS lead on the opposite side (Fig. 1).

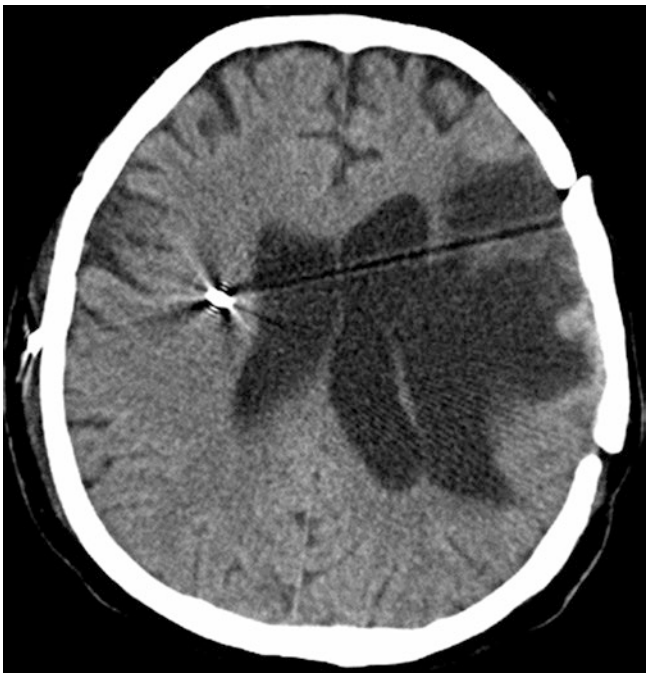

Fig. 1 Follow-up computed tomography of a patient who initially underwent deep brain stimulation (DBS) lead implantation on the left side, which was complicated by severe intracerebral hemorrhage, necessitating decompressive craniotomy. After recovery and cranioplasty, contralateral implantation of the DBS lead was done

Venous Infarction

Venous infarction can occur as a result of coagulation of a large draining vein during application of a burr hole or implantation of a cannula. For avoidance of this complication, in our practice, we prefer to plan an entry point that is anterior to the coronal suture. In such cases, any inadvertent cortical vein damage will most likely be asymptomatic [6].

Postoperative Seizures

In 3.1% of cases, the DBS procedure is complicated by postoperative seizures [1], which necessitate administration of antiepileptic drugs (AED). However, prophylactic use of AED in such cases is undesirable because of their variable side effects and possible interaction with other medications taken by the patient. In our series, postoperative seizures were observed in one case (0.5%).

Subcutaneous Fluid Collection

Subcutaneous hematomas are usually caused by insufficient intraoperative hemostasis. A leak of the cerebrospinal fluid may result in its subcutaneous accumulation, which may neces-

sitate aspiration or even more advanced treatment, including reoperation. A seroma in the area of an implantable pulse generator (IPG) may reflect a reaction to the foreign body and can be evacuated with needle aspiration [6]. Subcutaneous fluid collection may be a predisposing factor for infection of the surgical wound.

Pulmonary Infection

Since many patients with Parkinson's disease have disorders of swallowing, aspiration and pneumonia can occur in the perioperative period. The risk of such complications and possible preventive measures should be determined during preoperative examination [6].

Pulmonary Embolism

Pulmonary embolism is the main cause of death in neurosurgical patients. According to Inci et al. [8], the incidence of this complication ranges from 0.4% to 4.9%, and it is accompanied by an 8.6–59.4% mortality rate. Despite preventive use of compression stockings, the risk of perioperative pulmonary embolism in (usually elderly) patients with Parkinson's disease remains high and is related to the presence of comorbidities—such as heart disease, obesity, polycythemia, and involuntary immobility—as well as to withdrawal of anticoagulants on the eve of the intervention. It has been suggested that combined use of low-molecular-weight heparin and compression stockings may be more effective for prevention of this complication [9–11].

In our practice, the standard preoperative protocol for prevention of pulmonary embolism in cases of DBS implantation for Parkinson's disease include (1) water loading for 3–4 days before surgery (copious drinking and intravenous infusions of saline); (2) use of compression stockings during and after surgery until mobilization of the patient; (3) mechanical compression of the lower limbs; and (4) early postoperative mobilization of the patient (which presumes initial IPG programming in the early postoperative period). Still, we have experienced two cases (a 1% incidence) of this complication, and one of these patients died.

Complications Associated with a Deep Brain Stimulation Device

Among the complications associated with implantation of a foreign body such as a DBS device, local infection is, expectedly, the most common, followed by lead-related problems (misplacement, migration, disconnection) and IPG dysfunction.

Local Infection

The incidence of local infectious complications after DBS procedures varies from 3% to 10% [1, 5, 12–14]. Most often, they affect surgical wounds, being caused by their injury (e.g., scratching by the patient or friction with clothing), to which subcutaneous fluid collection may cause a predisposition. Possible preventive measures include full shaving of hair in the surgical areas before the intervention and use of prophylactic antibiotics both intraoperatively and for 2–3 days in the early postoperative period. Clearly, implantation of a DBS device should be performed under the strictest aseptic conditions, thorough intraoperative hemostasis should be achieved, and generous irrigation of all subcutaneous cavities with antiseptic solution should be done before closure of surgical wounds.

If wound infection occurs, its optimal management is selected on a case-by-case basis, but active treatment should be initiated immediately, considering the high risk of brain involvement; thus, the patient should be referred to a specialist (preferably, the same neurosurgeon who did the DBS implantation) without delay. Antibiotic therapy is usually tried initially. In our practice, we have observed a case of successful antibiotic treatment of local wound infection after DBS implantation. Still, rather often, the implanted system needs to be removed, at least partially (e.g., an IPG with extension cables, leads with extension cables, or extension cables only, depending on the localization of the infection).

Skin Erosion and Ulceration

Skin erosion or ulceration, with or without accompanying infection, usually occurs behind the ear (a typical location of the system connectors) or over the protruding parts of the device (Fig. 2). This complication is encountered more often

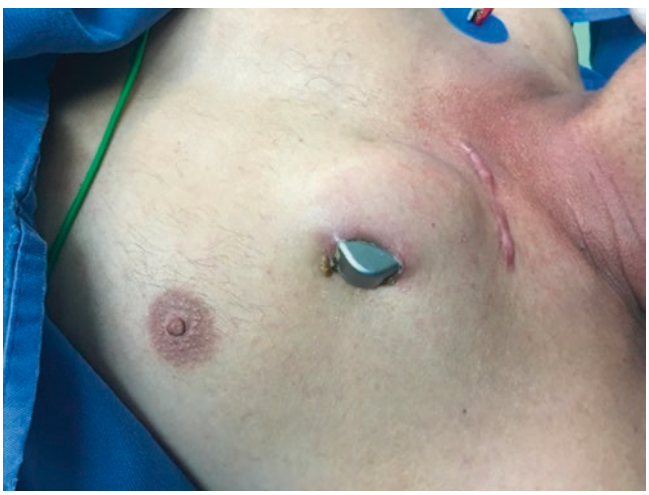

Fig. 2 Skin ulceration above the implantable pulse generator of the deep brain stimulation system

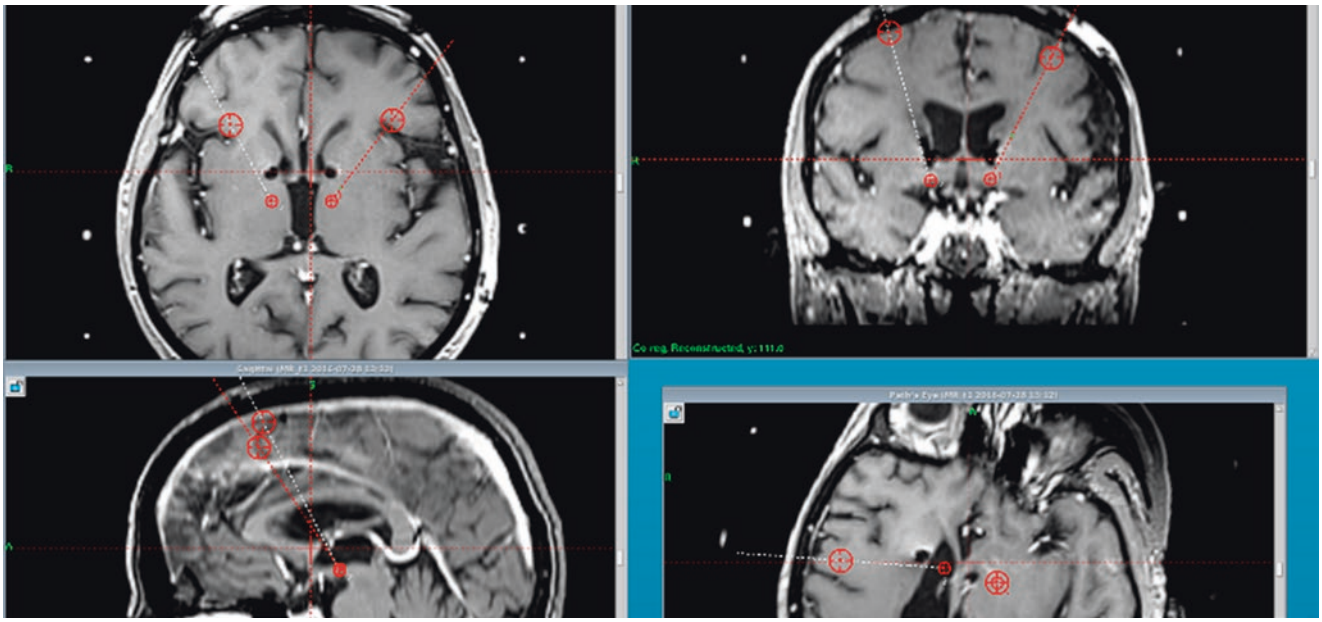

Fig. 3 Demonstration of deep brain stimulation lead misplacement with neuronavigation software

in fragile patients with an impaired health status and thin skin. Preventive measures include creation of appropriate subcutaneous cavities and tunnels with specific arrangement of the system connectors to avoid their projection against the skin incisions from below; it seems unacceptable to locate the electrode loops on the cap of the electrode retainer [5, 13]. The tissue cavity created for the IPG should be spacious enough for liberal insertion of the device without excessive tension on the adjacent tissues. It may be placed under the pectoralis major muscle, which is particularly preferable in thin patients with limited subcutaneous fat tissue. The importance of careful hemostasis, multilayer suturing, and careful matching of the skin edges during would closure cannot be overemphasized.

Lead-Related Problems

Appropriate implantation of the DBS leads may be controlled intraoperatively with MER, a clinical response to stimulation, and X-ray examination. Nevertheless, erroneous surgical techniques, particularly during wound closure, may result in implanted lead misplacement (Fig. 3); therefore, anatomical verification of the lead positions with MRI should be performed immediately after surgery [6].

Migration of the intracranial electrode may occur because of its inappropriate fixation to the skull or a shift in the IPG positioning translated through poorly fixed extension cables. It may have a significant negative impact on the clinical efficacy of the procedure and may even necessitate revision surgery. Therefore, additional titanium anchors or special systems to improve fixation of electrodes have been suggested [15]. In our opinion, however, the ring with the cap available in the standard kit for DBS implantation provides an excellent fixing if used appropriately.

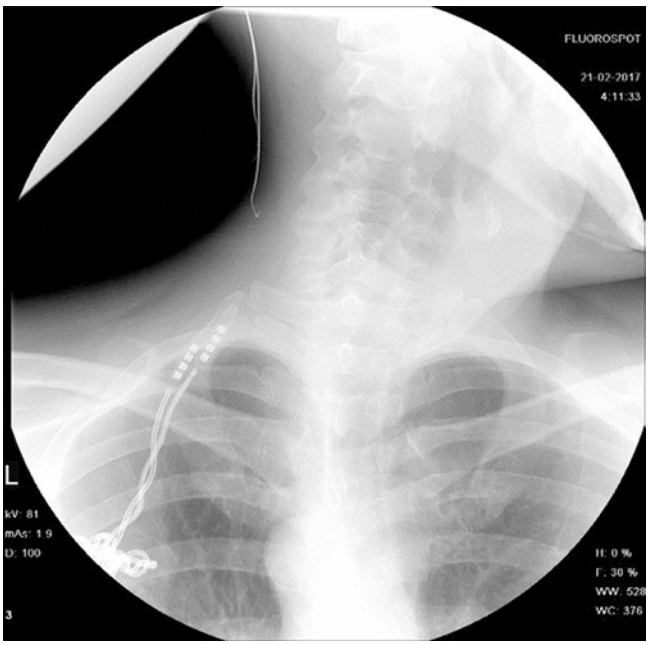

Fig. 4 An X-ray examination demonstrates damage of the deep brain stimulation extension leads at the neck

Disconnection or damage of the electrode or connecting wires occasionally happens in the area behind the ear or at the neck as a result of excessive head movements (Fig. 4) [13, 14, 16]. It may be prevented by subgaleal placement of the electrodes and connecting cables, with formation of their

loops there and in proximity to the IPG-containing cavity, allowing tension-free extension of the wires during neck movements. Disconnection at the system junction may also be caused by too-weak tightening of the fixing screws.

Implantable Pulse Generator Dysfunction

IPG dysfunction may be caused by technical problems (e.g., damage or discharge of the battery) or may result from external factors (e.g., the impact of a high-energy electromagnetic field) [13]. A sudden shutdown of the DBS system can lead to a potentially life-threatening Parkinsonian crisis, which can manifest as a neuroleptic malignant syndrome [17]. In such cases, the patient should be referred immediately to a specialized facility for inspection of the IPG by the neurosurgeon and the device manufacturer's technical support staff, and decision-making on early reimplantation of the device should be done.

Complications Associated with Applied Electrical Stimulation

Postoperative MRI allows one to determine the positions of the electrodes before starting the IPG programming. Further changes of the stimulation parameters are usually needed in order to improve the clinical response and to minimize side effects. Complications associated with applied electrical stimulation of the target structures are unique to the DBS system.

Subthalamic nucleus (STN) stimulation may induce dyskinesia, hemiballismus, dysarthria, paresthesia, diplopia, or other side effects related to irritation of structures located in proximity to the target (e.g., the corticobulbospinal tract laterally, a medial loop posteriorly, or fibers of the oculomotor nerve medially) [1, 5, 18, 19]. Nevertheless, such undesirable phenomena are usually temporary, since they may be controlled effectively by reprogramming of the IPG. In particular, dyskinesia caused by stimulation may be considered a sign of proper electrode placement, and its relief may be attained with adjustment of the stimulation parameters along with a decrease in the dopaminergic drug dosage, optimizing the balance between the effects of DBS and those of the medical therapy.

Apraxia of eye opening is an uncommon side effect, which is encountered in 5% of patients undergoing STN stimulation [1] and is frequently associated with a good response to DBS [20]. It has been described in cases of both idiopathic Parkinson's disease and other neurodegenerative disorders affecting the basal ganglia [21]. The causes of this phenomenon are not completely clear, but it may be related to modification of dopaminergic therapy effects during stimulation [5]. In our practice, apraxia of eye opening has been observed only infrequently; in most cases, it demonstrated self-resolution within a few months.

Weight gain is considered the most common side effect of STN stimulation [1, 22, 23]. It usually occurs during the first 3 months of treatment and either stabilizes or decreases thereafter. It is believed that weight gain is associated with the reduction of energy expenditure that results from relief of dyskinesia or tremors. In addition, the corrected doses of dopaminergic drug may lead to increased desire for food intake [23]. In such cases, a special diet and/or an increase in physical activity should be recommended [22].

Psychiatric Disorders

Psychiatric disorders after a DBS procedure may result from intraoperative frontal lobe damage or may be related to effects of electrical stimulation.

Immediately after DBS of the STN, a postoperative delirium is noted rather often, mainly in elderly patients with advanced Parkinson's disease, and it may be associated with levodopa withdrawal and the prolonged duration of the surgical procedure [1, 5]. Damage of the frontal lobes during implantation of electrodes may play a role in the pathogenesis of this complication as well. The delirium state usually lasts for 3–4 days and resolves spontaneously; thus, it does not require specific preventive measures or special therapy, besides precautions against aspiration, falls, etc. The patient usually recalls such postoperative delirium as a prolonged dream.

More serious mental problems—such as mania, depression, or psychosis—have also frequently been noted during DBS for Parkinson's disease, mostly in patients with preexisting psychopathological alterations [1, 23–28]. Mood changes may be particularly related to inadvertent stimulation of the limbic system. Mania is usually observed during the early postoperative period and resolves spontaneously thereafter. In contrast, depression develops within several months after the start of the stimulation and may be caused by insufficient doses of dopaminergic drugs; of note, untreated depression following implantation of a DBS device can lead to suicide attempts [29]. It is believed that STN stimulation generally does not cause cognitive impairment, but this issue is still under active investigation [27].

Conclusion

In comparison with other neurosurgical interventions, the risks of associated major morbidity or a permanent neurological deficit after DBS implantation are definitely very low. Nevertheless, awareness of the possible complications and application of appropriate preventive measures for their avoidance are very important. Obviously, a high level of pro-

fessional expertise and sufficient practical experience of the surgeon, along with use of up-to-date medical technologies, are crucial factors in provision of safe and effective treatment.

Conflict of Interest Statement The author has no conflict of interest concerning the reported materials or methods.

References

1. Hamani C, Richter E, Schwalb JM, Lozano AM. Bilateral subthalamic nucleus stimulation for Parkinson's disease: a systematic review of the clinical literature. Neurosurgery. 2005;56:1313–24.
2. Binder DK, Rau GM, Starr PA. Risk factors for hemorrhage during microelectrode-guided deep brain stimulator implantation for movement disorders. Neurosurgery. 2005;56:722–32.
3. Deep-Brain Stimulation for Parkinson's Disease Study Group, Obeso JA, Olanow CW, Rodriguez-Oroz MC, Krack P, Kumar R, Lang AE. Deep-brain stimulation of the subthalamic nucleus or the pars interna of the globus pallidus in Parkinson's disease. N Engl J Med. 2001;345:956–63.
4. Gorgulho A, De Salles AA, Frighetto L, Behnke E. Incidence of hemorrhage associated with electrophysiological studies performed using macroelectrodes and microelectrodes in functional neurosurgery. J Neurosurg. 2005;102:888–96.
5. Umemura A, Jaggi JL, Hurtig HI, Siderowf AD, Colcher A, Stern MB, Baltuch GH. Deep brain stimulation for movement disorders: morbidity and mortality in 109 patients. J Neurosurg. 2003;98:779–84.
6. Umemura A. Complications and avoidance. In: Baltuch GH, Stern MB, editors. Deep brain stimulation for Parkinson's disease. New York: Informa Healthcare; 2007. p. 103–12.
7. Rosenow JM, Rezai AR. Surgical technique and complication avoidance. In: Baltuch GH, Stern MB, editors. Surgical management of movement disorders. Boca Raton: Taylor & Francis; 2005. p. 45–62.
8. Inci S, Erbengi A, Berker M. Pulmonary embolism in neurosurgical patients. Surg Neurol. 1995;43:123–9.
9. Cerrato D, Ariano C, Fiacchino F. Deep vein thrombosis and low-dose heparin prophylaxis in neurosurgical patients. J Neurosurg. 1978;49:378–81.
10. Nurmohamed MT, van Riel AM, Henkens CM, Koopman MM, Que GT, d'Azemar P, Büller HR, ten Cate JW, Hoek JA, van der Meer J, van der Heul C, Turpie AG, Haley S, Sicurella A, Gent M. Low molecular weight heparin and compression stockings in the prevention of venous thromboembolism in neurosurgery. Thromb Haemost. 1996;75:233–8.
11. Agnelli G, Piovella F, Buoncristiani P, Severi P, Pini M, D'Angelo A, Beltrametti C, Damiani M, Andrioli GC, Pugliese R, Iorio A, Brambilla G. Enoxaparin plus compression stockings compared with compression stockings alone in the prevention of venous thromboembolism after elective neurosurgery. N Engl J Med. 1998;339:80–5.
12. Oh MY, Abosch A, Kim SH, Lang AE, Lozano AM. Long-term hardware-related complications of deep brain stimulation. Neurosurgery. 2002;50:1268–76.
13. Lyons KE, Wilkinson SB, Overman J, Pahwa R. Surgical and hardware complications of subthalamic stimulation: a series of 160 procedures. Neurology. 2004;63:612–6.
14. Blomstedt P, Hariz MI. Hardware-related complications of deep brain stimulation: a ten year experience. Acta Neurochir (Wien). 2005;147:1061–4.
15. Favre J, Taha JM, Steel T, Burchiel KJ. Anchoring of deep brain stimulation electrodes using a microplate. Technical note. J Neurosurg. 1996;85:1181–3.
16. Mohit AA, Samii A, Slimp JC, Grady MS, Goodkin R. Mechanical failure of the electrode wire in deep brain stimulation. Parkinsonism Relat Disord. 2004;10:153–6.
17. Chou KL, Siderowf AD, Jaggi JL, Liang GS, Baltuch GH. Unilateral battery depletion in Parkinson's disease patients treated with bilateral subthalamic nucleus deep brain stimulation may require urgent surgical replacement. Stereotact Funct Neurosurg. 2004;82:153–5.
18. Hariz MI. Complications of deep brain stimulation surgery. Mov Disord. 2002;17(Suppl 3):S162–6.
19. Pollak P, Krack P, Fraix V, Mendes A, Moro E, Chabardes S, Benabid AL. Intraoperative micro- and macrostimulation of the subthalamic nucleus in Parkinson's disease. Mov Disord. 2002;17(Suppl 3):S155–61.
20. Krack P, Fraix V, Mendes A, Benabid AL, Pollak P. Postoperative management of subthalamic nucleus stimulation for Parkinson's disease. Mov Disord. 2002;17(Suppl 3):S188–97.
21. Boghen D. Apraxia of lid opening: a review. Neurology. 1997;48:1491–4.
22. Barichella M, Marczewska AM, Mariani C, Landi A, Vairo A, Pezzoli G. Body weight gain rate in patients with Parkinson's disease and deep brain stimulation. Mov Disord. 2003;18:1337–40.
23. Macia F, Perlemoine C, Coman I, Guehl D, Burbaud P, Cuny E, Gin H, Rigalleau V, Tison F. Parkinson's disease patients with bilateral subthalamic deep brain stimulation gain weight. Mov Disord. 2004;19:206–12.
24. Krack P, Batir A, Van Blercom N, Chabardes S, Fraix V, Ardouin C, Koudsie A, Limousin PD, Benazzouz A, LeBas JF, Benabid AL, Pollak P. Five-year follow-up of bilateral stimulation of the subthalamic nucleus in advanced Parkinson's disease. N Engl J Med. 2003;349:1925–34.
25. Rodriguez-Oroz MC, Obeso JA, Lang AE, Houeto JL, Pollak P, Rehncrona S, Kulisevsky J, Albanese A, Volkmann J, Hariz MI, Quinn NP, Speelman JD, Guridi J, Zamarbide I, Gironell A, Molet J, Pascual-Sedano B, Pidoux B, Bonnet AM, Agid Y, Xie J, Benabid AL, Lozano AM, Saint-Cyr J, Romito L, Contarino MF, Scerrati M, Fraix V, Van Blercom N. Bilateral deep brain stimulation in Parkinson's disease: a multicentre study with 4 years follow-up. Brain. 2005;128(Pt 10):2240–9.
26. Takeshita S, Kurisu K, Trop L, Arita K, Akimitsu T, Verhoeff NP. Effect of subthalamic stimulation on mood state in Parkinson's disease: evaluation of previous facts and problems. Neurosurg Rev. 2005;28:179–87.
27. Funkiewiez A, Ardouin C, Caputo E, Krack P, Fraix V, Klinger H, Chabardes S, Foote K, Benabid AL, Pollak P. Long term effects of bilateral subthalamic nucleus stimulation on cognitive function, mood, and behaviour in Parkinson's disease. J Neurol Neurosurg Psychiatry. 2004;75:834–9.
28. Piasecki SD, Jefferson JW. Psychiatric complications of deep brain stimulation for Parkinson's disease. J Clin Psychiatry. 2004;65:845–9.
29. Burkhard PR, Vingerhoets FJ, Berney A, Bogousslavsky J, Villemure JG, Ghika J. Suicide after successful deep brain stimulation for movement disorders. Neurology. 2004;63:2170–2.

Cottonoid Retention After Craniotomy: Causes and Ways to Avoid It

Anton V. Kalinovskiy and Jamil A. Rzaev

Abstract

Nonabsorbable surgical material left in an surgical wound may cause early postoperative infections and specific types of granulomas; thus, it represents a dangerous complication in neurosurgery. The authors have analyzed their experience and present four cases of cottonoid retention after intracranial tumor resection. During 5-year period (from 2013 until 2017), the incidence of such an undesirable event after craniotomy for various indications was 0.07%. It was not related to the professional experience of the operating neurosurgeon, but cases of deep-seated lesions, the presence of brain edema or excessive bleeding of neoplastic or peritumoral tissue, prolonged surgeries, use of cottonoids without marking thread, and inadequate counting of disposable surgical materials at the end of the procedure may increase the risk of this complication. In all of the presented cases, the retained cottonoids were clearly seen on postoperative computed tomography because of the presence of radiopaque identifiers. All of the patients underwent an urgent reoperation for removal of the foreign body within 24 h after completion of the primary surgery, and they subsequently experienced an uneventful postoperative course without any complications. Well-coordinated work of the surgical team—in particular, appropriate communication between the surgeon and the circulating nurse during counting of surgical materials at the end of the procedure—is absolutely necessary for prevention of cottonoid retention after brain surgery.

Keywords

Complication · Cottonoids · Craniotomy · Neurosurgery · Preventive measures · Retained cottonoid · Retained foreign body · Risk factors

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Introduction

Nowadays, during neurosurgical operations, both absorbable and nonabsorbable materials are used routinely, either for local control of bleeding or for protection of brain tissue from possible mechanical traumatic effects of surgical instruments. Hemostatic collagen sponges (such as Gelfoam® [Pfizer; New York, NY, USA] or Spongostan™ [Ethicon Inc.; Somerville, NJ, USA]), oxidized cellulose (such as Surgicel® [Ethicon Inc.; Somerville, NJ, USA] or Okcel® [Synthesia; Pardubice, Czech Republic]), and polysaccharides (such as PerClot® [CryoLife Inc.; Kennesaw, GA, USA]) are resorbed completely within several weeks after being retained in the human body; thus, they can be left in the surgical wound upon completion of the operation with few related concerns. In contrast, nonabsorbable materials (such as cottonoids, also known as patties or paddies) should be removed at the end of the procedure but are occasionally retained *in situ*, which results in various consequences [1–5]. Herein, we analyze our unpleasant experience with such cases that happened during brain surgery and discuss possible causes, diagnostic and treatment options, and feasible measures for avoidance of this complication.

Materials and Methods

During a 5-year period (from 2013 until 2017), 22,621 various neurosurgical operations were performed overall at the Novosibirsk Federal Neurosurgical Center (Novosibirsk, Russia), and in 5565 of these cases, craniotomy was done. Two types of cottonoids (those with and without marking thread; Fig. 1) with radiopaque identifiers were used intraoperatively during cranial operations. Our standard treatment protocol includes routine control computed tomography (CT) examination of the head in the early postoperative period (i.e., within 24 h after surgery) in all patients undergoing craniotomy.

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_16

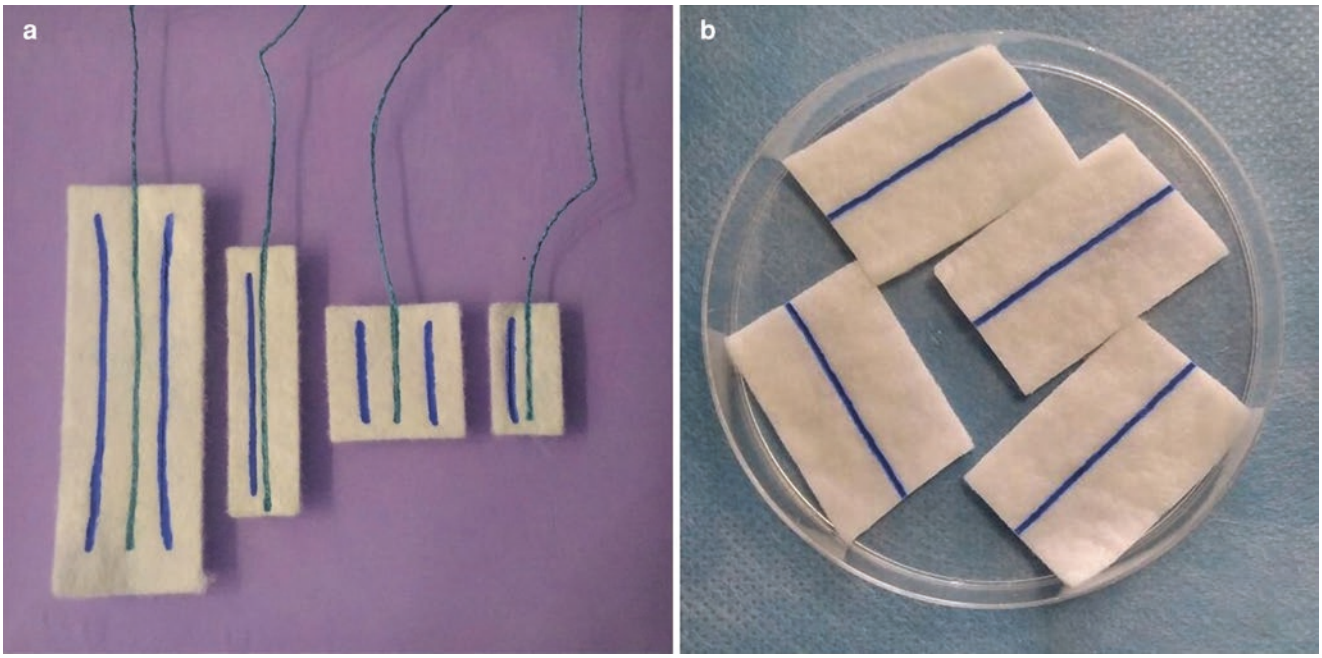

Fig. 1 Cottonoids with radiopaque identifiers and with (**a**) and without (**b**) marking thread, used during cranial operations at the Novosibirsk Federal Neurosurgical Center (Novosibirsk, Russia)

Results

During the study period, four cases of cottonoid retention after craniotomy were noted; thus, the overall incidence of this complication following such procedures in our practice was 0.07%.

All cases happened during the practice of neurosurgeons whose professional experience varied from 10 to 25 years (mean 16.5 years). The retained cottonoids were revealed by CT either immediately after the primary surgery (in two cases) or on the next day (in two cases). The distance between the retained cottonoid and the nearest margin of the craniotomy ranged from 48 to 68 mm (mean 56 mm). All patients underwent an urgent reoperation aimed at removal of the intracranially retained foreign body, which was done within 1–6 h after its imaging-based detection. All of the patients were discharged on the 8th–12th postoperative day (mean 10th postoperative day) after the reoperation, which is no different from our usual practice after brain surgery.

Case 1

A 70-year-old woman underwent removal of a giant olfactory groove meningioma >70 mm in diameter (Fig. 2a) via a right-side lateral supraorbital approach. The surgery was complicated by excessive bleeding of the tumor tissue and prominent edema of the adjacent brain, and lasted for 9 h. Cottonoids with radiopaque identifiers without marking thread were used, and their counting at the end of the operation was inadequate. Control CT was performed in 12 h after the surgery and revealed brain edema mainly affecting the frontobasal regions and caused by venous congestion and traction-induced injury, as well as a radiopaque foreign body on the left side of the anterior cranial fossa (Fig. 2b) adjacent to the basal surface of the left frontal lobe (i.e., on the opposite side from the surgical approach to the tumor). There were no clinical manifestations attributable to the intracranial presence of the foreign body, and reoperation was performed in 6 h after its imaging-based detection. It appeared to be a cottonoid strongly soaked with blood and partially obstructed by adjacent pieces of Surgicel®, which complicated its visual identification in the surgical field. The cottonoid was removed, and the reoperation lasted for 50 min in total. The postoperative period was uneventful, and the patient was discharged without any complications related to the foreign body retention (Fig. 2c).

Case 2

A 7-year-old girl underwent removal of a tumor located within the anterior horn of the left lateral ventricle (Fig. 3a) via an image-guided left-side transcortical approach through the middle frontal gyrus. The surgery was complicated by excessive bleeding of the tumor tissue and lasted for 8 h. Cottonoids with radiopaque identifiers without marking thread were used, and their counting at the end of operation

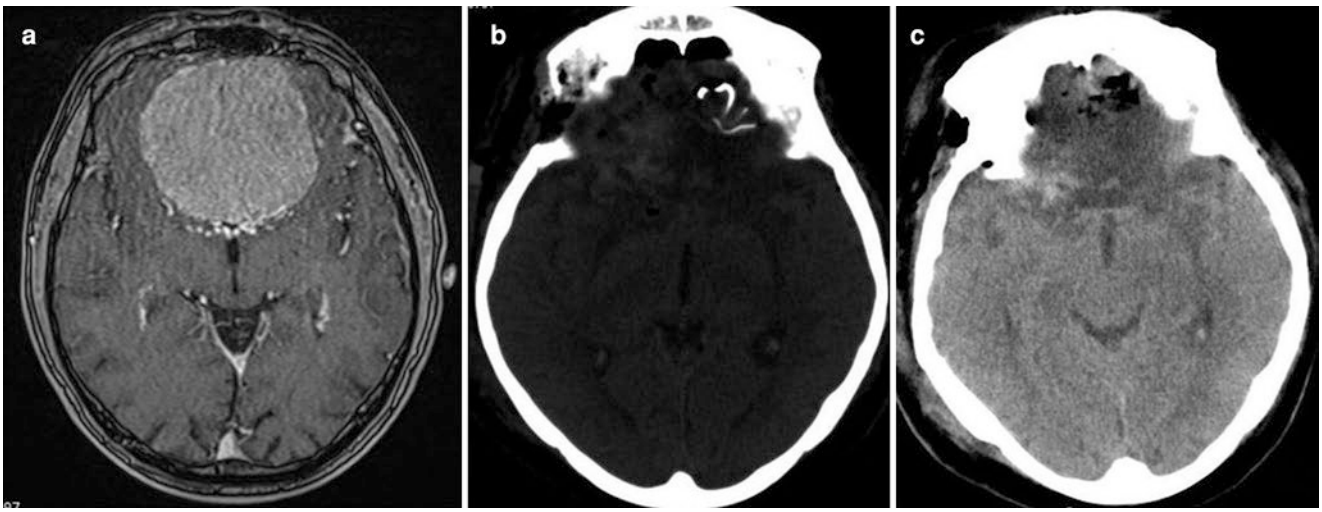

Fig. 2 In a 70-year-old woman, surgical removal of a giant olfactory groove meningioma was complicated by retention of a cottonoid in the wound. The tumor, >70 mm in diameter (**a**), was resected via a right-side lateral supraorbital approach. Control computed tomography (CT) in 12 h after the surgery (**b**) revealed a radiopaque foreign body on the left side of the anterior cranial fossa, opposite the side of the surgical approach, at a distance of 68 mm from the nearest margin of the craniotomy. The retained cottonoid was removed during a reoperation, as was confirmed by postoperative CT (**c**)

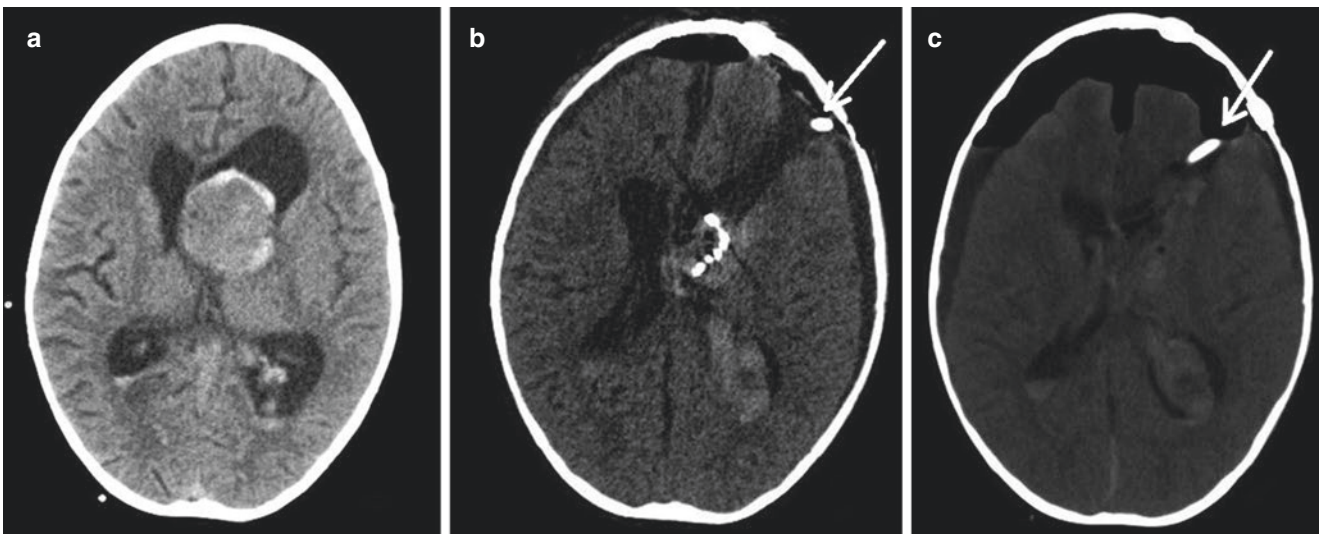

Fig. 3 In a 7-year-old girl, surgical removal of a tumor of the left lateral ventricle was complicated by retention of a cottonoid in the wound. The lesion, which predominantly occupied the anterior horn (**a**), was resected via a left-side transcortical approach. Control computed tomography (CT) in 12 h after the surgery (**b**) revealed a radiopaque foreign body, identified as a cottonoid, within an intraventricular hematoma in the area of the tumor resection. The retained cottonoid was removed during a reoperation, as was confirmed by postoperative CT (**c**). External ventricular drainage of the left lateral ventricle is indicated (*arrow*)

was inappropriate. Control CT was performed in 12 h after the surgery and revealed residual blood within the left lateral ventricle, as well as a radiopaque foreign body, identified as a cottonoid, within the intraventricular hematoma in the area of the tumor resection (Fig. 3b). Reoperation was performed in 6 h after the CT examination. The retained cottonoid was found inside the blood clot (which had obstructed its visualization intraoperatively) and removed. The postoperative period was uneventful, and the patient was discharged without any complications related to the foreign body retention (Fig. 3c).

Case 3

A 35-year-old woman with meningiomatosis underwent removal of a right trigone meningioma (Fig. 4a) via a right-side transcortical approach through the superior parietal lob-

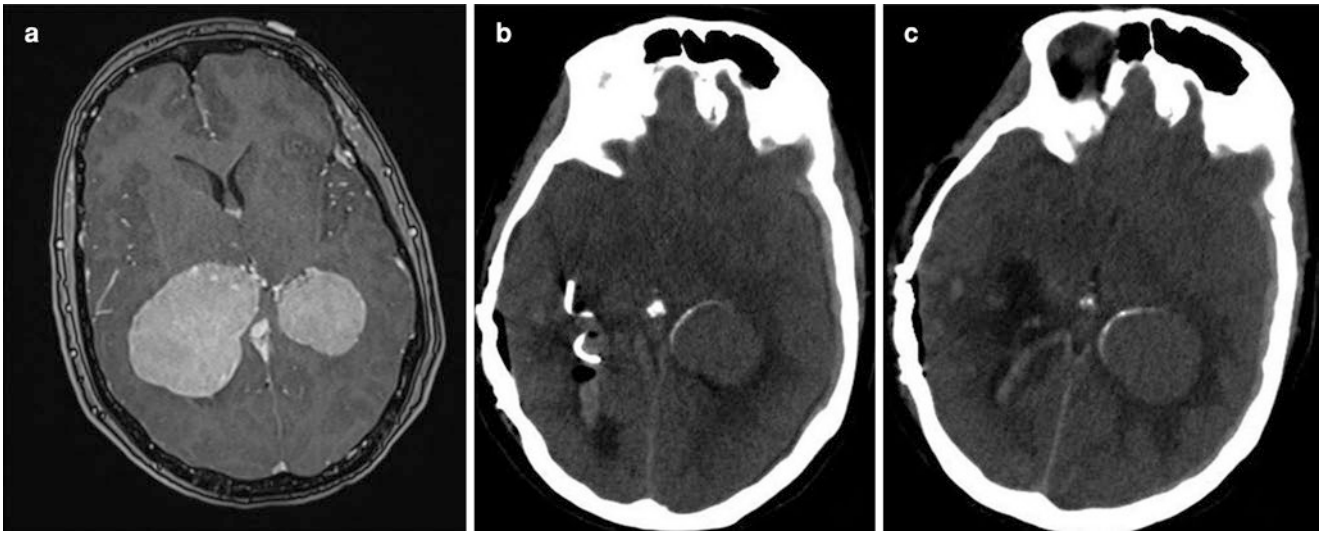

Fig. 4 In a 35-year-old woman with meningiomatosis, surgical removal of a right trigone meningioma was complicated by retention of a cottonoid in the wound. Preoperative magnetic resonance imaging demonstrated bilateral intraventricular tumors (**a**). The resection of the right-side mass lesion was uncomplicated, but the absence of one cottonoid was noted at the end of the surgery, and, despite all attempts, it was not possible to disclose its location. Immediate postoperative computed tomography (CT) revealed a radiopaque foreign body within the temporal horn of the right lateral ventricle (**b**). The patient was moved back to the operating room, and the cottonoid was removed during a reoperation, as was confirmed by postoperative CT (**c**)

ule. The tumor resection was routine and uncomplicated, and the surgery lasted for 3 h. However, at the time of hemostasis, pronounced brain edema developed as a result of premature awakening of the patient from anesthesia, which complicated precise inspection of the resected tumor bed. Cottonoids with radiopaque identifiers without marking thread were used. The absence of one cottonoid was noted during their counting at the end of the operation, but, despite all attempts, it was not possible to disclose its location. Therefore, the surgery was completed, and, immediately thereafter, the patient was transferred to the radiology department for head CT examination, which revealed a radiopaque foreign body within the temporal horn of the right lateral ventricle (Fig. 4b). The patient was moved back to the operating room, and reoperation for removal of the cottonoid was performed (approximately in 1 h after its identification by CT). The postoperative period was uneventful, and the patient was discharged without any complications related to the foreign body retention (Fig. 4c).

Case 4

A 64-year-old woman with a left-side anterior clinoid meningioma (Fig. 5a) underwent tumor removal via a pterional approach. The tumor resection was routine and uncomplicated, and the surgery lasted for 7 h. Cottonoids with radiopaque identifiers without marking thread were used. The absence of one cottonoid was noted during their counting at the end of operation, but, despite all attempts and thorough inspection of the surgical wound, it was not possible to disclose its location. Therefore, the surgery was completed, and, immediately thereafter, the patient was transferred to the radiology department for head CT examination, which revealed a radiopaque foreign body under the basal surface of the left temporal pole (Fig. 5b). The patient was moved back to the operating room, and reoperation for removal of the cottonoid was performed (approximately in 1 h after its identification by CT). It was noted that coverage of the cottonoid by pieces of Surgicel® may have significantly complicated its visual identification in the surgical field at the time of the initial operation. The postoperative period was uneventful, and the patient was discharged without any complications related to the foreign body retention (Fig. 5c).

Discussion

Retention of nonabsorbable foreign bodies in surgical wounds is widely recognized as a dangerous complication. Such incidents have been well investigated in abdominal, thoracic, and gynecological surgery [6]. Their reported rate in general surgery is 0.3–1.0 cases per 1000 operations, and suboptimal organization of the work in the operating room—particularly a lack of appropriate communication between surgical team members—is considered one of the main causes of this undesirable event [6]. In contrast, retention of

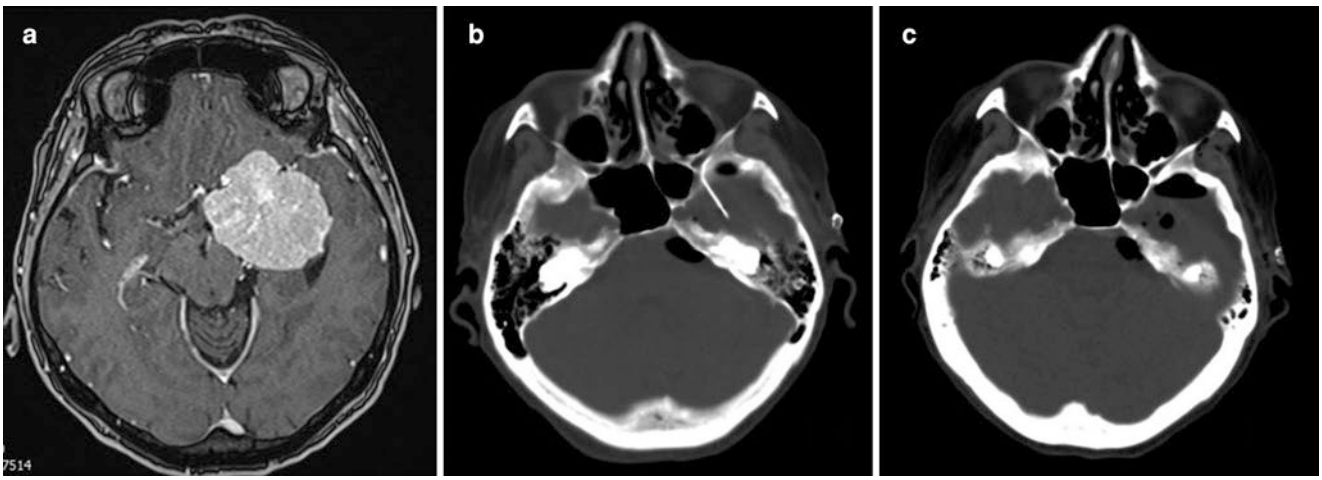

Fig. 5 In a 64-year-old woman, surgical removal of a left-side anterior clinoid meningioma was complicated by retention of a cottonoid in the wound. Preoperative magnetic resonance imaging demonstrated a large tumor (**a**), and its resection was uncomplicated, but absence of one cottonoid was noted at the end of the surgery, and, despite thorough inspection of the surgical wound, it was not possible to disclose its location. Immediate postoperative computed tomography (CT) revealed a radiopaque foreign body under the basal surface of the left temporal pole (**b**). The patient was moved back to the operating room, and the cottonoid was removed during a reoperation, as was confirmed by postoperative CT (**c**)

foreign bodies, such as cottonoids, in surgical wounds is rare after craniotomy, and only occasional observations of this complication, along with its short- and long-term consequences after various neurosurgical interventions, have been reported [1–5]. The analysis of four such cases from our own practice presented herein allows us to highlight several important issues related to possible causes and preventive measures.

Risk Factors for Cottonoid Retention After Craniotomy

Several lessons regarding possible risk factors for cottonoid retention after craniotomy and inability of the surgeon to identify them at the end of procedure can be learned from our unpleasant experience.

First of all, it should be emphasized that this complication is seemingly not related to the professional background of the operating neurosurgeon, which, in all our cases was sufficiently extensive.

Since the operated lesions were located either at the skull base or intraventricularly, all operative procedures in the presented cases were characterized by significant depth of the surgical wounds (the mean distance between the retained cottonoid and the nearest margin of the craniotomy was 56 mm). This might have created some obstacles for wide visualization of the entire resection cavity and identification of cottonoids, especially in the presence of brain edema or excessive bleeding of neoplastic or peritumoral tissue, which was observed in three of our four cases. The mean length of the surgery was 7.5 h (range 3–12 h), which suggests prolonged presence of cottonoids in the surgical wound and their gradual coverage by blood clots and tissue debris, complicating their visualization at the end of the procedure. In all of the presented cases, cottonoids without marking thread were used; thus, it may be considered that this type of disposable surgical material carries a somewhat greater risk of being left in the surgical wound. Indeed, the marking thread of the cottonoid usually extends a long way proximally, which effectively ensures prevention of foreign body retention (although at the cost of possible obstruction of the operative field view during the procedure). Finally, in two of the four presented cases, the counting of the disposable surgical materials at the end of the procedure was inadequate, since the circulating nurse did not report to the surgeon that the number of used cottonoids did not match the number recovered from the surgical wound. This emphasizes the crucial role of good communication between surgical team members and their clear comprehension of the importance of correct counting of surgical materials.

Detection of Retained Cottonoids

In our practice, postoperative CT is performed routinely within 24 h in all patients undergoing craniotomy to assess the brain condition and to check for possible surgical complications (e.g., an intracranial hematoma). In all of the pre-

sented cases, CT clearly detected the retained cottonoids because of the presence of their radiopaque identifiers. This may further support the usefulness of early postoperative CT examinations.

Moreover, in the two cases with mismatched material counts at the end of the procedure, head CT was performed immediately after the surgery and facilitated clinical decision-making with regard to urgent reoperation (which was done approximately within 1 h) and identification and removal of the foreign body. Thus, it may be considered a useful clinical strategy if the surgeon is unable to identify a cottonoid in the surgical wound at the end of a procedure. Clearly, intraoperative CT or magnetic resonance imaging (MRI), if available, may be a much better option in such a clinical scenario, since it allows detailed examination in the operating room before completion of the primary surgery, which may aid detection of cottonoids in the surgical wound and avoid the need for a subsequent reoperation.

Management of Cottonoid Retention After Craniotomy

If a retained cottonoid is detected in the surgical field after the operation, it should be removed without delay in order to prevent secondary complications. The latter may develop in the short term and/or the long term, and, depending on the reaction of the adjacent tissues to the presence of the foreign body, these complications may generally be divided into exudative and fibrotic ones [4]. Exudative complications usually appear early and are often associated with various infections (e.g., meningitis, encephalitis, and brain abscesses), whereas fibrotic ones are typically delayed and related to the formation of granulomas (also referred to as a gossypiboma or textilomas) around the retained material [4, 7, 8]. In many cases, such pathological processes may be misinterpreted on neuroimaging as residual or progressing neoplasms [2, 4, 8], and their clinical manifestations may include seizures or neurological deficits caused by pseudotumor formation and an associated mass effect [1].

All of our patients underwent urgent reoperation for removal of the retained cottonoid within 24 h after completion of the primary surgery. Thereafter, all of them experienced an uneventful postoperative course, and no specific requirements with regard to perioperative pharmacotherapy were noted. No infectious, neurological, or local surgical complications were observed in any case. Finally, there was no evident impact on the length of hospitalization. This experience demonstrates that in cases of cottonoid retention, urgent reoperation does not significantly increase the perioperative risks, and that early removal of the foreign body before development of secondary consequences allows their effective prevention.

It should be underlined, however, that reoperation, in itself, may be accompanied by certain complications, and—while it is absolutely necessary under such conditions from the medical viewpoint—it clearly increases the overall cost of treatment, may be accompanied by medicolegal consequences, and may result in litigation expenses, since retention of a foreign body in an operative wound is ultimately considered a serious error of surgical practice [9]. Therefore, every effort should be devoted to possible prevention of this undesirable event.

Measures to Prevent Cottonoid Retention in Surgical Wounds

On the basis of our analysis of the presented cases, we developed an algorithm for safe use of nonabsorbable surgical materials (cottonoids, swabs, and cloths) and introduced it into our practice in 2016. It largely corresponds to the guidelines for prevention of surgical item retention issued by the Association of Perioperative Registered Nurses (AORN) for use in the USA [10] and is mainly related to the counting of surgical materials at the end of the procedure, which is performed as described below.

A circulating nurse performs counting of all surgical materials before the operation, each time when a surgical team member is replaced, immediately before the final hemostasis in the surgical wound starts, before suturing of the dura mater, and immediately after the end of the operation. The final counts of the materials used during the surgery are noted in the corresponding records. During the course of the procedure, all used materials recovered from the wound are handed back to the circulating nurse. If a mismatch is found between the number of cottonoids used and those recovered from the wound, the circulating nurse immediately reports the shortage and informs the entire surgical team about the number of missing cottonoids. If the location of the missing cottonoids remains unclear, particularly at the end of the procedure, this fact is recorded in the emergency log. The responsible authorities (e.g., the chief of the surgical department) are notified immediately. If intraoperative CT is unavailable, a brain CT examination is performed immediately after completion of the procedure, and the operating surgeon makes a decision on the necessity and timing of reoperation.

During the intervention, the number of cottonoids placed in the surgical wound at the same time should not exceed the required minimum, which may reduce the risk of their loss. It can also be suggested that timely replacement of cottonoids during the course of the procedure might allow avoidance of their retention in the surgical wound and may be recommended as a preventive measure, especially if materials without marking thread are used. The latter require spe-

cial attention, since they may carry a somewhat greater risk of being retained in the surgical wound after the procedure.

Cottonoids without marking thread are preferred by many neurosurgeons in certain situations (e.g., during microdissection of an aneurysm neck or separation of an intrameatal facial nerve from an adjacent tumor) to minimize possible traumatic effects of the thread itself or of the knot at the edge of the cottonoid. Although, in general, cottonoids with marking thread should preferably be utilized during the subdural stage of an intracranial procedure, we consider use of cottonoids without marking thread fully justifiable, and this can be left to the discretion of the operating surgeon, who bears full responsibility for this decision. However, as a rule, we request that no more than one cottonoid without marking thread is used at the same time, and that it is replaced with a new one, as needed, in accordance with the one-for-one principle. In other words, the presence of more than one cottonoid without marking thread in the surgical wound during the subdural stage of the procedure is not allowed. Needless to say, use of cottonoids without radiopaque identifiers is prohibited.

Conclusion

Well-coordinated work of the surgical team—in particular, appropriate communication between the surgeon and the circulating nurse during surgical material counting at the end of the procedure—is absolutely necessary for prevention of cottonoid retention after brain surgery. If a foreign body is missing and there is even minimal suspicion of its presence in the surgical wound, immediate postoperative CT should be done. Identification of the retained cottonoid on neuroimaging should be followed by early reoperation for its removal. Such measures allow the risk of this complication to be minimized and prevent its possible consequences.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Bilginer B, Yavuz K, Agayev K, Akbay A, Ziyal IM. Existence of cotton granuloma after removal of a parasagittal meningioma: clinical and radiological evaluation—a case report. Kobe J Med Sci. 2007;53(1–2):43–7.
2. Ganau M, Nicassio N, Tacconi L. Postoperative aseptic intracranial granuloma: the possible influence of fluid hemostatics. Case Rep Surg. 2012;2012:614321.
3. Hsieh CT, Chung TT, Chen YH, Li YF, Liu MY. Textiloma as a complication of transspheoidal surgery. Neurosciences (Riyadh). 2011;16:369–71.
4. Kim AK, Lee EB, Bagley LJ, Loevner LA. Retained surgical sponges after craniotomies: imaging appearances and complications. AJNR Am J Neuroradiol. 2009;30:1270–2.
5. Kim E. A textiloma on the pterion: a rarely occurred craniotomy complication. J Korean Neurosurg Soc. 2013;53:252–4.
6. Zejnullahu VA, Bicaj BX, Zejnullahu VA, Hamza AR. Retained surgical foreign bodies after surgery. Open Access Maced J Med Sci. 2017;5:97–100.
7. Nishio Y, Hayashi N, Hamada H, Hirashima Y, Endo S. A case of delayed brain abscess due to a retained intracranial wooden foreign body: a case report and review of the last 20 years. Acta Neurochir (Wien). 2004;146:847–50.
8. Ribalta T, McCutcheon IE, Neto AG, Gupta D, Kumar AJ, Biddle DA, Langford LA, Bruner JM, Leeds NE, Fuller GN. Textiloma (gossypiboma) mimicking recurrent intracranial tumor. Arch Pathol Lab Med. 2004;128:749–58.
9. Kaiser CW, Friedman S, Spurling KP, Slowick T, Kaiser HA. The retained surgical sponge. Ann Surg. 1996;224:79–84.
10. Association of Perioperative Registered Nurses [AORN]. Guidelines for perioperative practice. Denver: AORN Publishing; 2017.

Complication Avoidance in Neurosurgery with Use of Intraoperative Ultrasonography

D. Gavin Quigley

Abstract

Intraoperative ultrasonography is an extremely valuable tool for avoidance of complications during neurosurgical procedures, including resection of intracranial and spinal cord tumors, removal of spontaneous intracerebral hemorrhages and arteriovenous malformations, and ventricular access for shunt placements. Nevertheless, application of this highly useful technique may be accompanied by some challenges and difficulties, as well as human errors; thus, it requires specific knowledge and continuous training.

Keywords

Complication · Human error · Intraoperative ultrasound · Neurosurgery · Preventive measures

Introduction

The use of intraoperative ultrasonography in neurosurgery offers a number of key advantages over other imaging modalities. Ultrasound scanners offer portability, favorable costs, single-user operation, and, perhaps most critically, real-time live images. This combination of features makes such a technique an ideal addition to any neurosurgical operative suite [1, 2]. However, intraoperative acquisition of useful images requires the understanding of basic ultrasonographic principles and careful consideration of patient positioning during surgery [3].

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Basic Issues

Experience and training within neurosurgical departments across the globe vary widely from units that have used intraoperative ultrasonography for many years to those with no previous exposure to it. Nevertheless, for ultrasonography to be used successfully in neurosurgery, a few fundamental principles must be adhered to. The most critical one is "air is the enemy of ultrasound"—something that all sonographers and radiologists are acutely aware of [4]. Neurosurgeons, however, have rarely encountered diagnostic ultrasonography in their training.

In the vast majority of cases, poor ultrasound image quality is a result of inadequate bone opening and/or air between the probe and the brain (or the spinal cord). It is often necessary to enlarge the bone opening to accommodate the ultrasound transducer; this is particularly true during the use of smaller burr-hole probes [5]. Modern drills with disposable perforators leave a small lip of bone on the inside of the burr hole, which prevents secure acoustic contact with the dura. Good acoustic contact requires the use of sterile ultrasound gel or saline between the transducer and the brain/dura. This can be achieved by a number of methods; the transducer can be covered with a sterile sleeve and gel placed inside, gel/saline can be used to fill the holes, and larger cavities can be filled with saline or water.

The display screen of the ultrasound scanner must be positioned within the surgeon's eyeline and be clearly visible without the need for movement away from the operative field. It is critically important that consideration is given to the position of the scanner before surgery commences, and it is generally best to ensure that the ultrasound scanner is up and running before the surgical procedure begins. Surgeons may find it helpful to dim the ambient lighting during scanning.

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_17

As a general rule, larger transducers, with their greater density of crystals within the ultrasound array, produce the highest-quality images. Therefore, a larger craniotomy-type transducer should be used in preference to burr-hole designs, space permitting. These larger transducers have a much wider field of view and much greater lateral resolution.

Integration with image guidance systems is possible with a number of dedicated ultrasound devices, and, if attainable, their use in combination is highly recommended for those practitioners who are unfamiliar with ultrasonography. This allows the live ultrasound image to be overlaid on the preoperative navigation images [6, 7]. It is a much more intuitive way of viewing real-time ultrasound images and avoids the spatial disorientation associated with their freehand acquisition. Since it is possible to image in any direction with an ultrasound probe, discipline must be maintained in order to acquire images in at least two of the three common planes. During imaging of lesions close to the vertex, sagittal and coronal images should be obtained; lesions in the parietal and temporal regions allow imaging in both axial and coronal planes. The author recommends the acquisition of two images scanned at 90° to each other prior to dural opening; ideally, these images should be saved to permit future comparison.

It is beyond the scope of this review to discuss the underlying assumptions that ultrasound imaging is based upon. (Readers are encouraged to look through one of the standard ultrasonography texts, such as *Diagnostic Ultrasound: A Logical Approach* by McGahan and Goldberg [4] or *Intraoperative Imaging in Neurosurgery* by Narang and Jha [5].) These assumptions are the basis for a number of artifacts created by ultrasonography in the brain and lead to poor image quality. Potential solutions are outlined in an excellent article by Selbekk et al. [8]; in particular, the use of saline/water gives rise to a brightness artifact at the base of resection cavities during tumor removal, and the authors propose the development of a fluid with better ultrasound characteristics, the performance of which is already being tested in ongoing trials.

Ultrasound technology has improved markedly over the last two decades, thanks in no small part to the increase in the power of graphic processing units; neurosurgeons can be reassured that ultrasound images are very much on par with the resolution of computed tomography (CT) scanners. Indeed, in some instances, they produce even better resolution than CT, particularly in relation to lesions such as low-grade gliomas [9]. As discussed, care, attention, and patience are required to gain the best from this imaging modality. Centers that possess the latest generation of intraoperative CT and/or magnetic resonance imaging (MRI) scanners will still find value in the use of intraoperative ultrasonography, since it permits a very rapid image to be obtained prior to any move toward more time-consuming and expensive fixed scanners.

Complication Avoidance

Perhaps the most reassuring feature of intraoperative ultrasonography is that imaging confirmation of pathology can be obtained prior to dural opening. Although it does not prevent wrong-site surgery from occurring, it can at least avert unnecessary neural injury if wrong-site surgery has occurred.

Tumors

Increasing scientific evidence has led neurosurgeons to undertake increasingly aggressive resection of intrinsic gliomas over the last decade [10–12]. There are numerous strategies, such as intraoperative neuronavigation, intraoperative MRI/CT, fluorescence-guided resection, and awake surgery with intraoperative brain mapping. All of these adjuncts offer some advantages to the surgeon, but none is a single solution guaranteeing complete resection of the neoplasm. It is perhaps best to think of each strategy as a small piece of a puzzle, adding definite but incremental benefits to the surgeon's ability to completely resect intrinsic lesions [13]. Individual units will have clear preferences for one strategy over another, and the best results come from understanding the limitations of each technology.

The unique ability of intraoperative ultrasonography to provide live images during tumor resection is perhaps its most obvious strength for many surgical oncologists. Many high-grade lesions are easily identifiable on ultrasonography, and, with regular scanning, it is a valuable aid to resection (Fig. 1) [14, 15].

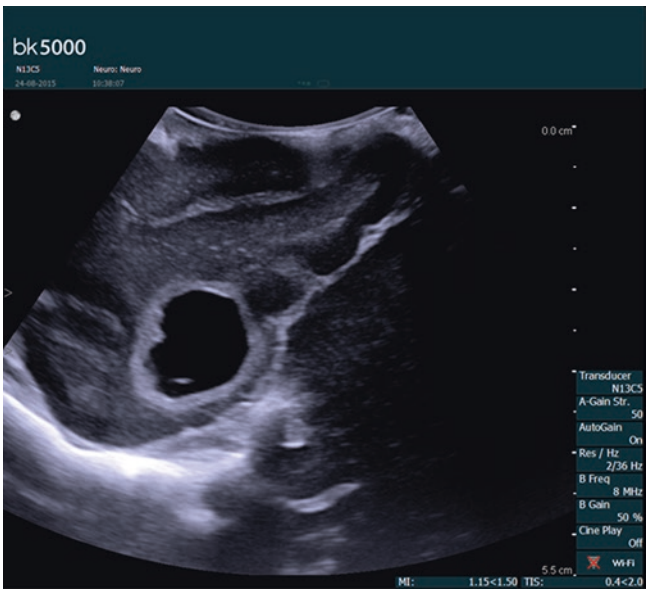

Fig. 1 Intraoperative image of a temporal lobe high-grade glioma, obtained with a modern ultrasound scanner

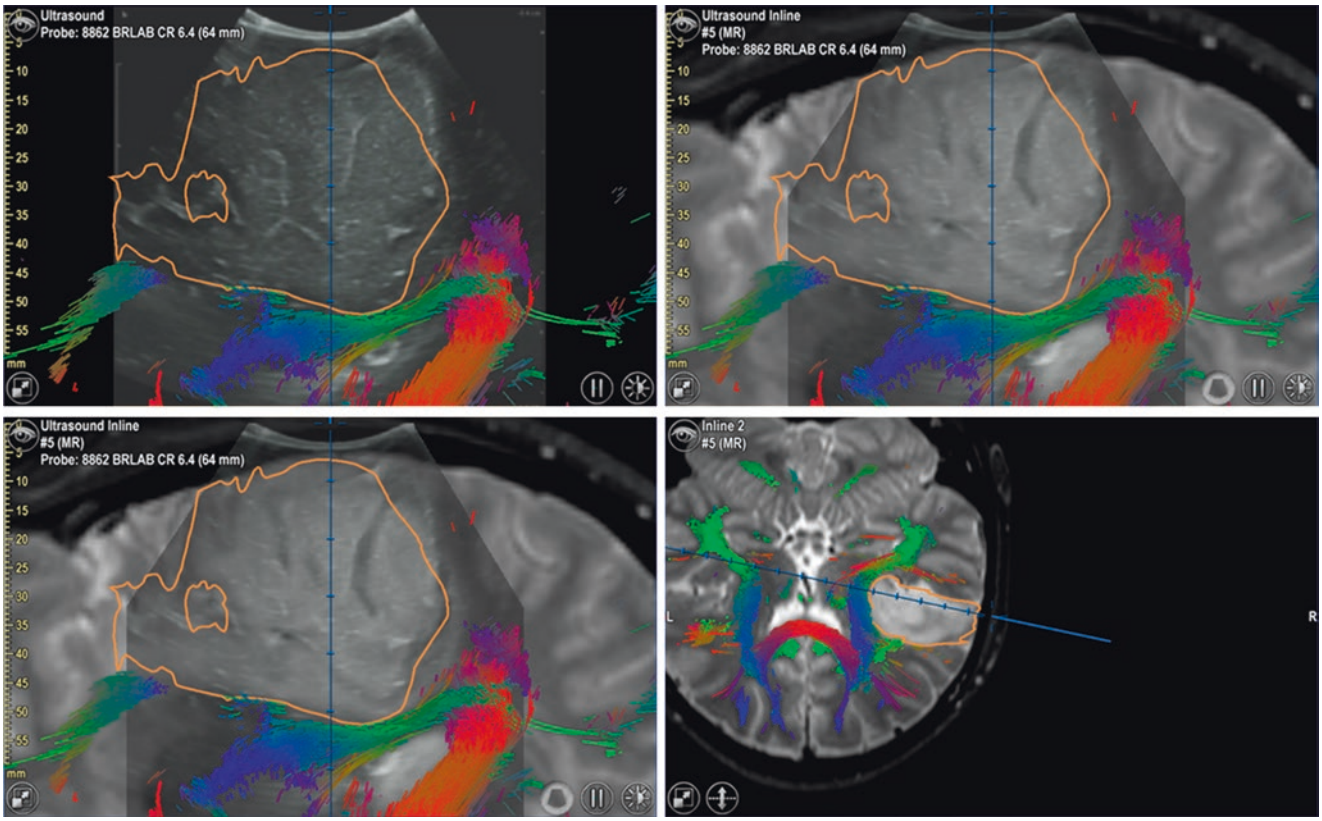

Fig. 2 Screenshot of intraoperative ultrasonography overlaid onto a preoperative navigation planning scan. The image demonstrates a subtle but definite brain shift even though the dura has yet to be opened

Low-grade gliomas continue to present multiple challenges for neurosurgeons, though clear evidence is emerging of the role of maximum gross resection in their management [11, 16]. Intraoperative ultrasonography in combination with previously discussed strategies provides a neurosurgeon with valuable real-time information during these challenging cases. The combination of intraoperative ultrasonography and navigation technology lends itself to low-grade glioma reception and may reveal a brain shift even though the dura has yet to be opened (Fig. 2). This alerts the surgeon to the problem early in the course of the operation and allows corrective action to occur. Obviously, the brain shift is more pronounced in high-grade lesions or superficial metastatic lesions. Modern navigation systems permit object shift correction based on intraoperative ultrasonography, which is clearly desirable when the surgeon is looking for small-volume lesions.

Virtually continuous live imaging obtained with intraoperative ultrasonography allows the surgeon to be reassured that the surgical approach is proceeding in the correct direction and avoiding any critical structures (Fig. 3).

Modern navigation systems permit the acquisition of three-dimensional (3D) ultrasound volumes and allow sub-

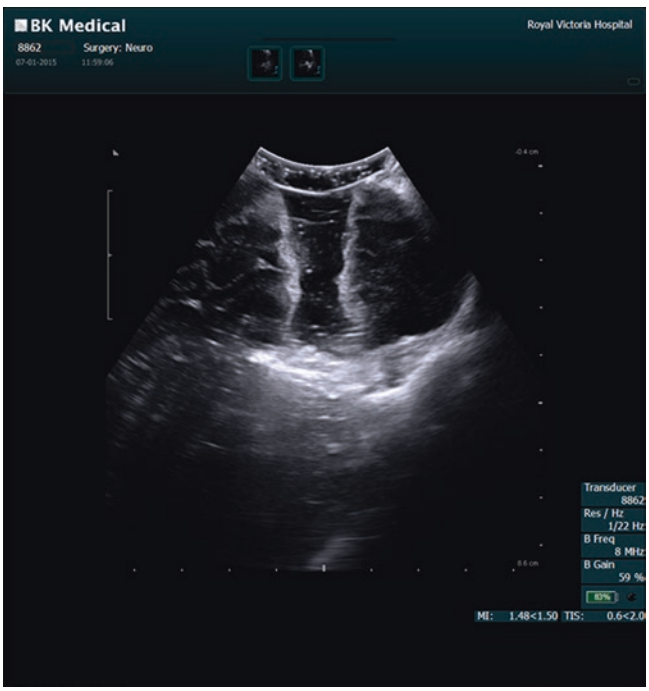

Fig. 3 A typical ultrasound view of the surgical tract through the brain (in this case, toward a cavernous malformation adjacent to the cavernous sinus)

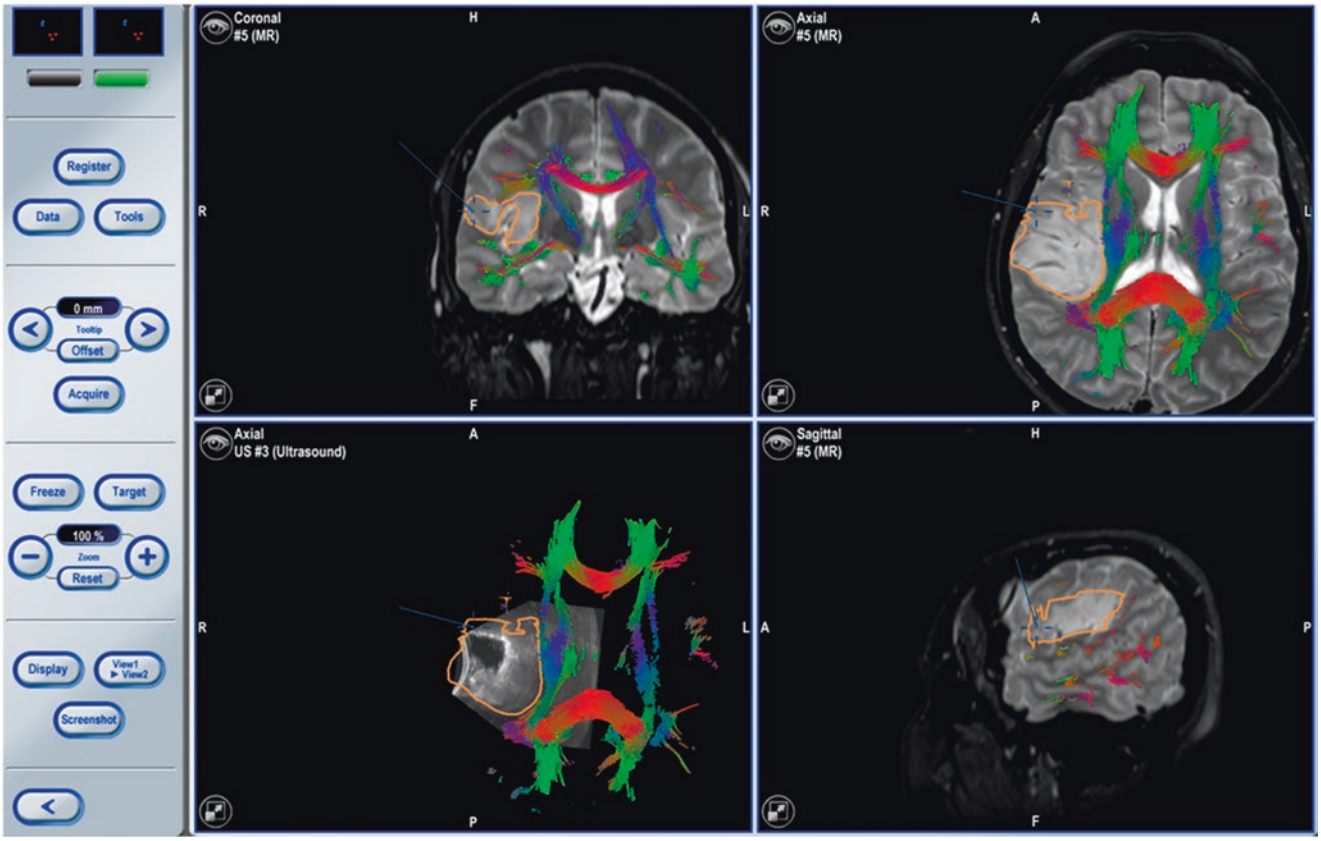

Fig. 4 Three-dimensional ultrasound volume created during resection of a low-grade glioma. Partial resection of the lesion is shown. Further updates will help the surgeon to identify how the resection is proceeding

sequent navigation from these acquired data sets [3, 14, 17]. This is a particularly useful feature during resection of large lesions, such as superficial low-grade gliomas (Fig. 4). It can be a very helpful feature in the scenario where the image guidance has become inaccurate, perhaps because of a brain shift. New data sets can be continually acquired with the use of intraoperative ultrasonography; this can also be done using color flow imaging, which allows 3D demonstration of blood vessels around the lesion.

Vascular Lesions

Spontaneous intracerebral hemorrhage represents a ubiquitous challenge worldwide, and while the role of surgery may not have been definitively demonstrated, evacuation of a hematoma remains a common procedure [18]. In most cases, navigation is not routinely applied, and often no preoperative angiography is available. Not only does ultrasonography show the extent of the hemorrhage, but also the use of Doppler imaging can avoid unplanned exploration into the nidus of an arteriovenous malformation (AVM). Of note, even simple Doppler ultrasonography can show the biphasic flow characteristic of an AVM. Intraoperative ultrasonography has also been shown to be helpful during elective surgical resection of an AVM, and this technique can be combined with the use of contrast material to demonstrate the arterial and venous components of the malformation [19].

Spinal Cases

Intraoperative ultrasonography can be a very valuable adjunct in the performance of spinal surgery, particularly during resetting of intradural lesions [20]. For example, when the surgeon is faced with a meningioma covering several vertebral levels, small window laminotomies can be created to allow ultrasound assessment of the extent of laminectomy required. The spine is well suited to ultrasonography after removal of laminae; the patient position is typically prone, and the cord itself is surrounded by cerebrospinal fluid (CSF) sitting in a bony canal. This relatively short imaging distance means that high-frequency linear probes may be used, giving very detailed images of the underlying tissue. Color Doppler imaging of the spine is also possible and can quickly identify feeding vessels. Intramedullary lesions such as a syrinx or

tumor are particularly well demonstrated, and ultrasonography lends itself specifically effective to drainage or placement of catheters within a syrinx [21].

Ventricular Access and Shunt Placement

Accurate placement of intraventricular catheters remains a challenge for all neurosurgical departments [22, 23], and, since the ventricular system is clearly visible on ultrasonography, these cases are perhaps the most obvious use for this technique in neurosurgery. The smaller ultrasound arrays used in burr hole–type probes inevitably produce a narrow field of view and lower resolution. These factors can present significant difficulties where the ventricular system is extremely small. That said, practice and patience will produce satisfactory results in almost all cases [24, 25].

Not only can ultrasonography assist with insertion of the interventricular component of shunt devices, but also it can be used to accurately place distal catheters in the jugular venous system [26]. Lost or broken catheters either under the subcutaneous tissue or even within the thecal sack can be located accurately with ultrasonography. Very superficial pieces of some tubing can be detected with the use of high-frequency linear probes, eliminating the need for C-arm imaging.

Challenges

Because of person-to-person variation or indeed iatrogenic acts, no single imaging modality has the ability to image the human body without technical difficulties. Ultrasonography is no exception to this; in particular, the effect of previous surgery can chnge the ultrasound characteristics of neural tissue dramatically. In the case of previous cranial or spinal radiotherapy, this can result in nondiagnostic imaging from an ultrasound scan, caused by the effects of radiation [15]. This effect varies from patient to patient, and, in some instances, satisfactory imaging can be obtained in spite of previous surgery or radiotherapy. Further studies are necessary to confirm whether or not contrast-enhanced ultrasonography may help to overcome some of these difficulties [27].

Conclusion

Complications in surgical practice are unavoidable by nature; however, we must learn lessons from avoidable or recurring mistakes. Reason has written extensively on the subject of human error and notes that “we cannot change the human condition, but we can change the conditions under which humans work” [21, 28]. It is tempting for us to blame individuals for mistakes, but, as Reason and others have pointed out, this person-centered approach to error is unlikely to be helpful within medical systems. It is far better that we learn via a systematic approach to errors and consider ways of making the system safer for both patients and the staff involved. If we consider poor image quality failure, then, by looking at models such as Reason’s Swiss cheese model, we can see that the majority of failures are latent by nature [21]. In the case of ultrasound imaging, this scenario is typically due to a rushed setup, failure to open the bone widely enough, attempts to image with air between the transducer and the target tissue, or failure to pay sufficient attention to depth or gain settings.

Conflict of Interest Statement The author has no conflict of interest concerning the reported materials or methods.

References

1. Chandler WF, Knake JE, McGillicuddy JE, Lillehei KO, Silver TM. Intraoperative use of real-time ultrasonography in neurosurgery. J Neurosurg. 1982;57:157–63.
2. Dohrmann GJ, Rubin JM. History of intraoperative ultrasound in neurosurgery. Neurosurg Clin N Am. 2001;12:155–66, ix.
3. Moiyadi AV, Shetty P. Direct navigated 3D ultrasound for resection of brain tumors: a useful tool for intraoperative image guidance. Neurosurg Focus. 2016;40(3):E5.
4. McGahan JP, Goldberg BB, editors. Diagnostic ultrasound: a logical approach. New York: Lippincott-Raven; 1998.
5. Narang KS, Jha AN, editors. Intraoperative imaging in neurosurgery. Jaypee Brothers: New Delhi; 2017.
6. Solheim O, Selbekk T, Jakola AS, Unsgård G. Ultrasound-guided operations in unselected high-grade gliomas—overall results, impact of image quality and patient selection. Acta Neurochir (Wien). 2010;152:1873–86.
7. Nikas DC, Hartov A, Lunn K, Rick K, Paulsen K, Roberts DW. Coregistered intraoperative ultrasonography in resection of malignant glioma. Neurosurg Focus. 2003;14(2):E6.
8. Selbekk T, Jakola AS, Solheim O, Johansen TF, Lindseth F, Reinertsen I, Unsgård G. Ultrasound imaging in neurosurgery: approaches to minimize surgically induced image artefacts for improved resection control. Acta Neurochir (Wien). 2013;155:973–80.
9. Gerganov VM, Samii A, Akbarian A, Stieglitz L, Samii M, Fahlbusch R. Reliability of intraoperative high-resolution 2D ultrasound as an alternative to high-field strength MR imaging for tumor resection control: a prospective comparative study. J Neurosurg. 2009;111:512–9.
10. Sanai N, Polley MY, McDermott MW, Parsa AT, Berger MS. An extent of resection threshold for newly diagnosed glioblastomas. J Neurosurg. 2011;115:3–8.
11. Duffau H. Long-term outcomes after supratotal resection of diffuse low-grade gliomas: a consecutive series with 11-year follow-up. Acta Neurochir (Wien). 2016;158:51–8.
12. Brown PD, Maurer MJ, Rummans TA, Pollock BE, Ballman KV, Sloan JA, Boeve BF, Arusell RM, Clark MM, Buckner JC. A prospective study of quality of life in adults with newly diagnosed high-grade gliomas: the impact of the extent of resection on quality of life and survival. Neurosurgery. 2005;57:495–504.

13. Altieri R, Meneghini S, Agnoletti A, Tardivo V, Vincitorio F, Prino E, Zenga F, Ducati A, Garbossa D. Intraoperative ultrasound and 5-ALA: the two faces of the same medal? J Neurosurg Sci. 2019;63:258–64.
14. Gronningsaeter A, Kleven A, Ommedal S, Aarseth TE, Lie T, Lindseth F, Langø T, Unsgård G. SonoWand, an ultrasound-based neuronavigation system. Neurosurgery. 2000;47:1373–80.
15. Hammoud MA, Ligon BL, Elsouki R, Shi WM, Schomer DF, Sawaya R. Use of intraoperative ultrasound for localizing tumors and determining the extent of resection: a comparative study with magnetic resonance imaging. J Neurosurg. 1996;84:737–41.
16. Sanai N, Berger MS. Glioma extent of resection and its impact on patient outcome. Neurosurgery. 2008;62:753–66.
17. Lindseth F, Langø T, Bang J, Nagelhus Hernes TA. Accuracy evaluation of a 3D ultrasound–based neuronavigation system. Comput Aided Surg. 2002;7:197–222.
18. Mendelow AD, Gregson BA, Fernandes HM, Murray GD, Teasdale GM, Hope DT, Karimi A, Shaw MD, Barer DH. Early surgery versus initial conservative treatment in patients with spontaneous supratentorial intracerebral haematomas in the International Surgical Trial in Intracerebral Haemorrhage (STICH): a randomised trial. Lancet. 2005;365:387–97.
19. Wang Y, Wang Y, Wang Y, Taniguchi N, Chen XC. Intraoperative real-time contrast-enhanced ultrasound angiography: a new adjunct in the surgical treatment of arteriovenous malformations. J Neurosurg. 2007;107:959–64.
20. Solanki SP, White BD. The anaesthetist's SonoSite probe—successful adjunct to complex intradural spinal surgery or poor man's intraoperative ultrasound? Br J Neurosurg. 2016;30:464–6.
21. Reason J. Human error: models and management. BMJ. 2000;320:768–70.
22. Abdoh MG, Bekaert O, Hodel J, Diarra SM, Le Guerinel C, Nseir R, Bastuji-Garin S, Decq P. Accuracy of external ventricular drainage catheter placement. Acta Neurochir (Wien). 2012;154:153–9.
23. Wan KR, Toy JA, Wolfe R, Danks A. Factors affecting the accuracy of ventricular catheter placement. J Clin Neurosci. 2011;18:485–8.
24. Kullmann M, Khachatryan M, Schuhmann MU. Ultrasound-guided placement of ventricular catheters in first-time pediatric VP shunt surgery. Childs Nerv Syst. 2018;34:465–71.
25. Phillips SB, Gates M, Krishnamurthy S. Strategic placement of bedside ventriculostomies using ultrasound image guidance: report of three cases. Neurocrit Care. 2012;17:255–9.
26. McCracken JA, Bahl A, McMullan J. Percutaneous ultrasound-guided insertion of ventriculo-atrial shunts. Br J Neurosurg. 2016;30:411–3.
27. Prada F, Perin A, Martegani A, Aiani L, Solbiati L, Lamperti M, Casali C, Legnani F, Mattei L, Saladino A, Saini M, DiMeco F. Intraoperative contrast-enhanced ultrasound for brain tumor surgery. Neurosurgery. 2014;74:542–52.
28. Reason J. The human contribution: unsafe acts, accidents and heroic recoveries. Burlington: Ashgate; 2008.

Complication Avoidance in Spine Surgery

Mehmet Zileli

Abstract

The outcomes of spine surgery are closely related to postoperative morbidity. Therefore, an experienced surgeon must be aware of various complications and should apply all necessary preventive measures to avoid them. It is widely considered that complications of spine surgery are underreported and that their real incidence is much higher than expected. This review highlights methods to prevent various types of morbidity that may be encountered during different spinal procedures, considering general complications, approach-related complications, fusion- and implant-related complications, and systemic complications.

Keywords

Cerebrospinal fluid leakage · Complication · Implant failure · Neurological deterioration · Postoperative infection · Pseudoarthrosis · Spine surgery · Vascular injury

Introduction

The main reasons for complications in spine surgery include poor patient selection, incorrect diagnosis, an ill-chosen approach, inadequate execution of the procedure (e.g., incomplete decompression of a compressive lesion), and injury of normal anatomical structures [1]. The surgeon should have clearly established the diagnosis and have a precise, three-dimensional (3D) understanding of the pathological anatomy, as demonstrated by imaging studies. Finally, an astute surgeon should use common sense by measuring twice, cutting once, and paying meticulous attention to all details [1].

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In a meta-analysis, Nasser et al. [2] noted a 16.4% overall incidence of complications after spine surgery, which were found to be more common in cases of thoracolumbar procedures (17.8%) than in cases of cervical procedures (8.9%). In a retrospective study conducted by the Scoliosis Research Society [3], the overall complication rates in 9692 lumbar microdiscectomy procedures, 6735 anterior cervical discectomy and fusion (ACDF) procedures, and 10,329 lumbar stenosis decompression procedures were 3.6%, 2.4%, and 7.0%, respectively. However, retrospective reviews may significantly underestimate the rates of such morbidity. Another problem is that the recognition of complications by the surgeon and the patient is different. In a study by Mannion et al. [4], surgeons reported lower complication rates than patients did, and there was only moderate agreement between them in such assessments; as a result, in a group of 2303 patients, the complication rates reported by surgeons and patients were 15.3% and 27%, respectively.

This review summarizes common general, approach-related, fusion- and implant-related, and systemic complications in spine surgery, and highlights necessary preventive measures for their avoidance.

General Complications

General complications of spine surgery are related to neurological injury, dural laceration, patient positioning during anesthesia, air embolism, intubation, and postoperative infection.

Neurological Injury

Injuries of the spinal cord or nerve roots are not rare. For their avoidance, the surgeon should apply advanced microsurgical techniques, meticulous handling of neural structures, and use of high-speed drills during bony decompression.

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_18

Attention should be paid to (1) patient positioning, (2) illumination and visualization, (3) anesthetic and surgical techniques, (4) surgeon positioning, and (5) intraoperative evoked potentials monitoring.

Steroids: The role of perioperative steroid use in spine surgery to prevent injuries of the spinal cord and nerve roots is controversial. In any case, administration of steroids before spinal cord injury confers greater benefit than their administration after injury [5, 6]. Although the literature data are inconclusive, some surgeons prefer to administer 4–8 mg of dexamethasone (or an equivalent dosage of methylprednisolone) preoperatively and to continue steroid administration for 24 h postoperatively in high-risk cases. Because short-term use of steroids has reportedly been effective in experimental studies [5, 7] whereas long-term administration is associated with an increased risk of complications, their use for more than 24 h seems unnecessary (and may be harmful).

Dural Laceration

An unintended tear of the dura mater is a common complication of spine surgery. Its incidence rates in different reported series have ranged from 3.1% to 14% [8–10]. Immediately after surgery, an incidental dural tear may cause headaches. Subsequently, it may result in a wound infection, meningitis, or a cerebrospinal fluid (CSF) fistula. In the longer term, it frequently leads to persistent CSF leakage, pseudomeningocele formation, a neurological deficit, and arachnoiditis [8]. Persistent CSF leakage may result in wound dehiscence and subsequent infection. If a CSF fistula is big enough, fluctuations in the conscious state may be observed [11], and intracranial hemorrhage may develop [12]. After ventral cervical spine surgery, a CSF fistula may even cause airway obstruction [13], whereas after ventral or dorsolateral surgery of the thoracic spine, it may cause formation of a subarachnoid–pleural fistula [14, 15]. Therefore, a dural tear should be recognized in a timely manner and treated appropriately.

To prevent CSF leakage, the surgeon may effectively use fibrin sealants, which are biologically derived substances consisting of fibrinogen solution and thrombin, with a calcium cofactor [16]. They are commonly applied as adhesives to augment other layers of wound closure. A retrospective review of fibrin sealants indicated that they reduce the incidence of postoperative CSF leakage and tension pneumocephalus, while also decreasing the overall costs of treatment [16]. Nakamura et al. [17] reported that in terms of cost, autologous fibrin tissue adhesive is superior to commercial fibrin tissue adhesive.

A CSF cutaneous fistula and pseudomeningocele are end-stage complications of an improperly managed dural tear. They may dramatically increase morbidity, treatment costs, pain, and neurological deficits, and so they must be treated properly and aggressively [18]. The first priority is to implement CSF diversion (i.e., external lumbar drainage). A percutaneous blood patch may also be tried. Revision surgery to repair a dural defect may be indicated. In particular, if a pseudomeningocele is noted and CSF leakage persists, it may become necessary to perform dural and myofascial closure via an open reoperation. In difficult cases, a CSF shunt (most often, a lumboperitoneal shunt) may also be necessary.

Patient Positioning

Numerous complications—including air embolism, quadriplegia, peripheral nerve palsies, piriformis syndrome, posterior compartment syndrome, and excessive bleeding—are associated with improper patient positioning during anesthesia and surgery. For their prevention, several measures may be recommended.

Elastic bandages or sequential compression devices should be placed on the lower extremities before induction of anesthesia. The legs must not be lower than the hips in the sitting position. Great care should be taken in moving the patient into the prone position. Compression of the eyes, with resulting blindness, has been reported with use of a horseshoe headrest [19, 20]. Therefore, the head should be positioned appropriately to prevent it from slipping on the horseshoe headrest. Three-point skull fixation in the prone position is a viable alternative option and can reduce the incidence of this complication, although it can itself be associated with a variety of other (generally minor) adverse events.

Extreme rotation, extension, or flexion of the head may result in cervical spinal cord damage. Older patients with cervical spondylotic bars are more prone to this complication. Awake positioning, awake intubation, and intraoperative evoked potentials monitoring may be helpful as preventive measures. Loss of somatosensory evoked potentials (SSEP) with neck flexion and recovery with its repositioning have been reported [21]. In patients with severe spinal canal narrowing, the neutral or near-neutral position of the neck is preferred.

A stretching injury of the brachial plexus may occur in both the prone and supine positions through abduction of the arm by more than 90°. An axillary roll should be used to prevent injury during the lateral decubitus position when the dependent arm is compressed. The ulnar nerve could be injured because of its superficial position at the elbow; a pad under an extended elbow helps to prevent this. Elbow extension minimizes exposure of the ulnar nerve to compression. The radial nerve may be injured if the arm hangs over the operating table edge; padding under the arm may prevent compression injury. Common peroneal nerve injury with resulting foot drop may occur in the supine, sitting, and lat-

eral decubitus positions; the superficial location of this nerve at the head of the fibula may increase the risk of its compression. The superficial femoral nerve may be compressed in the prone position, which can cause transient meralgia paresthetica postoperatively. The rate of injury of the lateral femoral cutaneous nerve has been reported to be as high as 20% [22]. External pressure on the anterior superior iliac spine during the prone position is the main reason for its injury; on the other hand, this nerve may be injured at the retroperitoneum by a hematoma or traction, as well as during bone graft harvesting at the ventral iliac crest.

Compression and stretching injury of any nerve is possible during surgical positioning. A general rule of thumb is to use a position without excessive compression of the extremities and to place appropriate pads beneath potentially exposed nerves. If the patient appears comfortable, nerve injury is less likely.

Air Embolism

Air embolism is one of the most serious complications encountered in spine surgery. It is predominantly related to operations performed above the level of the heart [23]. Two precautions to avoid air embolism are suggested. First, if possible, avoid the sitting position. The incidence (which is as high as 50%) and clinical importance of air embolism are greater in the sitting position than in other positions during surgery under general anesthesia. In addition, one should not administer nitrous oxide when using the sitting position. Second, during intervention, monitor the patient at risk meticulously with Doppler ultrasound and end-tidal CO_2, particularly if the operation is performed in the sitting position. Of note, Doppler ultrasound is not necessarily a decisive monitoring technique, as it may show very small volumes of air that do not change the partial arterial pressure of CO_2 ($PaCO_2$) and vital signs. In addition, in such patients, a central venous catheter should be used, and the central venous pressure should be kept above 10 cm H_2O, so that the pressure in epidural veins does not decline. If air embolism is detected, air can be emergently evacuated from the right atrium via the central venous catheter.

If air embolism occurs, the surgeon should flood the wound with Ringer's solution and immediately search for a source of air entrance into the venous system, with inspection and control of any open veins with bipolar coagulation. Bleeding bone surfaces should be treated with wax. If the responsible vessel cannot be identified and the end-tidal CO_2 drops, the wound should be precisely packed with wet gauze and/or sponges. If signs of air embolism persist, the patient should be quickly placed in a side-lying position, with the right side facing up, to aid removal of air from the right atrium via the central venous catheter. If hemodynamic stability is diminished, the wound must be closed.

Intubation

Intubation is another maneuver warranting caution, particularly during cervical spine approaches. Neck positioning during intubation is important in patients with cervical spinal cord compression. C1–C2 extension is most commonly associated with intubation and is usually well tolerated by the patient. However, in cases of severe stenosis at or above the level of C3/4, intubation with fiberoptic guidance, while the patient is awake and under local anesthesia, is usually preferred. Preoperative skull or halter traction may facilitate intubation and surgery by providing gentle traction and extension. Some surgeons suggest that patients with severe cervical myelopathy should be positioned for operation before induction of general anesthesia [24].

Infection

Although postoperative infection is considered a common complication of spine surgery, its average incidence is relatively low. However, its risk may be increased if an instrumented spinal fusion is performed. While the role of preoperative and perioperative antibiotics in such cases remains controversial, the available evidence suggests that the incidence of infections may be lower if antibiotics are administered before start of the operation [24–27]. Because the most frequently detected microorganism is a *Staphylococcus* spp., a first-generation cephalosporin is usually given unless the patient is known to have a propensity toward an allergic reaction to it [14].

Approach-Related Complications

There are a variety of approach-related complications in spine surgery, which are also related to the level of the intervention. Of note, intraoperative imaging can ensure the correct level of the operation and provide information about the degree of decompression, realignment, or stabilization; thus, it should be used whenever it is deemed appropriate. The benefits of an operating microscope in enabling optimal illumination and visualization of the operative field (especially a narrow field, as in the case of a transoral approach) and avoidance of inadvertent injury of neurovascular structures cannot be overemphasized [28–31]. Finally, use of high-speed drills, while highly effective, may increase the incidence of intraoperative soft tissue injuries.

Upper Cervical Spine: General Issues

The reducibility of a subluxation is a critically important consideration for management of pathological processes of the upper cervical spine. If the lesion is reducible, only a

dorsal fixation and fusion procedure may be indicated. If the lesion is not reducible, the optimal approach and general surgical strategy depend on the localization of the compression.

Upper Cervical Spine: The Transoral Approach

Cerebrospinal Fluid Fistula: For intradural pathology, a lateral, transcondylar, or dorsal approach is associated with a significantly lower risk of a CSF fistula than the transoral approach. If the latter is used and CSF leakage occurs, the dural leaves may be covered with fascia and fibrin glue. Placement of a lumbar drain to treat a CSF fistula is necessary.

Severe Tongue Swelling: Intermittent release of the tongue retractor during transoral surgery can be used to minimize tongue swelling. Other methods to avoid this complication include intravenous administration of dexamethasone and postoperative massaging of the tongue to reconstitute venous and lymphatic flow [32]. Patients should not be extubated prior to complete resolution of tongue swelling.

Meningitis: Meningitis is commonly associated with intradural operations by means of transoral approach. Mouth irrigation with an antibiotic solution may be used preoperatively for 2–3 days, as long as cultures of the oropharynx smear are obtained. The presence of a retropharyngeal abscess is a contraindication for transoral surgery. Intraoperatively, the mouth is swabbed with povidone–iodine (Betadine®) solution. In patients with meningitis, postoperative antimicrobial therapy is initiated.

Retropharyngeal Abscess and Palatal or Pharyngeal Wound Dehiscence: In the event of late wound dehiscence after transoral surgery, a retropharyngeal abscess should be sought. Palatal or pharyngeal wound dehiscence is often related to inadequate wound closure. These complications most commonly occur within the first week after the operation.

Neurological Worsening and Cervical Instability: Neurological worsening is often related to inadequate decompression. It may also be caused by loss of alignment or iatrogenic injury of neuronal structures. Use of fluoroscopy during surgical positioning and awake fiberoptic intubation may be helpful for prevention of related neurological injury. Cervical instability can be revealed with postoperative dynamic (flexion/extension) X-rays. If it is present, an occipitocervical fusion may be required [32].

Upper Cervical Spine: Anterolateral Retropharyngeal Approach

Hypoglossal nerve injury and carotid artery injury are commonly observed in association with a transcervical retropharyngeal approach. To avoid intraoperative stroke via embolization, some surgeons use preoperative angiography or Doppler ultrasound examination of the carotid artery [32].

Upper Cervical Spine: Lateral Transcondylar Approach

The most feared complications of the lateral transcondylar approach are vertebral artery injury, air embolism, CSF leakage, and hypoglossal nerve injury. Several preventive measures for avoidance of such morbidity may be recommended.

Appropriate decompression and protection of the vertebral artery minimize the risk of its injury. Air embolism may be prevented by the aforementioned neuroanesthesiology techniques. Regarding CSF leakage, the surgeon should consider that an inverted J-shaped incision may provide a more effective closure of the muscle flaps than that achieved with a paramedian vertical incision. In comparison with the transoral approach, a CSF fistula is a less frequent and less serious complication of the lateral transcondylar approach. Hypoglossal nerve injury is not uncommon during this procedure and usually happens during condylectomy. Thorough preoperative evaluation of the occipital condyle region with "bone window" computed tomography (CT) may help to localize the hypoglossal canal and its inner and outer orifices, and thus decrease the risk of hypoglossal nerve injury during drilling.

Anterior Cervical Approaches

Anterior cervical approaches are commonly used in spine practice. For cervical spondylotic pathologies, the shape of the cervical curvature should be considered in deciding on the operative approach. In general, cervical kyphosis is a specific indication for a ventral approach to avoid postoperative cervical instability [33] and to provide adequate ventral decompression [34].

Dysphagia: Dysphagia after ventral cervical surgery is a well-known complication. The reported incidence and prevalence of postoperative dysphagia in such cases and the risk factors associated with its development vary widely. In a systematic review of a total of 126 articles [35], the rates of dysphagia were high immediately after surgery but declined to a range of 13–21% by one year thereafter. The risk factors included multilevel surgery and female sex of the patient [35].

Dysphonia and Recurrent Laryngeal Nerve Injury: Hoarseness after surgery is usually related to traction of the recurrent laryngeal nerve. It occurs in 3–11% of patients and is usually transient. Although recurrent laryngeal nerve palsy after ventral cervical spine surgery was thought to be caused by direct injury of the nerve, there are no published data that support this hypothesis. The results of some studies indicate that the most common cause of vocal cord paralysis in such cases is compression of the recurrent laryngeal nerve within the endolarynx [28, 34].

The recurrent laryngeal nerve passes under the subclavian artery on the right side and under the aorta on the left side. When using a right-side approach, the surgeon can identify the recurrent laryngeal nerve between the trachea and the esophagus. The right recurrent laryngeal nerve exits the carotid sheath at a variable level, coursing medially and entering the tracheoesophageal groove behind the upper pole of the thyroid gland. Because the high variability of the nerve course on this side increases the risk of its injury, a left-side approach is usually preferred for a cervicothoracic lesion [36]. Nevertheless, while the right recurrent laryngeal nerve is thought to be more susceptible to stretching as midline structures are retracted, comparison of recurrent laryngeal nerve injury rates in cases of right- and left-side surgeries has actually demonstrated no difference.

On the basis of our personal experience, intraoperative monitoring of the endotracheal tube cuff pressure, with deflation of the cuff after retractor placement allowing for the endotracheal tube migration away from the inner laryngeal wall and presumable reducing compression of the submucosal part of the recurrent laryngeal nerve, followed by reinflation of the cuff to the just-sealed pressure (around 15 mmHg), can be suggested for prevention of this complication. In concordance, in a series reported by Apfelbaum et al. [28], use of such a technique was associated with a decrease in the temporary laryngeal paralysis rate from 6.4% to 1.69%.

Spinal Cord Damage: One of the reasons for spinal cord damage during cervical surgery is improper positioning. It is perhaps best to place the patient in a neutral position, although mild extension may aid exposure. Care must be taken to avoid hyperextension. Neurological examination of the awake patient in an extension posture preoperatively may help to avoid complications related to surgical positioning.

C5 Radiculopathy: The C5 motor nerve root is most frequently adversely affected by cervical spine surgery, which may occur in association with both ventral and dorsal operations. Because the mechanism of this injury is not well understood, its prevention is also controversial. It has been suggested that excessively wide exposures result in tethering of nerve roots. Therefore, Saunders [37] recommended that ventral cervical decompression should not exceed 15–16 mm in diameter, because an excessive degree of spinal cord displacement may cause traction on relatively fixed cervical nerve roots. Fortunately, this complication is usually self-limited and resolves spontaneously in most cases [37].

Dural Laceration: Dural tears, CSF fistulae, and pseudomeningoceles may occur, especially in cases of ossification of the posterior longitudinal ligament (OPLL) or severe trauma. Use of good illumination of the operative field, an operating microscope, and diamond-tipped burrs in the vicinity of the dura mater may decrease the frequency of these complications. Of note, the posterior longitudinal ligament thins out laterally; therefore, the spinal cord is relatively less protected in this region. The reported incidence rates of CSF leakage after anterior cervical OPLL resection have ranged from 6.7% to 31.8% [38]. In our practice, to prevent dural tears during OPLL decompression, the cervical "floating method" is used, as was initially suggested by Matsuoka et al. [39]. Those authors described several steps of this technique directed at circumferential release of OPLL. First, the ossification is scalloped and gradually thinned with a diamond burr until its thickness is becoming less than 5 mm. Second, the cranial and caudal margins of the ossification are transected. Third, the lateral bony protuberances are released. Finally, the ossification is freed from the side wall of vertebral bodies. Long-term outcomes after application of this technique were evaluated in 63 patients who underwent anterior cervical decompression, and it was noted that CSF leakage or fistula occurred in 5.1% of cases [39].

If laceration of the dura mater occurs, repair via a ventral approach is not always possible. A tear is best managed with a piece of fascia with a hemostatic gelatin sponge (Gelfoam®) and fibrin glue application, along with external lumbar drainage placed postoperatively for 48–72 h. If the dura mater has been excised, Gelfoam® and fascia application under the bone graft (without suturing), together with lumbar drainage, may be used as well. Prophylactic insertion of lumbar drainage before surgery should be considered in high-risk patients.

Vertebral Artery Injury: Vertebral artery injury occurs in approximately 1% of cases and is usually caused by too lateral use of cutting burrs. For avoidance of this complication, the surgeon should respect the midline. The longus colli muscles and uncovertebral joints are the key structures for its identification. Because the uncinate processes are the lateral borders of the spinal canal, bony removal or dissection lateral to them may damage the vertebral artery and nerve roots. Therefore, the uncinate processes should be clearly defined, and their careful high-speed drilling should be done just medial to the vertebral artery.

To avoid vertebral artery injury, ventral cervical bone resection wider than 18–20 mm should not be carried out. Of note, the distance between the medial borders of the foramen transversarium on both sides is 30 mm. In addition, anomalous positioning of the vertebral artery should be carefully sought on preoperative CT and magnetic resonance imaging (MRI). During the ventrolateral approach, the vertebral artery may be displaced laterally with a narrow-tipped retractor, but not by more than 1–2 mm [40].

If an injury of the vertebral artery occurs, it may be controlled by application of Gelfoam® or bone wax. However, to see if a pseudoaneurysm has developed, postoperative angiography should be performed [41]. If a pseudoaneurysm is revealed, it may be managed with an endovascular approach.

Esophageal or Tracheal Injury: Injury of the esophagus is a rare but life-threatening complication and may result in disastrous consequences, including septicemia, mediastini-

tis, pneumonia, and meningitis. For its avoidance, some authorities suggest use of finger dissection, rather than sharp dissection, below the superficial cervical fascia. The surgeon should be aware of any preoperative problems with esophageal dysmotility (which is observed in 10% of patients, mostly elderly ones). In addition, the surgeon should avoid injuring the pharyngeal muscles during dissection in the upper cervical region. During lengthy operations, it may be necessary to release medial blades of the retractor regularly to avoid esophageal necrosis. The surgeon should inspect the esophagus and the trachea before closure in order to detect inadvertent injury of these structures. Graft dislocations or implant failure with loosened screws may also cause perforation of the esophagus [42, 43].

Fiberoptic endoscopy is the procedure of choice to detect injury of the esophagus or trachea. Esophageal motility films may also help in the diagnosis. If leakage from the wound arouses suspicion a few days after surgery, one can simply have the patient drink methylene blue and look for that color in the drainage fluid.

Broad-spectrum antibiotics and primary repair form the basis for early management of the esophageal perforation. In delayed cases, however, it may not be possible to place primary sutures on the esophagus. In the event of a perforation with abscess formation, incision and drainage, broad-spectrum antibiotic therapy, and a gastrostomy should be instituted. If the infection has subsided, the defect can be sutured and covered with a myofascial flap.

Hypoglossal Nerve Injury: Injury of cranial nerve XII is a rare but possible complication, particularly during high cervical dissections. Knowledge of the hypoglossal nerve anatomy and course should minimize the risk of its damage. The hypoglossal nerve runs downward, lateral to the internal and external carotid arteries. Lateral to the occipital artery, the nerve usually turns forward a little above the level of the hyoid bone to disappear deep to the suprahyoid muscles. As it turns around the occipital artery, the superior root of the ansa cervicalis branches off it.

Horner's Syndrome: Injury of the sympathetic chain is associated with an ipsilateral Horner's syndrome. The sympathetic chain can be easily injured during the ventrolateral approach, which is usually attributed to dissection of the longus colli muscles too far from the midline. The sympathetic chain is located between the carotid sheath and the longus colli muscles in the midcervical region; thus, lateral retraction of the longus colli muscles during foramen transversarium or uncovertebral joint exposure at the lower cervical levels may lead to injury of the sympathetic chain [44]. Horner's syndrome, visual symptoms, and an odd sense over the face may result. To avoid this complication, it is necessary to mobilize the sympathetic chain and the longus colli muscles over the full length of the exposure and insert medial blades of the retractor after lateral ones.

Inadequate Decompression: Most patients improve neurologically after surgery. If such improvement is expected but does not occur, CT and/or MRI examination is prudent. The most likely reason for lack of neurological improvement is inadequate decompression. It is common for a right-handed surgeon operating from the right side to leave residual compression on the right side. Frequently, the surgeon inadvertently obtains more extensive decompression on the side opposite the side of the approach. This can be prevented either by working alternately from both sides of the patient or by using the correct angle of view through an operating microscope.

Another cause of failure to achieve neurological improvement may be the presence of OPLL, which can easily be overlooked on preoperative MRI.

Posterior Cervical Approaches

Use of posterior cervical approaches may be accompanied by neurological worsening and postlaminectomy kyphosis.

Neurological Worsening: Patients with cervical kyphosis are poor candidates for cervical laminectomy. A lordotic or neutral position is preferred. Instrumentation under the lamina in the cervical region can cause neurological damage. The predominant risk during keyhole foraminotomy is direct nerve root trauma. To avoid this, dissection should only be performed from the axilla of the root.

Lateral mass plating may also cause nerve root injury and, occasionally, vertebral artery injury. With transarticular screw fixation, if a vertebral artery injury is detected after a screw is placed, a second screw should be placed. The screw causing the vertebral artery injury can be left in place, since it may effectively serve to tamponade the bleeding. Residual bleeding may be adequately managed with use of oxidized cellulose (Surgicel®).

Postlaminectomy Kyphosis: Kyphosis is a late complication after cervical laminectomy without fusion. Respect for the facet joints and joint capsules is necessary to prevent postlaminectomy instability [45]. Two additional precautions may be considered for prevention of this complication. First, use of laminoplasty instead of laminectomy may decrease the risk of instability (although this has not been proven). Second, lateral mass fixation and fusion may be carried out to prevent deformity, minimize instability, and decrease the amount of movement associated with the degenerative process.

Cervicothoracic Junction (C7–T3) Approaches

Since degenerative diseases in the cervicothoracic region are rare, the indications for surgery at this level most commonly

include tumors, trauma, and infections, and the related clinical decision-making is usually not so difficult.

Ventral approaches to the cervicothoracic junction are technically demanding. Because the kyphotic angle of the upper thoracic spine may compromise the surgical view, the need to access lesions at and below T1 and T2 necessitates a more caudal exposure than is afforded by the ventromedial cervical approach in most patients. Although surgery of the T3 vertebral body is feasible with the ventromedial approach, the surgical view is so limited that only a tumor biopsy or partial decompression may be achieved. With adequate extension of the neck, it is possible to perform T1/2 discectomy in nonobese patients with long necks.

Therefore, if only partial decompression or a biopsy without instrumentation is anticipated in a nonobese patient, the standard ventromedial cervical approach with mild neck extension is appropriate for ventral pathologies in the cervicothoracic region. If, however, extensive resection (with or without instrumentation) is required, upper sternal osteotomy (with or without medial claviculotomy) may be performed, but since this approach is associated with high morbidity, it is usually considered a last resort. Another option is transpleural thoracotomy through the fourth rib.

Pulmonary Injury: Atelectasis, pneumothorax, pneumonia, and pleural effusions may occur after thoracotomy. A tube thoracostomy may be necessary to treat these complications, and it should be removed only after the drainage diminishes significantly. A pneumothorax usually clears within 2–3 days.

Thoracic Duct Injury: The thoracic duct is located on the left side. During left-side incisions, the thoracic duct can be identified as it enters the dorsal aspect of the subclavian vein. Injury of the thoracic duct results in a chylothorax. If this occurs, the duct should be ligated [36, 46].

Major Vessel, Lung Apex, and Gland Injuries: Major vessel injury may occur because of coarse tissue manipulation or excessive traction [47]. A lung apex injury can be detected by filling of the wound with saline solution and application of positive pressure ventilation. If a ventromedial exposure is used, the esophagus, trachea, and thyroid gland are susceptible to injury and should be carefully inspected before wound closure.

Brachial Plexus Injury: The brachial plexus may be injured during the transaxillary and supraclavicular approaches. In addition, stretching injuries of the plexus can be sustained by improper surgical positioning; thus, meticulous attention paid to surgical positioning helps to prevent their occurrence. Any change in patient positioning during the course of surgery, whether inadvertent or intentional, should prompt a re-evaluation of its safety.

Intercostal Neuralgia: Intercostal neuralgia may occur as a complication of axillary dissection, for instance during transaxillary approach. Incision of the nerve proximal to the dorsal root ganglion (i.e., disrupting the nerve by destroying the cell body) should eliminate the risk of this complication.

Chest Wall Deformity and Scar Formation: Chest wall deformities and scars are particularly associated with transsternal and transmanubrial approaches. This issue must be considered during preoperative planning and when the patient's consent is being obtained.

Posterior Thoracolumbar Approaches

If thoracic, lumbar, and sacral lesions are completely dorsal, a posterior approach with laminectomy is appropriate. Complications of dorsal approaches to the thoracolumbar spine include neurological deterioration, hemorrhage, major vessel injury, incidental durotomy, and postoperative instability. Of note, the lateral extracavitary approach to the thoracolumbar spine is reportedly associated with a high rate of complications (55%), among which pulmonary morbidity is predominant [48].

Neurological Deterioration: Neurological deterioration after dorsal thoracic or lumbar spine surgery is predetermined by many factors. In particular, insertion of hooks [33] or wires may injure and compress the spinal cord.

Hemorrhage: Blood loss can be reduced during dorsal exposures by anticipating the presence of the dorsal branch of the interarticular artery, which emerges just lateral to the facet joints in the thoracic and lumbar regions.

Major Vessel Injury: Major vascular injury may also occur during a dorsal approach, particularly during lumbar disc surgery. The mortality associated with these complications may be as high as 50% [49]. Most frequently, vascular injury in such cases is caused by pituitary forceps during overaggressive disc resection. Use of up-angled pituitary forceps and marked instruments may help avoid penetration beyond the anterior longitudinal ligament. Decompression of the abdomen by proper positioning facilitates displacement of the great vessels away from the spine [47].

Anterolateral Retroperitoneal Lumbar Approaches

A vertebral body lesion between L1 and L4 may be exposed via a retroperitoneal ventrolateral approach. If the lesion is located between the L5 and S1 levels, and a limited operation (e.g., a biopsy or simple discectomy) and interbody fusion are required, a pelvic brim extraperitoneal approach may be suitable. If the lesion is located between the L5 and S1 levels and requires extensive exposure (e.g., a high-grade spondylolisthesis or an L5 tumor), a direct ventral approach (e.g., the transperitoneal approach) may be appropriate.

The lumbar retroperitoneal approach is a valuable technique for fusion of the lumbar spine. However, it is associated with several common complications, such as injuries of

abdominal viscera, major vessels, the ureter, the sympathetic chain (leading to retrograde ejaculation), peripheral nerves, and may result in ileus, pseudoarthrosis, and subsidence. To avoid such morbidities, the surgeon should have detailed knowledge of the relevant anatomy from the outset.

Visceral Injury: Injury of the liver, spleen, or kidney is a severe complication. This occurs most commonly with transdiaphragmatic approaches to the thoracolumbar spine. Because handheld retractors are responsible for some of these injuries, meticulous care must be taken during their use.

Major Vessel Injury: Surgical experience and excellent knowledge of the vascular anatomy are prerequisites for avoidance of major vessel injury during ventral lumbar surgery. Iliac vessel mobilization is usually difficult in retroperitoneal dissections at lower lumbar levels. Care should be taken to protect the iliolumbar veins that emerge from the iliac veins laterally. At the L5/S1 level, working between two iliac arteries and veins may be easier for disc surgery and cage insertion. However, working at L4/5 and the upper levels sometimes necessitates excessive retraction of great vessels. Application of fine retractors and meticulous use of high-speed drills are necessary for protection of the vessels. To avoid venous lacerations, utilization of nonthreaded interbody grafts has been recommended [50]. The risk of iliac artery thrombosis can be minimized by intermittent release of the retraction during the procedure.

Lumbar Sympathetic Plexus Injury: The lumbar sympathetic plexus, located on the lateral aspects of the lumbar vertebrae, consists of "line structures," which may be stretched and injured during ventral spine dissection. This injury often causes a "warm leg" on the ipsilateral site and reportedly occurs in 10% of ventral lumbar surgeries [51]. It usually resolves spontaneously.

Superior Hypogastric Plexus Injury: Superior hypogastric plexus injury may result in bladder dysfunction in females and either retrograde ejaculation or sterility (or both) in males. Although this complication is rare (occurring in 0.42% of cases [52]), careful dissection of the fascia ventral to the promontory and avoidance of electrocautery in this region may help to prevent it. The superior hypogastric plexus is situated in the retroperitoneal space on the bifurcation of the aorta, the L5 vertebral body, and the sacrum. This sympathetic plexus innervates the smooth muscles of the seminal vesicles, which contract as the bladder neck closes during ejaculation. It also activates transport of spermatozoa from the testes to the seminal vesicles. Laparoscopic approaches (with which retrograde ejaculation commonly occurs) should preferably be avoided in young male patients [50].

The Artery of Adamkiewicz: The artery of Adamkiewicz plays an important role in the vascular supply to the thoracic spinal cord. It is usually found on the left side at the level of T9. Some surgeons routinely obtain a preoperative angiogram to identify its anatomy and location. On the basis of this information, the surgeon may prefer to approach the spine from the side opposite the artery [34].

Deep Vein Thrombosis: Deep vein thrombosis (DVT) is a common problem related to retraction of venous structures. Careful manipulations of vessels and avoidance of their injury, along with use of a compressive stocking intra- and postoperatively, may prevent this complication. It has been shown that routine use of perioperative prophylactic anticoagulants or intermittent use of compression boots may help to reduce the incidence of DVT.

Abdominal Incisional Hernia and Postoperative Ileus: Abdominal wall hernias can be avoided by meticulous reapproximation of the muscle layers during wound closure. After use of the retroperitoneal approach, postoperative ileus may last for 24–48 h. After utilization of the transperitoneal approach, it may last even longer.

Complications of Minimally Invasive Spine Surgery

Minimally invasive surgical approaches to the spine can reduce tissue trauma, lessen the patient's postoperative pain, and shorten hospital stays. However, they are not devoid of complications, the risks of which seem similar to those after open surgeries. Considering morbidity, the only proven advantage of minimally invasive spine surgeries is reduced rates of infection. For example, in a series reported by O'Toole et al. [53], the incidence of infectious complications after 1338 minimally invasive spine surgeries (78% decompressive, 20% instrumented arthrodesis, and 2% intradural) was <1%—roughly one-tenth of that after open spine surgeries. On the other hand, dural tears may occur more often after minimally invasive spine procedures. In addition, the occasional need for conversion of such interventions into open surgeries may be considered a complication.

Some minimally invasive spine procedures are associated with specific complications related to the applied surgical technique, and the incidence rates of these adverse events are higher during the learning curve. To decrease morbidity during the learning curve, subspecialty and fellowship training (after completion of the conventional surgery training), as well as active attendance at cadaveric workshops and participation in animal laboratory studies, are recommended [54–56].

Microendoscopic Discectomy: Repair of dural tears during tubular microendoscopic discectomy may be rather difficult. However, technical advances and the availability of node pushers have facilitated dural repair in such cases.

Transforaminal Discectomy: Transforaminal discectomy through the safety triangle may be effectively applied in cases of extraforaminal and foraminal disc herniations, but injury of the spinal ganglia and nerve roots may occasionally result in dysesthesia.

Transpsoatic Lumbar Interbody Fusion: Transpsoatic lumbar interbody fusion is also known as extreme lateral interbody fusion (XLIF) or the direct lateral transpsoas approach. It comprises a lateral retroperitoneal approach used for fusions above the L5–S1 segment, which allows placement of very large cages in the disc space. The associated complications are variable and include bowel and ureteral injury during placement of dilators; psoas muscle injury, resulting in its weakness on the side of the approach (encountered in approximately 10% of cases [54]); and injury of the lumbosacral plexus and genitofemoral nerve during muscle dissection [57]. In a series reported by Cummock et al. [58], 62.7% of patients had numbness, paresthesia, and weakness in the ipsilateral thigh; in most of them, these symptoms subsided after 3 months. To avoid injury of nerves overpassing the psoas muscle, intraoperative electromyography (EMG) monitoring has been recommended [59].

Thoracoscopic Approaches: Thoracoscopic approaches are used for management of thoracic disc herniations, sympathectomy, and small thoracic vertebral body tumors. Beside possible anesthetic morbidity, common complications are related to placement of access ports and manipulation of endoscopic instruments, including injuries of the lung and vascular structures [54, 55]. Effective and safe performance of these procedures requires special experience with thoracoscopy, use of various long instruments for surgical manipulations, and unilateral ventilation of the lung.

Vertebroplasty and Kyphoplasty: Vertebroplasty and kyphoplasty have revolutionized management of osteoporotic compression fractures and fractures caused by metastatic disease of vertebral bodies. The most common complications of these procedures are neurological deficits, radiculopathy, cord compression, adjacent-level vertebral body compression, and pulmonary and venous thromboembolism. Moreland et al. [60] reported a 6% overall complication rate per treated vertebral level. The major complications are mostly related to cement leakage, which seems to be less common with balloon kyphoplasty than with vertebroplasty [61], but its clinical significance is not so apparent. To avoid complications, accurate needle placement, adequate barium radiopacification of poly(methyl methacrylate) (PMMA), and viscous low-pressure delivery of PMMA under direct fluoroscopic visualization have been recommended [60].

Fusion-Related and Implant-Related Complications

Use of spinal instrumentation is associated with more complications than decompressive surgery alone. Campbell et al. [62] evaluated outcomes in 202 patients who underwent spinal fusion, and noted some sort of complications in 114 of them (56.4%). There was a significant correlation between the number of levels fused and the overall complication rate [62]. Complications may be encountered more often in surgeries for adult spinal deformity and frequently lead to reoperation; in a study by Charosky et al. [63], the risk of reoperation due to complications in such cases was 48% at 49 months. Furthermore, complication rates are higher after revision surgeries. Cho et al. [64] examined complication rates in revision surgery for adult spinal deformities; overall, 34.3% of 166 patients had major complications, including 19.3% perioperatively and 18.7% during follow-up. To reduce the incidence of complications and reoperations in cases of adult spinal deformities, shorter fixations and avoidance of prophylactic fixations may be recommended.

Improperly Placed Implants

Hardware "failure" is quite common in spine surgery, and its causes usually rest squarely on the shoulders of the surgeon.

Cervical Ventral Plating: Cervical ventral plating may be done improperly, which may result in screw breakage, plate breakage, esophageal erosion, pain, and difficulty in swallowing. Of note, many surgeons do not advocate placing a screw in a graft, for fear that this may dislodge or weaken the graft.

Pedicle Screw Malpositioning: The most common complication of the pedicle screw fixation is screw malpositioning (Fig. 1), the incidence of which ranges between 0% and 42% [65–67]. However, most malpositioned screws do not cause any symptoms. Fisher et al. [68] evaluated the accuracy of screw placement and the safety of pedicle screws in management of unstable thoracic spine fractures. They found that only 66.2% of screws (133 of 201) were fully contained within the pedicle wall. In patients with improperly placed screws, lateral, medial, and anterior perforations were noted in 53%, 40%, and 7.4% of cases, respectively. There were no adverse neurological, vascular, or visceral injuries [68]. In their study, Davne and Myers [69] examined the complication rates associated with pedicle screw fixation and found a neural injury rate of 1.1% and a technical problem rate of 8.1%. In a large meta-analysis, clinically relevant screw-related complications were noted in 0.18% of the screws [69]. Nevertheless, cases of malpositioned screws leading to neural and vascular injury may be underreported.

Graft Dislocation

Graft dislocation is an important complication of ACDF and corpectomy (Fig. 2). Graft dislocation may occur ventrally or dorsally. Dorsal dislocation is rare but more serious because it may cause significant compression of the spinal cord. Partial graft extrusion is of little consequence and usu-

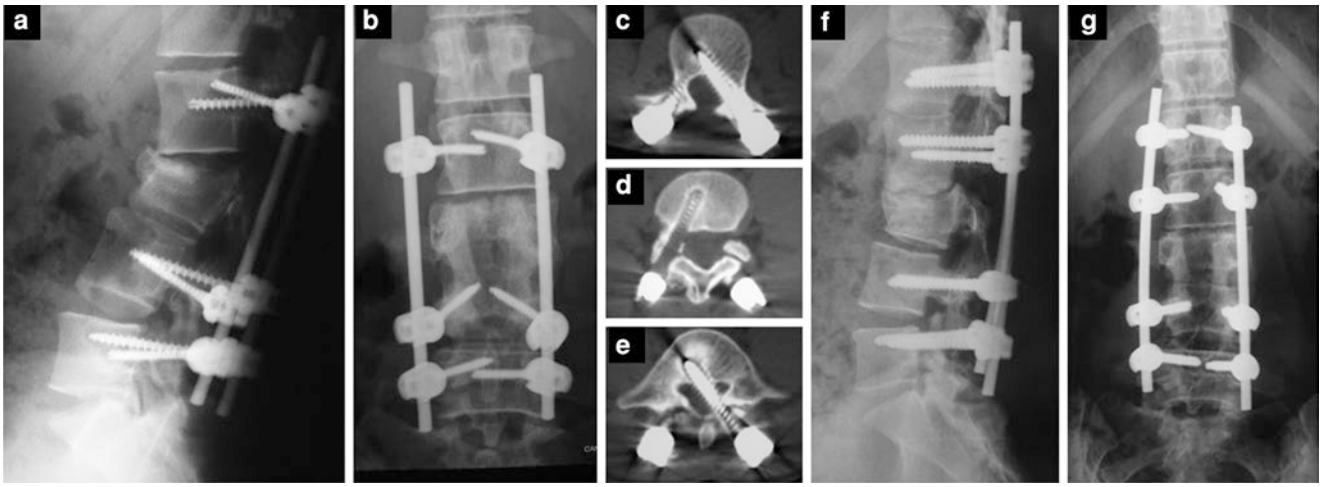

Fig. 1 Clinical case illustrating screw malpositioning, improper construct design, and pseudoarthrosis. After being injured in a fall from a height 3 years earlier, this 18-year-old man was operated on three times for an L3 unstable burst fracture with a spinal cord injury (grade B according to the American Spinal Injury Association [ASIA] impairment scale). L2, L4, and L5 pedicle screws were placed (**a**, **b**). However, by the time of examination in our clinic, all of the screws had loosened (**c**–**e**), two screws placed at left L2 (**c**) and left L5 (**e**) pedicles were inside the canal, and there was an L2–L3 kyphosis. In addition to the screw malpositioning, an insufficient graft, lack of anterior support, and pseudoarthrosis were noted, and there were upper screws protruding to the skin. Revision surgery was performed. The previously placed screws were removed, and larger screws were placed at L1, L2, L4, and L5. Osteotomy at the L2/3 disc level reduced the kyphosis. At 3-year follow-up after the revision surgery (**f**, **g**), the patient had no back pain and the injured level was fused, but he still had an ASIA grade B spinal cord injury with sphincter disturbance and only a mild improvement in motor power

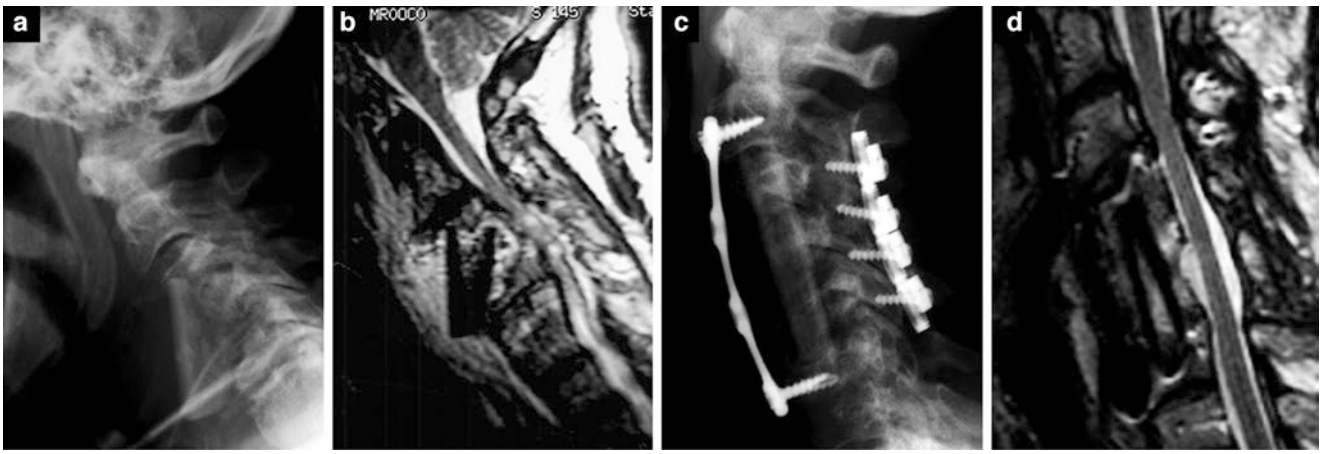

Fig. 2 Clinical case illustrating the invariable necessity to support graft placement after corpectomy using a plate and screw system. In this patient, after 2-level corpectomy, the graft was dislocated, which led to significant kyphosis (**a**, **b**). Revision surgery was performed. Since part of the C3 vertebral body had to be removed, the 3-level corpectomy area had to be supported by an anterior plate and posterior lateral mass fixation (**c**, **d**)

ally does not require treatment. However, significant anterior extrusions may cause swallowing difficulty.

For avoidance of related complications, the graft should be placed no deeper than 13 mm. It should distract the intervertebral space by approximately 2 mm and be recessed approximately 3 mm. Excessive endplate removal may increase the incidence of graft subsidence. Several additional technical considerations may be suggested for prevention of graft dislocation. First, contour the graft into a shape that fits snugly into the mortise of the graft bed; obsessive tailoring of grafts is entirely appropriate. Second, placement of a ventral cervical plate may help to avoid graft dislocation. Third, postoperative bracing may decrease the risk of graft dislocation.

Graft Donor Site Complications

If a graft has been taken from the dorsal iliac crest, possible complications are superior gluteal artery injury, sciatic nerve injury, or deep wound infection, among others. If the donor

site is the ventral iliac crest, donor site herniation, meralgia paresthetica, and pelvic fracture may result [70]. Use of allografts, cages, or ceramics is recommended for avoidance of graft donor site complications.

Pseudoarthrosis/Nonunion

The reported rates of pseudoarthrosis after cervical fusion surgery with use of different graft techniques vary from 0% to 26% [21, 30, 71, 72]. The risk of this complication is generally increased if more than one level is fused; however, if one long piece of cortical/cancellous graft or cortical bone is utilized, this risk is somewhat lower [30, 73]. Use of allografts is associated with a higher incidence of pseudoarthrosis. It should be emphasized that the presence of pseudoarthrosis after cervical fusion surgery does not necessarily compromise postoperative clinical outcomes [74].

In general, pseudoarthrosis is more common after posterolateral lumbar fusion than after interbody fusion. For that reason, most surgeons prefer to use the latter type of technique. There has recently been a trend toward utilization of transforaminal lumbar interbody fusion (TLIF) instead of posterior lumbar interbody fusion (PLIF), particularly because excessive retraction during PLIF may jeopardize the dura mater and nerve roots, whereas unilateral placement of a graft and a banana-shaped cage during TLIF is less risky. Other surgical options include anterior lumbar interbody fusion (ALIF) or transpsoatic cage placement/XLIF; however, the former carries risks to major vessels and the latter may result in lumbosacral plexus injury and some other complications, as described above.

Implant Failure: Different types of implant failures—including rod fracture and screw loosening, backout, and fracture—all may result from pseudoarthrosis (Fig. 3). In the event of rod or screw fractures, it is not appropriate to blame the implant quality. It is the type of surgery that causes implant failures, not the implant quality.

Instability After Spine Surgery

Instability and deformity after spine surgery depend on the level and amount of decompression, and the presence of preoperative instability. Disruption of dorsal ligaments and capsules of facet joints, as well as extensive laminectomy are the main reasons for this complication. Avoidance of excessive facetectomy and laminectomy in children and use of alternative methods (such as minimally invasive surgeries) may prevent development of postoperative instability.

Adjacent-Level Disease

Adjacent-level disease (Figs. 4 and 5) may occur at the upper and lower levels of the fused segment [75, 76]. Upper segment degeneration is more common than lower segment degeneration. There are two terms that characterize this condition, which carry different meanings. "Adjacent-level degeneration" is a radiological finding, which may be noted in 30–50% of cases at long-term follow-up (after ≥10 years) but it is not associated with any related symptoms and has no clinical importance. In contrast, "adjacent-level disease" is encountered less often and refers to symptoms in patients with typical radiological changes. In a review, Park et al. [77] reported that the incidence rates of symptomatic adjacent-level disease ranged from 5.2% to 18.5%.

Risk factors for this complication include preoperative degeneration, use of rigid instrumentation, long fusion, inability to control sagittal balance, facet injury, and older age of the patient. Avoiding adjacent-level degeneration is of particular concern during spinal instability surgery. The problem may be resolved by application of shorter fixations and less rigid fusion systems (e.g., a polyether ether ketone [PEEK] rods), and use of mobility-preserving techniques (disc arthroplasty, dynamic fixation, etc.).

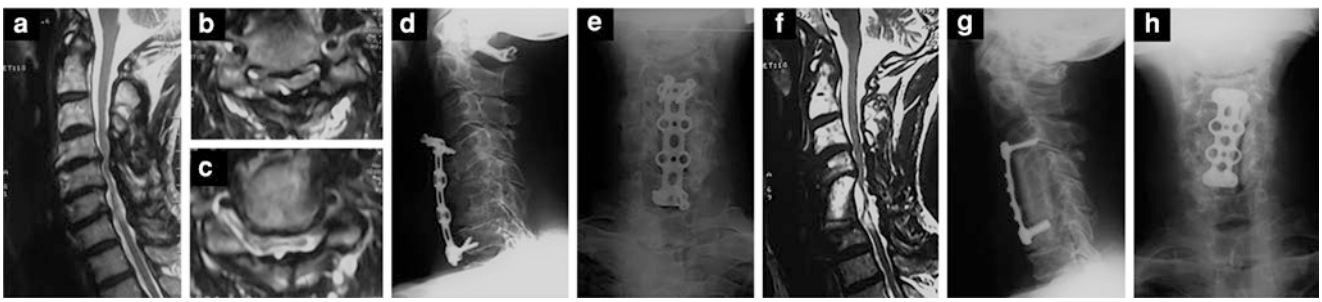

Fig. 3 Clinical case illustrating screw backout. This 64-year-old man underwent cervical laminectomy 20 years previously. In the past 3 years, he experienced progressive tetraparesis (**a**–**c**). A 2-level (C5 and C6) corpectomy, allograft placement, and ventral plating were done, but, because of use of short screws and improper planning, pseudoarthrosis developed, with plate and screw backout (**d**–**f**). Revision surgery was therefore needed, which resulted in a satisfactory outcome as demonstrated by X-rays at the 7-month follow-up examination (**g**, **h**)

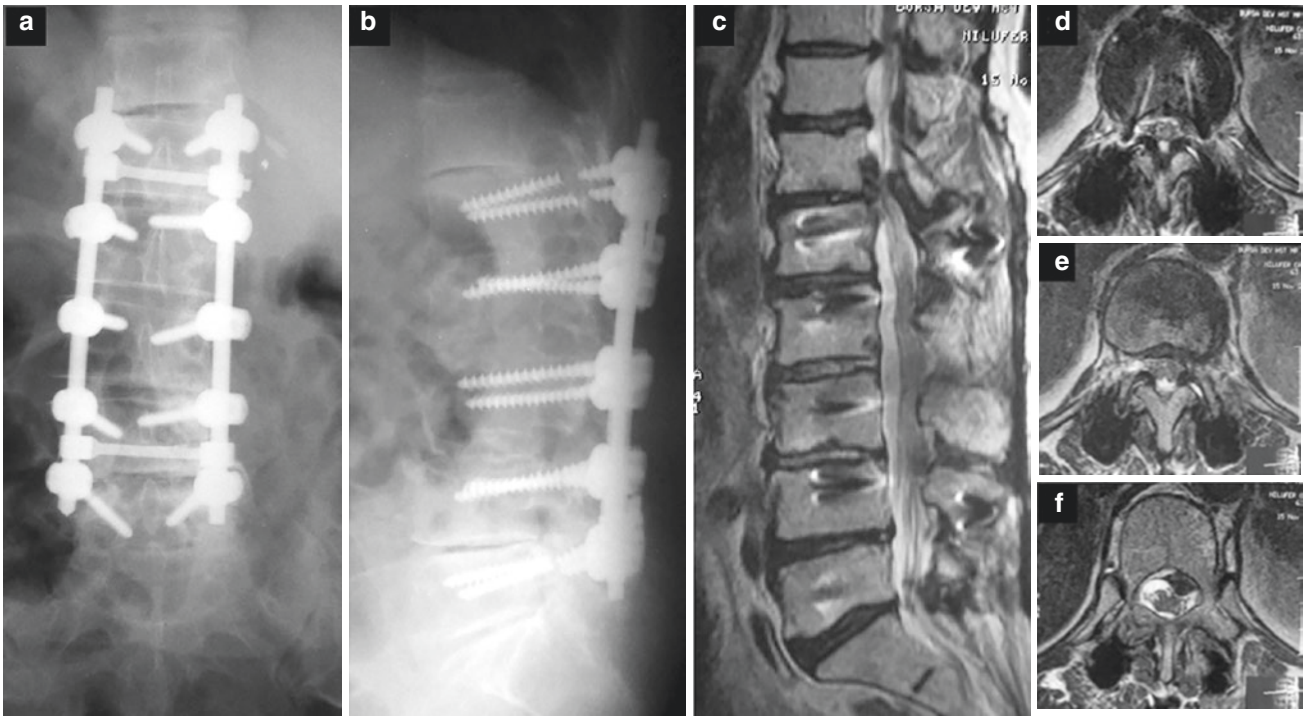

Fig. 4 Clinical case illustrating adjacent-level disease and screw backout. This 64-year-old woman underwent surgery for lumbar canal stenosis 5 years previously. A long fixation (L1–L5) was applied. However, she then experienced new pain and had an anteflexion posture. On examination, X-rays revealed that the L1 and L5 screws were broken (**a**, **b**), and magnetic resonance imaging showed significant lumbar canal narrowing and disc herniation at the T12/L1 level (**c**–**f**)

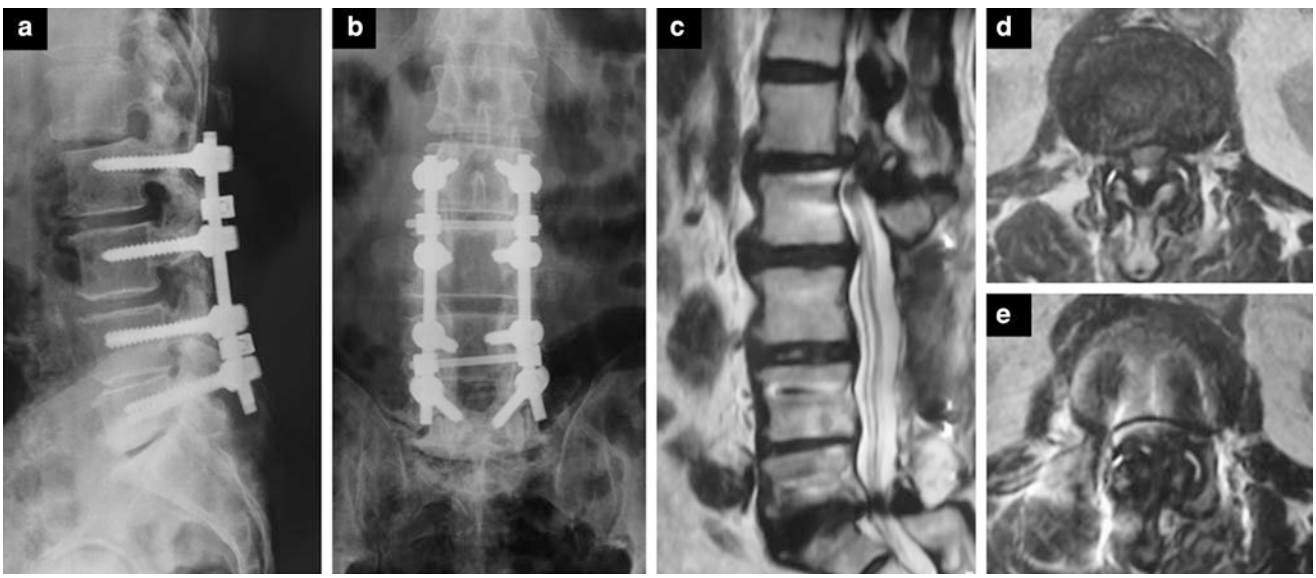

Fig. 5 Clinical case illustrating adjacent-level disease. This 65-year-old man previously underwent surgery for L2/3, L3/4, and L4/5 spinal stenosis (**a**, **b**). He had total symptomatic relief for more than 1 year but thereafter developed low back pain and left leg pain (femoralgia). He also had an anteflexion posture during walking. Magnetic resonance imaging showed a typical stenosis (adjacent-level disease) at the L1/2 level, with some listhesis (**c**–**e**). It was suspected that two factors contributed to the development of complications in this case: use of long and rigid fixation, and improper sagittal balance or lack of lordosis

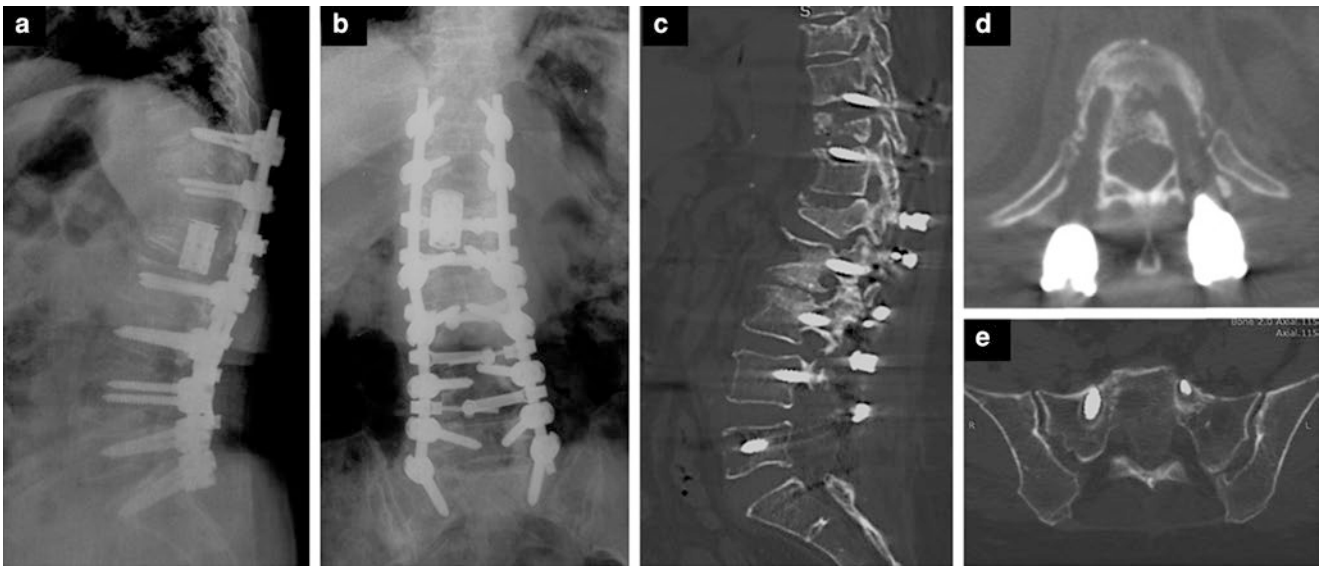

Fig. 6 Clinical case illustrating proximal junctional kyphosis after long (T11–S1) fixation (**a**, **b**). In addition, there was T11 and S1 screw backout, and radiolucency around some screws suggested they had loosened (**c**–**e**)

In the event of new disc herniation, spinal stenosis, or listhesis after previous fusion surgery, reoperation may be necessary. Surgical options at reoperation include simple decompression, extension of the fusion to the upper level, or hybrid surgery with mobility-preserving fixation.

Proximal Junctional Kyphosis

Proximal junctional kyphosis (Fig. 6) is a focal kyphosis involving the vertebral segments proximal to the upper instrumented vertebra. This is a common postoperative complication following multilevel fusion surgery for spinal deformity [6, 78]. This condition can be defined as the angulation between the upper instrumented vertebra and two levels cranial vertebrae, which should have increased ≥10° than before surgery [6].

Risk factors for development of the proximal junctional kyphosis include increased rigidity of fixations, longer-length instrumentation, poor bone quality, and older age of the patient. Many methods have been suggested for prevention of this complication, including use of hooks on the uppermost level of fixation, application of elastic tethers on the upper instrumented vertebra, and cement augmentation of the upper instrumented vertebra.

Proximal junctional kyphosis is sometimes revealed only radiographically and does not pose any clinical problems, but it is more typically associated with pain and neurological deficits, which may be considered as adjacent-level disease. Therefore, it is a very common reason for revision surgery after long-segment instrumented fusions [79].

Systemic Complications

There are many systemic complications that can be encountered during and after spine surgery. Especially in this era of wide indications for these interventions in geriatric patients, multiple precautions are necessary to avoid dangerous perioperative morbidities (myocardial infarction, heart failure, stroke, etc.). For their prevention, it is important to avoid significant changes in arterial blood pressure and excessive bleeding during surgery.

Thromboembolism

Venous thromboembolic disease is a serious and potentially life-threatening perioperative complication. In a meta-analysis, Sansone et al. [80] noted that the prevalence rates of DVT and pulmonary embolism following elective spine surgery were 1.09% and 0.06%, respectively. In a retrospective study of 108,419 cases of spine surgery, conducted by the Scoliosis Research Society [3], the overall rates of DVT, pulmonary embolism, and death due to pulmonary embolism were 1.18, 1.38, and 0.34 per 1000 patients, respectively.

To prevent thromboembolism, fitting of intermittent pneumatic compression devices (bandages, boots, stockings) to both legs before commencement of surgery is recommended. Administration of pharmacological prophylaxis also significantly reduces the prevalence of DVT ($P < 0.01$) [80]. If early mobilization of the patient after surgery is not possible, anticoagulant therapy, especially with low molecular weight synthetic heparins, should be started.

Conclusion

The outcomes of spine surgery are closely related to postoperative morbidity. Therefore, an experienced surgeon must be aware of the various complications and should apply all necessary preventive measures to avoid them.

Conflict of Interest Statement The author has no conflict of interest concerning the reported materials or methods.

References

1. Zileli M, Benzel EC. Preoperative and surgical planning for avoiding complications. In: Steinmetz MP, Benzel EC, editors. Benzel's spine surgery: techniques, complication avoidance, and management. 4th ed. Philadelphia: Elsevier; 2017. p. 210–8.
2. Nasser R, Yadla S, Maltenfort MG, Harrop JS, Anderson DG, Vaccaro AR, Sharan AD, Ratliff JK. Complications in spine surgery. J Neurosurg Spine. 2010;13:144–57.
3. Smith JS, Fu KM, Polly DW Jr, Sansur CA, Berven SH, Broadstone PA, Choma TJ, Goytan MJ, Noordeen HH, Knapp DR Jr, Hart RA, Donaldson WF 3rd, Perra JH, Boachie-Adjei O, Shaffrey CI. Complication rates of three common spine procedures and rates of thromboembolism following spine surgery based on 108,419 procedures: a report from the Scoliosis Research Society Morbidity and Mortality Committee. Spine (Phila Pa 1976). 2010;35:2140–9.
4. Mannion AF, Fekete TF, O'Riordan D, Porchet F, Mutter UM, Jeszenszky D, Lattig F, Grob D, Kleinstueck FS. The assessment of complications after spine surgery: time for a paradigm shift? Spine J. 2013;13:615–24.
5. Braughler JM, Hall ED. Current application of "high-dose" steroid therapy for CNS injury. A pharmacological perspective. J Neurosurg. 1985;62:806–10.
6. Glattes RC, Bridwell KH, Lenke LG, Kim YJ, Rinella A, Edwards C 2nd. Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion: incidence, outcomes, and risk factor analysis. Spine (Phila Pa 1976). 2005;30:1643–9.
7. Hall ED, Wolf DL, Braughler JM. Effects of a single large dose of methylprednisolone sodium succinate on experimental posttraumatic spinal cord ischemia. Dose–response and time–action analysis. J Neurosurg. 1984;61:124–30.
8. Cammisa FP Jr, Girardi FP, Sangani PK, Parvataneni HK, Cadag S, Sandhu HS. Incidental durotomy in spine surgery. Spine (Phila Pa 1976). 2000;25:2663–7.
9. Jones AA, Stambough JL, Balderston RA, Rothman RH, Booth RE Jr. Long-term results of lumbar spine surgery complicated by unintended incidental durotomy. Spine (Phila Pa 1976). 1989;14:443–6.
10. Wang JC, Bohlman HH, Riew KD. Dural tears secondary to operations on the lumbar spine. Management and results after a two-year-minimum follow-up of eighty-eight patients. J Bone Joint Surg Am. 1998;80:1728–32.
11. Hlincik P, Nowitzke A. Rapid fluctuations in conscious state in a patient with an extensive spinal dural fistula. J Clin Neurosci. 2005;12:717–20.
12. Sciubba DM, Kretzer RM, Wang PP. Acute intracranial subdural hematoma following a lumbar CSF leak caused by spine surgery. Spine (Phila Pa 1976). 2005;30:E730–2.
13. Chang HS, Kondo S, Mizuno J, Nakagawa H. Airway obstruction caused by cerebrospinal fluid leakage after anterior cervical spine surgery. A report of two cases. J Bone Joint Surg Am. 2004;86:370–2.
14. Ducker TB. Cervical radiculopathies and myelopathies: posterior approaches. In: Frymoyer JW, Ducker TB, Hadler NM, Kostuik JP, Weinstein JN, Whitecloud III TS, editors. The adult spine: principles and practice. New York: Raven; 1991. p. 1187–205.
15. Heller JG, Kim HS, Carlson GW. Subarachnoid–pleural fistulae—management with a transdiaphragmatic pedicled greater omental flap: report of two cases. Spine (Phila Pa 1976). 2001;26:1809–13.
16. Kassam A, Horowitz M, Carrau R, Snyderman C, Welch W, Hirsch B, Chang YF. Use of Tisseel fibrin sealant in neurosurgical procedures: incidence of cerebrospinal fluid leaks and cost–benefit analysis in a retrospective study. Neurosurgery. 2003;52:1102–5.
17. Nakamura H, Matsuyama Y, Yoshihara H, Sakai Y, Katayama Y, Nakashima S, Takamatsu J, Ishiguro N. The effect of autologous fibrin tissue adhesive on postoperative cerebrospinal fluid leak in spinal cord surgery: a randomized controlled trial. Spine (Phila Pa 1976). 2005;30:E347–51.
18. McCormack BM, Zide BM, Kalfas IH. Cerebrospinal fluid fistula and pseudomeningocele after spine surgery. In: Benzel EC, editor. Spine surgery: techniques, complication avoidance, and management. 2nd ed. Philadelphia: Churchill Livingstone; 2005. p. 2033–42.
19. Jampol LM, Goldbaum M, Rosenberg M, Bahr R. Ischemia of ciliary arterial circulation from ocular compression. Arch Ophthalmol. 1975;93:1311–7.
20. Mosdal C. Cervical osteochondrosis and disc herniation. Eighteen years' use of interbody fusion by Cloward's technique in 755 cases. Acta Neurochir (Wien). 1984;70:207–25.
21. Robinson RA, Walker AE, Ferlic DC, Wiecking DK. The results of anterior interbody fusion of the cervical spine. J Bone Joint Surg Am. 1962;44:1569–87.
22. Mirovsky Y, Neuwirth M. Injuries to the lateral femoral cutaneous nerve during spine surgery. Spine (Phila Pa 1976). 2000;25:1266–9.
23. Roberts MP. Complications of positioning for neurosurgical operations on the spine. In: Tarlov EC, editor. Complications of spinal surgery. Park Ridge: AANS Publication Committee; 1991. p. 1–13.
24. Dempsey R, Rapp RP, Young B, Johnston S, Tibbs P. Prophylactic parenteral antibiotics in clean neurosurgical procedures: a review. J Neurosurg. 1988;69:52–7.
25. Haines SJ. Systemic antibiotic prophylaxis in neurological surgery. Neurosurgery. 1980;6:355–61.
26. Savitz MH, Katz SS. Rationale for prophylactic antibiotics and neurosurgery. Neurosurgery. 1981;9:142–4.
27. Shapiro M, Wald U, Simchen E, Pomeranz S, Zagzag D, Michowiz SD, Samuel-Cahn E, Wax Y, Shuval R, Kahane Y, Sachs T, Shalit M. Randomized clinical trial of intra-operative antimicrobial prophylaxis of infection after neurosurgical procedures. J Hosp Infect. 1986;8:283–95.
28. Apfelbaum RI, Kriskovich MD, Haller JR. On the incidence, cause, and prevention of recurrent laryngeal nerve palsies during anterior cervical spine surgery. Spine (Phila Pa 1976). 2000;25:2906–12.
29. Benzel EC, editor. Surgical exposure of the spine: an extensile approach. Park Ridge: AANS Publication Committee; 1995.
30. Connolly ES, Seymour RJ, Adams JE. Clinical evaluation of anterior cervical fusion for degenerative cervical disc disease. J Neurosurg. 1965;23:431–7.
31. Saunders RL. Anterior reconstructive procedures in cervical spondylotic myelopathy. Clin Neurosurg. 1991;37:682–721.
32. Menezes AH. Surgical approaches to the cranio-vertebral junction. In: Frymoyer JW, Ducker TB, Hadler NM, Kostuik JP, Weinstein JN, Whitecloud II TS, editors. The adult spine: principles and practice. New York: Raven; 1991. p. 967–85.
33. Been HD, Kalkman CJ, Traast HS, Ongerboer de Visser BW. Neurologic injury after insertion of laminar hooks during Cotrel–Dubousset instrumentation. Spine (Phila Pa 1976). 1994;19:1402–5.

34. Batzdorf U, Batzdorff A. Analysis of cervical spine curvature in patients with cervical spondylosis. Neurosurgery. 1988;22:827–36.
35. Riley LH 3rd, Vaccaro AR, Dettori JR, Hashimoto R. Postoperative dysphagia in anterior cervical spine surgery. Spine (Phila Pa 1976). 2010;35(9 Suppl):S76–85.
36. Sundaresan N, DiGiancinto GV. Surgical considerations and approaches. In: Sundaresan N, Schmidek HH, Schiller AL, Rosenthal DI, editors. Tumors of the spine: diagnosis and clinical management. Philadelphia: Saunders; 1990. p. 358–79.
37. Saunders RL. On the pathogenesis of the radiculopathy complicating multilevel corpectomy. Neurosurgery. 1995;37:408–13.
38. Cardoso MJ, Koski TR, Ganju A, Liu JC. Approach-related complications after decompression for cervical ossification of the posterior longitudinal ligament. Neurosurg Focus. 2011; 30(3):E12.
39. Matsuoka T, Yamaura I, Kurosa Y, Nakai O, Shindo S, Shinomiya K. Long-term results of the anterior floating method for cervical myelopathy caused by ossification of the posterior longitudinal ligament. Spine (Phila Pa 1976). 2001;26:241–8.
40. DePalma AF, Rothman RH, Lewinnek GE, Canale ST. Anterior interbody fusion for severe cervical disc degeneration. Surg Gynecol Obstet. 1972;134:755–8.
41. Zileli M, Çağlı S, Oran I, Kalayci M, Islekel S. Iatrogenic cervical vertebral artery pseudoaneurysm successfully treated by an endovascular approach: case report. J Spinal Surgery (India). 2009;1(3):46–9.
42. Cagli S, Isik HS, Zileli M. Cervical screw missing secondary to delayed esophageal fistula: case report. Turk Neurosurg. 2009;19:437–40.
43. Sharma RR, Sethu AU, Lad SD, Turel KE, Pawar SJ. Pharyngeal perforation and spontaneous extrusion of the cervical graft with its fixation device: a late complication of C2–C3 fusion via anterior approach. J Clin Neurosci. 2001;8:464–8.
44. Ebraheim NA, Lu J, Yang H, Heck BE, Yeasting RA. Vulnerability of the sympathetic trunk during the anterior approach to the lower cervical spine. Spine (Phila Pa 1976). 2000;25:1603–6.
45. Whitecloud TS, Kelley LA. Anterior and posterior surgical approaches to the cervical spine. In: Frymoyer JW, Ducker TB, Hadler NM, Kostuik JP, Weinstein JN, Whitecloud III TS, editors. The adult spine: principles and practice. New York: Raven; 1991. p. 987–1013.
46. Watkins RG. Cervical, thoracic and lumbar complications—anterior approach. In: Garfin SR, editor. Complications of spine surgery. Baltimore: Lippincott Williams & Wilkins; 1989. p. 29–52.
47. Tarlov EC. Major vascular injury secondary to spine surgery. In: Tarlov EC, editor. Complications of spinal surgery. Park Ridge: AANS Publication Committee; 1991. p. 23–7.
48. Resnick DK, Benzel EC. Lateral extracavitary approach for thoracic and thoracolumbar spine trauma: operative complications. Neurosurgery. 1998;43:796–803.
49. Anda S, Aakhus S, Skaanes KO, Sande E, Schrader H. Anterior perforations in lumbar discectomies. A report of four cases of vascular complications and a CT study of the prevertebral lumbar anatomy. Spine (Phila Pa 1976). 1991;16:54–60.
50. Than KD, Wang AC, Rahman SU, Wilson TJ, Valdivia JM, Park P, La Marca F. Complication avoidance and management in anterior lumbar interbody fusion. Neurosurg Focus. 2011;31(4):E6.
51. Zdeblick TA. The treatment of degenerative lumbar disorders. A critical review of the literature. Spine (Phila Pa 1976). 1995;20(24 Suppl):126S–37S.
52. Flynn JC, Price CT. Sexual complications of anterior fusion of the lumbar spine. Spine (Phila Pa 1976). 1984;9:489–92.
53. O'Toole JE, Eichholz KM, Fessler RG. Surgical site infection rates after minimally invasive spinal surgery. J Neurosurg Spine. 2009;11:471–6.
54. Hussain NS, Perez-Cruet MJ. Complication management with minimally invasive spine procedures. Neurosurg Focus. 2011; 31(4):E2.
55. Perez-Cruet MJ, Fessler RG, Perin NI. Review: complications of minimally invasive spinal surgery. Neurosurgery. 2002;51(Suppl 2):S26–36.
56. Silva PS, Pereira P, Monteiro P, Silva PA, Vaz R. Learning curve and complications of minimally invasive transforaminal lumbar interbody fusion. Neurosurg Focus. 2013;35(2):E7.
57. Knight RQ, Schwaegler P, Hanscom D, Roh J. Direct lateral lumbar interbody fusion for degenerative conditions: early complication profile. J Spinal Disord Tech. 2009;22:34–7.
58. Cummock MD, Vanni S, Levi AD, Yu Y, Wang MY. An analysis of postoperative thigh symptoms after minimally invasive transpsoas lumbar interbody fusion. J Neurosurg Spine. 2011;15:11–8.
59. Uribe JS, Arredondo N, Dakwar E, Vale FL. Defining the safe working zones using the minimally invasive lateral retroperitoneal transpsoas approach: an anatomical study. J Neurosurg Spine. 2010;13:260–6.
60. Moreland DB, Landi MK, Grand W. Vertebroplasty: techniques to avoid complications. Spine J. 2001;1:66–71.
61. Han S, Wan S, Ning L, Tong Y, Zhang J, Fan S. Percutaneous vertebroplasty versus balloon kyphoplasty for treatment of osteoporotic vertebral compression fracture: a meta-analysis of randomised and non-randomised controlled trials. Int Orthop. 2011;35: 1349–58.
62. Campbell PG, Yadla S, Malone J, Maltenfort MG, Harrop JS, Sharan AD, Ratliff JK. Complications related to instrumentation in spine surgery: a prospective analysis. Neurosurg Focus. 2011; 31(4):E10.
63. Charosky S, Guigui P, Blamoutier A, Roussouly P, Chopin D. Complications and risk factors of primary adult scoliosis surgery: a multicenter study of 306 patients. Spine (Phila Pa 1976). 2012;37:693–700.
64. Cho SK, Bridwell KH, Lenke LG, Yi JS, Pahys JM, Zebala LP, Kang MM, Cho W, Baldus CR. Major complications in revision adult deformity surgery: risk factors and clinical outcomes with 2- to 7-year follow-up. Spine (Phila Pa 1976). 2012;37: 489–500.
65. Gautschi OP, Schatlo B, Schaller K, Tessitore E. Clinically relevant complications related to pedicle screw placement in thoracolumbar surgery and their management: a literature review of 35,630 pedicle screws. Neurosurg Focus. 2011;31(4):E8.
66. Hicks JM, Singla A, Shen FH, Arlet V. Complications of pedicle screw fixation in scoliosis surgery: a systematic review. Spine (Phila Pa 1976). 2010;35:E465–70.
67. Merloz P, Tonetti J, Pittet L, Coulomb M, Lavalleé S, Sautot P. Pedicle screw placement using image guided techniques. Clin Orthop Relat Res. 1998;354:39–48.
68. Fisher CG, Sahajpal V, Keynan O, Boyd M, Graeb D, Bailey C, Panagiotopoulos K, Dvorak MF. Accuracy and safety of pedicle screw fixation in thoracic spine trauma. J Neurosurg Spine. 2006;5:520–6.
69. Davne SH, Myers DL. Complications of lumbar spinal fusion with transpedicular instrumentation. Spine (Phila Pa 1976). 1992;17(6 Suppl):S184–9.
70. Banwart JC, Asher MA, Hassanein RS. Iliac crest bone graft harvest donor site morbidity. A statistical evaluation. Spine (Phila Pa 1976). 1995;20:1055–60.
71. Aronson N, Filtzer DL, Bagan M. Anterior cervical fusion by the Smith–Robinson approach. J Neurosurg. 1968;29:396–404.
72. Simmons EH, Bhalla SK, Butt WP. Anterior cervical discectomy and fusion. A clinical and biomechanical study with eight-year follow-up. J Bone Joint Surg Br. 1969;51:225–37.
73. White AA III, Hirsch C. An experimental study of the immediate load bearing capacity of some commonly used iliac bone grafts. Acta Orthop Scand. 1971;42:482–90.

74. Cloward RB. The anterior surgical approach to the cervical spine—the Cloward procedure: past, present, and future. Spine (Phila Pa 1976). 1988;13:823–7.
75. Kumar MN, Jacquot F, Hall H. Long-term follow-up of functional outcomes and radiographic changes at adjacent levels following lumbar spine fusion for degenerative disc disease. Eur Spine J. 2001;10:309–13.
76. Schlegel JD, Smith JA, Schleusener RL. Lumbar motion segment pathology adjacent to thoracolumbar, lumbar, and lumbosacral fusions. Spine (Phila Pa 1976). 1996;21:970–81.
77. Park P, Garton HJ, Gala VC, Hoff JT, McGillicuddy JE. Adjacent segment disease after lumbar or lumbosacral fusion: review of the literature. Spine (Phila Pa 1976). 2004;29:1938–44.
78. Kim HJ, Lenke LG, Shaffrey CI, Van Alstyne EM, Skelly AC. Proximal junctional kyphosis as a distinct form of adjacent segment pathology after spinal deformity surgery: a systematic review. Spine (Phila Pa 1976). 2012;37(22 Suppl): S144–64.
79. Schairer WW, Carrer A, Deviren V, Hu SS, Takemoto S, Mummaneni P, Chou D, Ames C, Burch S, Tay B, Sawyer A, Berven SH. Hospital readmission after spine fusion for adult spinal deformity. Spine (Phila Pa 1976). 2013;38:1681–9.
80. Sansone JM, del Rio AM, Anderson PA. The prevalence of and specific risk factors for venous thromboembolic disease following elective spine surgery. J Bone Joint Surg Am. 2010;92: 304–13.

Management of the Vertebral Artery in Craniovertebral Junction Stabilization Surgery

Atul Goel

Abstract

The vertebral artery (VA) has an intimate relationship with the bones of the craniovertebral junction. An exact understanding of the VA anatomy in general and in the specific surgical case in particular is absolutely necessary in order to avoid intraoperative vascular injury. The course of the VA on the inferior aspect of the superior facet of the C2 vertebra makes it susceptible to damage during transarticular and interarticular fixation with the screw insertion in the adjacent lateral mass. The consequences of the intraoperative VA injury will depend on the patency of other arteries supplying the brain. In case of this complication, quick decision-making is essential to avoid excessive blood loss and to preserve adequate cerebral blood flow.

Keywords

Atlantoaxial instability · Craniovertebral junction · Vertebral artery

Introduction

Surgery for atlantoaxial fixation entails perfect three-dimensional (3D) understanding of regional anatomy. All surgical steps need to be precise and controlled in order to achieve a satisfactory result of treatment. Intraoperative vascular and neural injury can lead to devastating clinical outcomes. The vertebral artery (VA) has an intimate relationship with the craniovertebral junction (CVJ) in general and with the superior facet of the axis in particular, and it can be susceptible to injury during surgery involving lateral mass fixation. The clinical outcome following intraoperative laceration and sacrifice of the VA is unpredictable and depends on the adequacy of collateral blood flow from other cranial arteries supplying the brain. During the period from 1988 to 2017, the author surgically treated more than 2500 cases of atlantoaxial instability by atlantoaxial stabilization, and details of the techniques used were published previously elsewhere [1–3]. The anatomical peculiarities of the VA, its traverse in the region of surgery, and issues related to its intraoperative injury are elaborated herein on the basis of anatomical studies and surgical experience [4–6].

Anatomical Peculiarity of the C2 Vertebra

Unlike the superior facets of all other vertebrae, the superior facets of the axis do not form a pillar with the inferior facets, being considerably anterior to them. Moreover, superior facets of the C2 vertebra differ from facets of all other vertebrae in two important characteristics, which make this region prone to VA injury during screw fixation [6]. The first is that the superior facet of C2 is in proximity to the body, whereas facets of other vertebrae are located in proximity to the lamina. The second is that the foramen transversarium is present partially or completely in the inferior aspect of the superior facet of C2, while in other cervical vertebrae, it is located entirely on the transverse process. In addition, the pedicle of the C2 vertebra is relatively small. The course of the VA in relation to the inferior aspect of the superior facet of C2 makes it susceptible to injury during transarticular and interarticular screw implantation procedures. Therefore, the surgeon should be extremely cautious about the possibility of such complication.

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_19

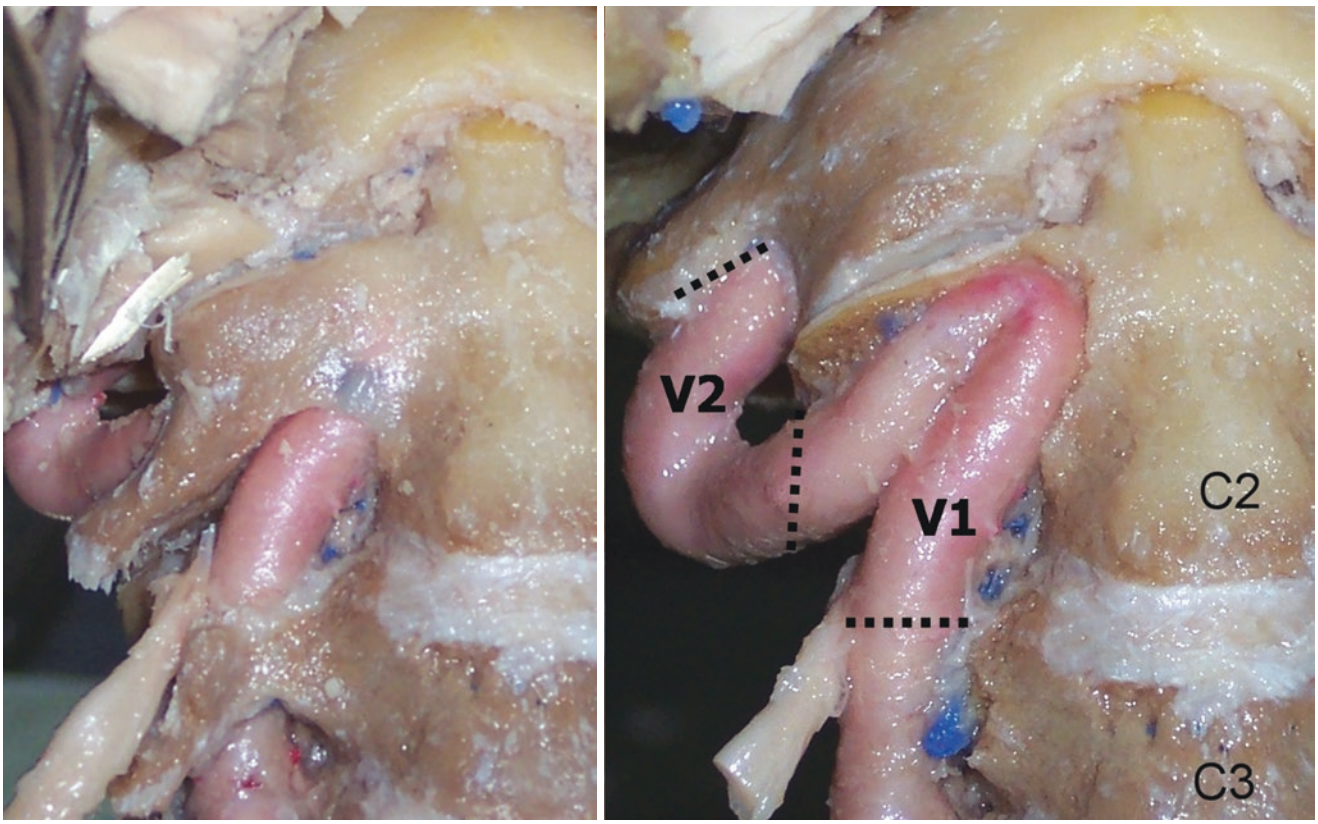

Fig. 1 Anterior view of the craniovertebral junction, showing the vertebral artery in the superior facet of the axis. Both V1 and V2 segments are seen from the front before and after unroofing of the bony groove in C2

Anatomy of the Vertebral Artery in the Vicinity of the Craniovertebral Junction

Perfect 3D understanding of the VA course in general, and in relation to the specific surgery in question, has to be diligently achieved in each individual case.

The VA adopts a serpentine path in the CVJ region, and has multiple loops and an intimate relation to the atlas and axis bones (Figs. 1 and 2). In an earlier study on the subject, we evaluated the anatomy of the VA in ten cadaveric specimens and observed a wide variability of its course [4]. Of the twenty VA we assessed, no two arteries matched exactly in their courses, lengths, and sizes. The diameter of all VA ranged from 2.3 to 7.4 mm (average 4.2 mm). The diameter of the left VA ranged from 2.3 to 4.5 mm, while for the right VA it ranged from 4.1 to 7.4 mm. In one specimen, there was a marked difference in sizes of the left and right VA, and the artery on the left side was significantly hypoplastic. Also, the shape, size, and location of the VA groove (VAG) on the inferior aspect of the superior facet of C2 and over the posterior arch of the atlas varied widely [4].

After its relatively direct course between transverse processes of C6 to C3, the VA makes several twists and turns in the vicinity of the atlantoaxial facet joint. Specifically, it makes a loop medially toward an anteriorly placed superior facet of the

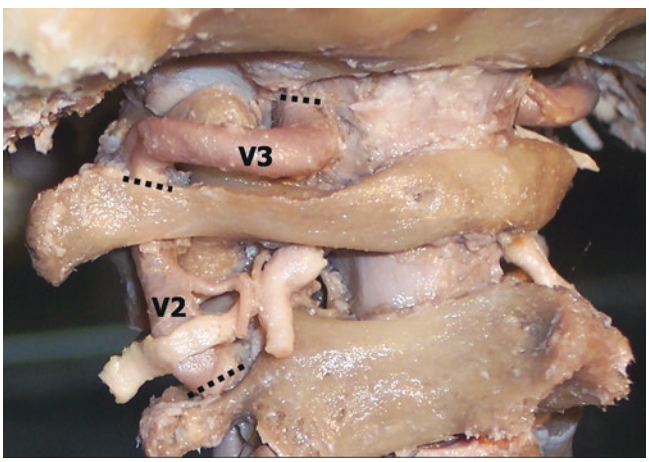

Fig. 2 Posterolateral view of the craniovertebral junction, showing the relation of the vertebral artery to the atlas and axis vertebrae. Both V2 and V3 segments are seen from the posterior aspect

C2 vertebra, making a deep groove on its inferior surface. The extent of the medial extension of this loop varies. Thereafter, VA loops away from the midline underneath the superior facet of C2. This course of the VA in relation to the superior facet of the axis is peculiar and can be critical during surgery that involves screw implantation in the lateral mass of the axis.

A large plexus of veins covers the VA during its entire course. The venous plexuses are largest in the region lateral

to the C1–C2 facet joint. It can result in troublesome venous bleeding during surgery that involves exposure of this region.

Classification of the Vertebral Artery in Relation to the Craniovertebral Junction

To facilitate its description, the VA in its course from the foramen transversarium of C3 to those one of C2 was labeled as V1, from the foramen transversarium of C2 to those one of C1 as V2, and from the foramen transversarium of C1 to the point of dural entry as the V3 segment [4].

The V1 Segment

After its exit from the foramen transversarium of the C3 vertebra, the V1 segment courses posterosuperiorly, forms a loop within the VAG on the inferior surface of the superior facet, and then exits from the foramen transversarium of the C2 vertebra. In our studied specimens, the total length of this segment ranged from 17.2 to 46.1 mm (average 23.4 mm) [4]. Its distal part was intraosseous and could not be seen until unroofing of the bone. The length of the V1 segment prior to its entry into the osseous compartment ranged from 6.4 to 14.6 mm (average 11.3 mm), whereas the length of the osseous segment of the artery ranged from 8.5 to 36.2 mm (average 14.8 mm). The VA courses medially and takes a reverse loop inside the foramen transversarium on the inferior surface of the superior facet of the C2 vertebra. In the studied specimens, the angle of this loop varied and ranged from 2° to 110° (average 86°) [4].

On the inferior surface of the superior facet the VAG had an average depth of 4.36 mm (range 2.8 to 8.2 mm), and it extended up to the medial, middle, and lateral thirds of the superior facet in 25%, 45%, and 30% of cases, respectively [4]. In none of our specimens did the VAG extend into the body of the axis vertebra or into the pars interarticularis. Specifically, the VAG was located 2.2–3.4 mm (average 2.8 mm) anteriorly to the anterior limit of the pars interarticularis [4].

Vertebral Artery Occupancy of the Vertebral Artery Groove: It was observed that the VA did not occupy the entire VAG on the inferior surface of the superior facet and over the posterior arch of the atlas. We found that, on average, the VA occupied 79% of the VAG on the inferior surface of the superior facet of C2 and about 57% of the VAG over the lateral part of the posterior arch of the atlas [4]. Paramore et al. [7] also noted that the VA might not completely occupy the VAG in relationship to the C2 facet. These findings indicate that use of only "bone window" computed tomography (CT) is not sufficient to assess the location of the VA. Moreover, multiple loops and the buffer space of the VA within the bony grooves suggest a dynamic nature of their relationships and the possibility of changes in the location of the artery during neck movements. There is also a possibility that the occupancy of the VAG by the VA changes with age. The old age of some examined specimens in our study and the reduced elasticity of the arteries could have resulted in a reduction in the occupancy rate. The relatively "tight" situation of the VA where the venous buffer space was less prominent, as compared with a "loose" VA in cases with significant buffer space, could also play a role in the appearance of symptomatic giddiness on extreme neck movement.

The V2 Segment

The VA exits from the foramen transversarium on the transverse process of the C2 vertebra, takes an initial lateral bend, and then traverses superiorly. Its course is anterior to the two roots of the C2 ganglion. In our studied specimens, the length of this V2 segment ranged from 12.6 to 32.2 mm (average 15.7 mm) [4]. The distance of the lateral edge of the ganglion from the VA ranged from 5.1 to 11.1 mm (average 7.5 mm). The distance of the VA from the lateral end of the dural tube ranged from 14.7 to 17.9 mm (average 15.3 mm) [4]. Two sets of branches arise from the V2 segment: a relatively large muscular branch and a small artery traversing along the C2 ganglion into the spinal canal.

The V3 Segment

After exiting the foramen transversarium on the transverse process of C1, the VA takes an approximate 90° posterior bend and turns medially to engage in the VAG on the superior surface of the posterior arch of the atlas, where, turning around the superior facet of the atlas, it bends anteriorly to enter the spinal canal. In our studied specimens, the total length of this V3 segment of the artery ranged from 32.3 to 43.5 mm (average 35.7 mm) [4]. The C1 root course is posterior–inferior in relation to the VA. The posterior inferior cerebellar artery (PICA) did not arise from this segment in any of our studied specimens. The distance between the most medial extension of the VA and the medial edge of the VAG on the outer cortex of the posterior arch of the atlas ranged from 2.1 mm to 5.2 mm (average 4.2 mm) [4].

The foramen transversarium is located on the transverse process, lateral to the lateral mass of the atlas. The VAG on the superior surface of the posterior arch of the atlas is converted into a complete bony foramen (known as the arcuate foramen, foramen arcuale atlantis, ponticulus posticus, posterior ponticle, or Kimmerle's anomaly) in approximately 6% of normal individuals. In our studied specimens, the thickness of the posterior arch of the atlas separating the VAG from the inferior facet of the atlas ranged from 2.2 mm to 4.8 mm (average 3.8 mm) [4]. The distance from the midline to the medial-most edge of the VAG on the outer cortex of the posterior arch ranged from 14.3 to 19.7 mm (average 18.2 mm) [4].

Vertebral Artery Variants

Embryologically, the VA arises from a longitudinal anastomosis, which links the first to seventh cervical intersegmental arteries. These intersegmental arteries are branches of the dorsal aorta, which supply the developing somites. As the embryo grows, the first to sixth intersegmental arteries disappear. The seventh cervical intersegmental artery persists and forms the subclavian artery and the VA. Variations in the development of the VA give rise to its anomalous course, which is relevant to our comprehension of the local anatomy during CVJ region surgery.

Three types of anatomical variations of the VA should be primarily considered. First, the most common anomaly, a persistent first intersegmental artery, which occasionally remains during adult life. In such case, there is an absence of the normal VA branch, and this embryonic artery takes an anomalous course and enters the spinal canal between C1 and C2. The second most common anomaly is an extracranial origin of PICA at the level of C1–C2 joint. In such case, the first intersegmental artery persists as the PICA without joining the VA. The third and rarest anomaly is fenestration of the VA. In such case, the first intersegmental artery is present in addition to the normal VA, and both vessels then unite in the spinal canal

Vertebral Artery Variations in Craniovertebral Junction Alterations

The VA essentially molds its course in accordance with the anatomical and functional needs of the region in the event of CVJ instability. The basic principle is that the bone formation is shaped in accordance with the dictates and needs of the soft tissues. In general, bone development cannot affect the VA circulation.

Nevertheless, even in a normal situation, the pulsations of an artery over long periods of time can erode adjacent bone, which may be also the case in a number of musculoskeletal abnormalities, including a short neck, torticollis, bone fusions, and platybasia. In the presence of atlantoaxial instability, the stress on the VA is exaggerated. Essentially, in such cases in general and in basilar invagination in particular, the neck is typically short and the VA is buckled because of its extra length. A neck tilt, excessive and unusual movements, and an unusual course of the VA can potentially lead to vascular compromise associated with acute or chronic ischemia. However, such adverse events are relatively rare and have been encountered by us in six cases only.

Anomalous Course of a Normal Vertebral Artery

The incidence of VA anomalies is greater in patients with CVJ anomalies. The exact reason for this is unknown. It is difficult to decipher whether an anomalous VA is truly aberrant because of segmentation abnormalities or whether its course alters because of bony alterations that have taken place in the context of CVJ instability.

In our series of approximately 2500 cases, we have encountered a wide spectrum of wayward VA traverses in and around the CVJ (Figs. 3, 4, 5, 6). These alterations were more frequently seen in cases of either occipitalization of the atlas or absent laminae and pedicles of C2. In both of these types of bony alterations, the normal osseous structures and foramina that form around and house the VA are absent, and this leads to the artery having an aberrant course.

Wang et al. [8] classified the anomalous path of the VA in presence of occipitalization of the atlas. According to these authors, in such cases after exit from the foramen transversarium of C2, the VA may have four different types of its

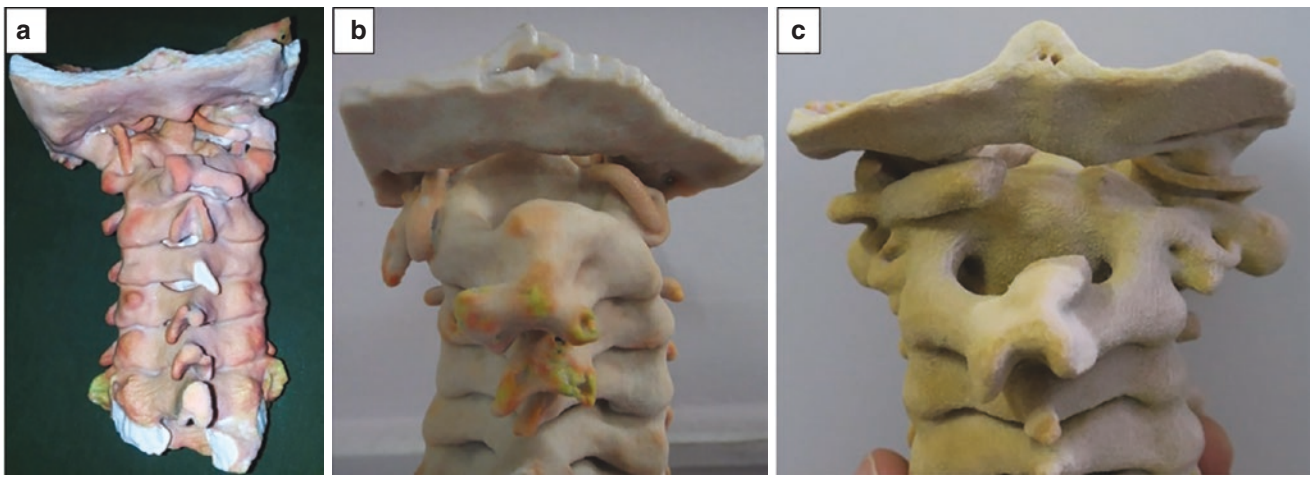

Fig. 3 Three-dimensional models of the craniovertebral junction, showing the bilateral abnormal course of the vertebral arteries (**a**) and occipitalization of the atlas along with the location of the right vertebral artery on the inferior facet of the atlas just above the atlantoaxial joint (**b**, **c**). Note that the right vertebral artery is seen to traverse the pedicle of C2, whereas the left vertebral artery is seen to have a close relation with the facet of the atlas

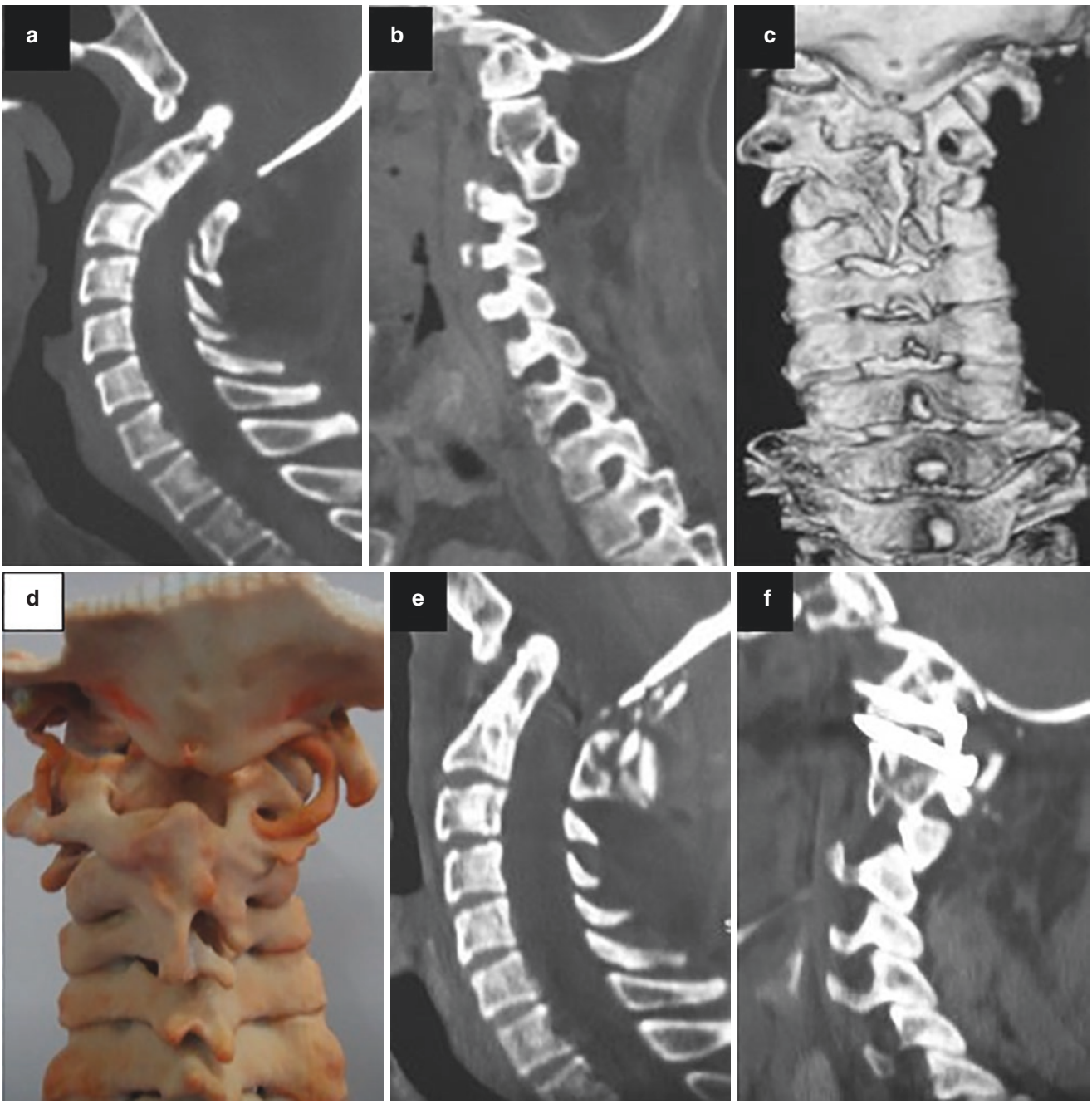

Fig. 4 Imaging findings in a 32-year-old man. Preoperative computed tomography (CT) shows basilar invagination and assimilation of the atlas (**a**) and facet alignment (**b**). Three-dimensional (3D) reconstructed CT (**c**) demonstrates assimilation of the atlas and the location of foramen transversarium on both sides (note the thin pedicle on the right side). A 3D model of the craniovertebral junction (**d**) defines the course of the vertebral arteries; on the right side, the vertebral artery is seen to be on the posterior surface of the lateral mass of the atlas. Postoperative CT reveals craniovertebral realignment (**e**) and the implant (**f**)

course. In type I (which was found in 8.3% of cases), the VA is below the occipitalized C1 lateral mass and enters the foramen magnum without curving medially. In type II (which was found in 25% of cases), the VA is below the occipitalized C1 posterior arch and enters the foramen magnum, making a curve on the posterior surface of the occipitalized C1 lateral mass. In type III (which was found in 61.1% of cases), the VA ascends laterally to enter an osseous foramen created between the fused atlas and occipital bone, then it reaches the cranium, and this anomalous pathway has its internal opening at the external edge or anterior part of the occipitalized C1 lateral mass. In type IV (which was found in 5.6% of cases), the VA is absent on one side of the CVJ [8].

We have encountered the following two abnormal locations of the VA in cases with occipitalization of the atlas. In the most frequent anomaly of this type, the VA can be found

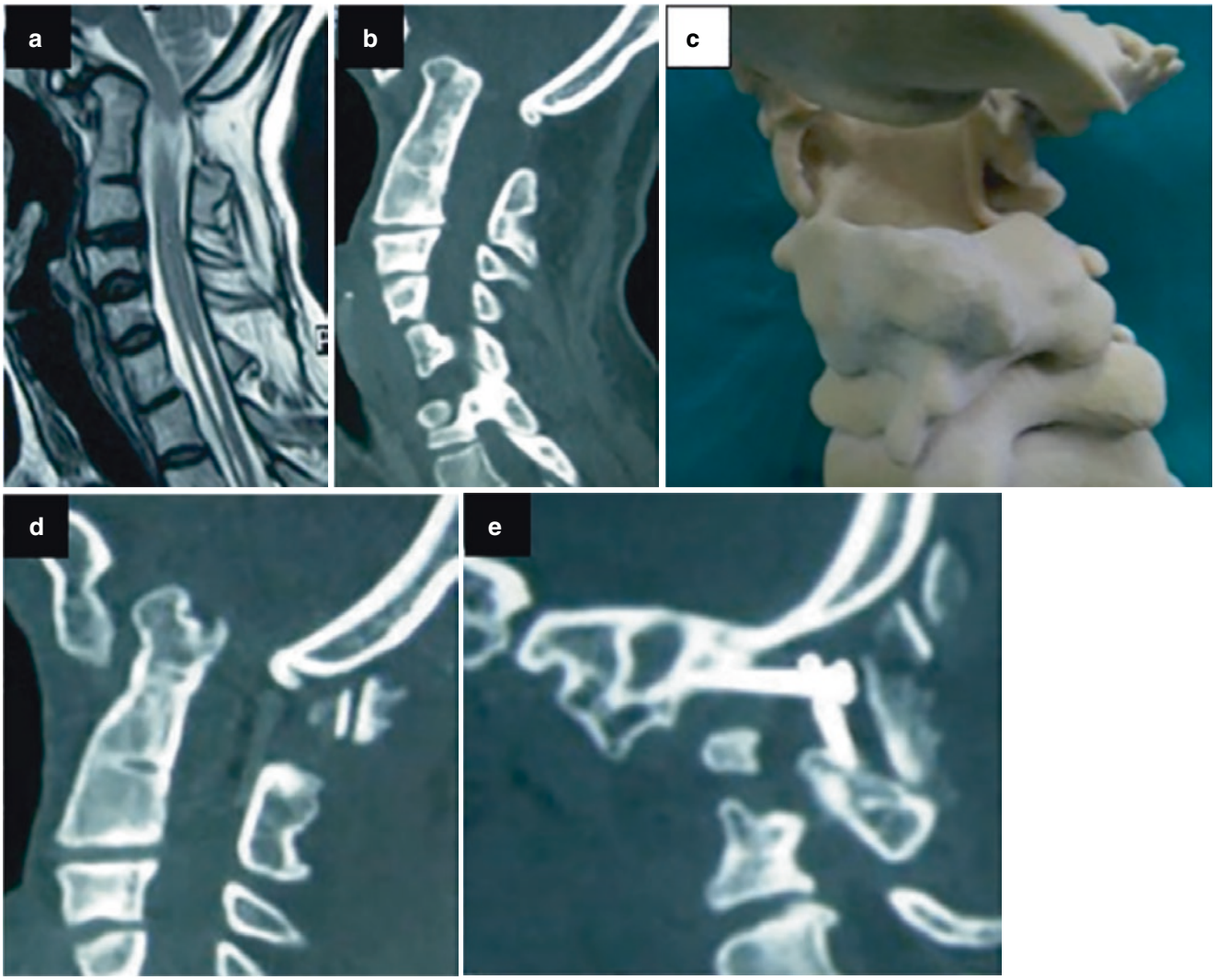

Fig. 5 Imaging findings in a 36-year-old woman. Preoperative T2-weighted magnetic resonance imaging shows basilar invagination, a Chiari malformation, and syringomyelia (**a**). Computed tomography (CT) demonstrates fusion of the C2–C3 vertebrae, assimilation of the atlas, basilar invagination, and atlantoaxial dislocation (**b**). A three-dimensional model defines assimilation of the atlas and C2–C3 fusion (**c**); note the thin C2 pedicle on the left side, the absent pedicle on the right side, the high vertebral artery groove, and the unusual course of the vertebral artery in relation to the posterior aspect of the atlantoaxial joint. Postoperative CT reveals the C1 facet and C2–C3 inferior facet screw insertion (**d**), and screws in facets of C1 and in fused facets of C2 and C3 (**e**)

on the superior surface of the C1–C2 facet joint, and it lies over the dorsal part of the occipitalized C1 lateral mass (Figs. 3c, 4d, 6c) being most vulnerable during opening of the joint and insertion of the C1 lateral mass screw. Occasionally, however, the VA runs on the pedicle of C2 (Fig. 3b). In such cases, after exiting from the foramen transversarium of C2, the artery turns medially and courses posteriorly to the C2 ganglion, closely abutting it on the C2 pedicle, and then enters the spinal canal. Here, the VA becomes susceptible to injury during the dissection of the C2 ganglion, and can sometimes be mistaken for the C2 ganglion and cut inadvertently. We consider that in cases of the VA course corresponding to types III and IV, as described by Wang et al. [8], the risk of its injury during surgery in the CVJ region is generally rather low.

In cases where the C2 pedicles are absent (Fig. 5), the VA after its exiting from the foramen transversarium of C2 turns medially and directly enters the spinal canal between C1 and C2 [9, 10]. It is important to recognize the absence of the pedicles preoperatively, as it may not be very obvious during routine craniovertebral imaging. The use of 3D models and 3D reconstructed images may be indispensable to identify this abnormality [11]. The routine C1 lateral mass and C2 pedicle fixation may have to be altered in such a situation to a reverse C2–C3 fixation, as described by us previously [12].

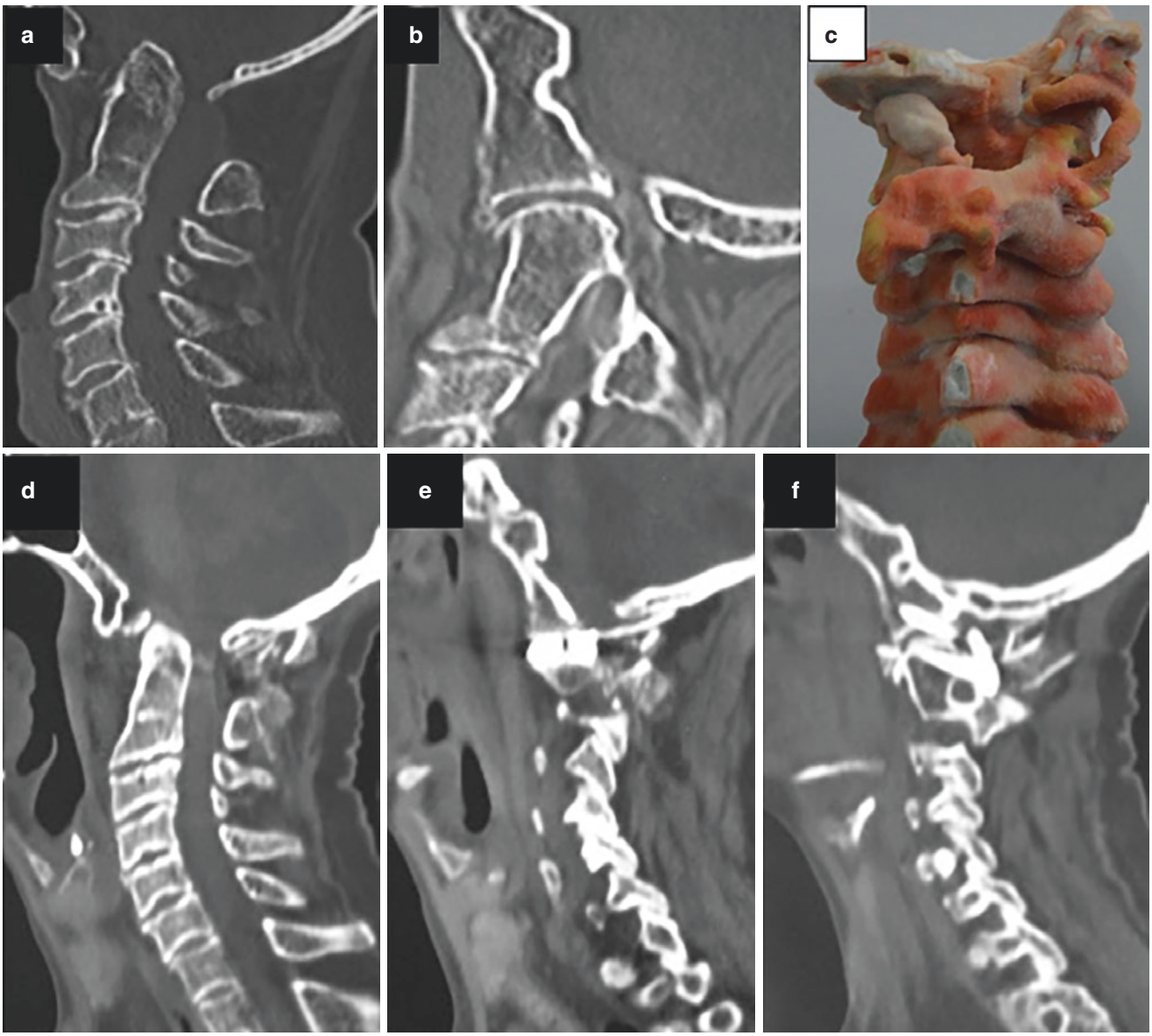

Fig. 6 Imaging findings in a 52-year-old woman. Preoperative computed tomography (CT) shows basilar invagination, assimilation of the atlas, and C2–C3 fusion (**a**), and evidence of instability-related osteophytes (**b**; sagittal cut through the facets). A three-dimensional model demonstrates the anatomy of the region (**c**); osteophytes can be seen around the atlantoaxial joint on the left side; the abnormal course of the vertebral artery over the facet of the atlas can be visualized. Postoperative CT reveals a reduction in basilar invagination (**d**), a spacer in the atlantoaxial joint (**e**), and the implant (**f**)

Sites of Vertebral Artery Injury

Injury of the VA during surgery can lead to catastrophic intraoperative bleeding, and compromise of the cerebral blood flow can result in unpredictable neurological deficits, which will depend on the adequacy of collateral blood flow from the contralateral VA.

The VA can be injured at the following sites and stages of surgery for lateral mass plate/rod and screw fixation, and it may be linked to some predisposing factors:

1. Injury during insertion of a C2 screw, which is the most common and most feared. The typical cause of injury is a "high-riding" VA that loops into the C2 superior facet. Inadequate analysis and erroneous insertion of a screw can lead to this complication.
2. Injury of the V2 segment during dissection in the region, in particular during sectioning of the C2 ganglion because of its close anatomical relationship with VA [13].
3. Injury of the V3 segment.
4. An abnormal traverse of the VA that is posterior–inferior to the posterior arch of the atlas.
5. Anatomical variations of the VA in cases with assimilation of the atlas.

Complication Avoidance

It has been clarified that screw implantation in the superior facet of the C2 vertebra has to be done under direct visual control after wide and panoramic surgical exposure. The medial surface of the pedicle of C2 should be appropriately seen prior to screw insertion. Neuronavigation is of great help in identifying the correct site of screw insertion and its direction. The screw insertion has to be sharply medial and directed toward the anterior tubercle of C1 for transarticular fixation and toward the vertebral body of C2 for interarticular fixation. As discussed in our previous publication on this subject [6], the pars interarticularis can be divided into nine quadrants. The superior and medial compartment are best suited for an interarticular technique of screw implantation.

The V2 segment is closest to the C1–C2 joint near the inferior facet of C1. In our anatomical study, the average distance of the VA from the C2 ganglion was 7.5 mm [4]. This suggests that dissection around the lateral end of the ganglion should be done carefully and under direct visual control.

Paramore et al. [7] estimated that approximately 20% of cases are not suitable for lateral screw implantation. However, in our opinion (which is based on treatment of a large number of patients over the course of many years) screw fixation using our technique can be completed in all cases if the anatomy of the CVJ region and of the VA is adequately studied prior to surgery. Overall, to avoid arterial injury during insertion of a C2 screw, the following precautions should be taken and several recommendations can be done:

1. The course of the artery should be appropriately studied and analyzed.
2. 3D CT can provide good visualization of the course of the artery in relation to the facets.
3. 3D models are the most useful preoperative investigation and can help in guiding the entire surgical procedure.
4. Neuronavigation can be useful and can guide the surgeon to identify the point for insertion of a screw and determine its traverse.
5. The site of insertion of a screw should be as high and as medial as possible, and the course of the screw should be as medial and as superior as appropriate.
6. Part of the pars interarticularis can be drilled such that the screw insertion is aimed superiorly and directly into the pedicle and into the facet.
7. The foramen transversarium in the substance of the superior facet of the axis can be drilled to expose the artery. Use of a diamond drilling burr can be helpful and can provide safety for the drilling procedure.
8. The artery can then be mobilized away from the screw insertion site.
9. In the event of absolute inability to perform screw insertion into the pedicle and the superior facet of C2, the inferior facet of C2 can be selected for screw insertion. An inferior facet screw can be inserted from the same point of insertion and directed inferiorly and laterally. As the VA does not come into direct contact with the inferior facet (whereas it does with the superior facet), screw insertion can be safe and effective.

Vertebral Artery Injury

In the event of vessel injury during insertion of a screw-guiding drill, and blood gushing out of the hole that has been made, it is most appropriate to rapidly complete the screw insertion process. In the vast majority of cases, this will stop the bleeding. If the bleeding from the hole continues, it is best to forcefully pack Surgicel® into the hole. Bone wax can also be used for the same purpose. Essentially, in such cases we prefer to sacrifice the artery. This is because significant venous bleeding in the region makes the bloodless exposure required for direct vascular anastomosis difficult. Moreover, the artery is significantly damaged during power drilling, making direct suturing problematic. Exposure of both the proximal and distal ends of the artery is challenging and will entail drilling of the bone in a situation of heavy bleeding.

In the event of arterial injury, the question arises as to whether the fixation procedure should be done on the contralateral side. It seems that quick sacrifice of the VA in C2 is associated with a "small" risk (maybe less than 5%) of related brain infarction. Even a bilateral VA injury is tolerated well in a significant majority of patients. Younger individuals tolerate bleeding caused by VA injury and its sacrifice much better than older ones. This means that the surgeon should not consider that all is lost if an intraoperative VA injury occurs; rather, they should continue positively with the surgical procedure. Therefore, we always attempt to perform fixation bilaterally, even if there is a VA laceration on one side.

The other common sites of injury of the VA are on its course lateral to the C1–C2 facet joint and over the posterior arch of the atlas. In both situations, an attempt must be made to suture the arterial wall defect. However, extensive venous bleeding in the vicinity makes the procedure of suturing difficult.

Sequelae of Vertebral Artery Injury

Although a VA injury in the superior facet of C2 is tolerated reasonably well in the majority of patients, the clinical outcome is unpredictable and will depend significantly on the efficacy and adequacy of the collateral blood flow from other cerebral arteries. Therefore, the consequences of an intraoperative VA injury can vary. The author has previously observed the following complications:

1. A relatively small infarct in the region of posterior arterial circulation; this may be clinically insignificant.
2. A large cerebellar infarct, leading to ataxia.
3. A large infarct in the posterior cerebral artery (PCA) territory, leading to a visual field defect (Fig. 7).

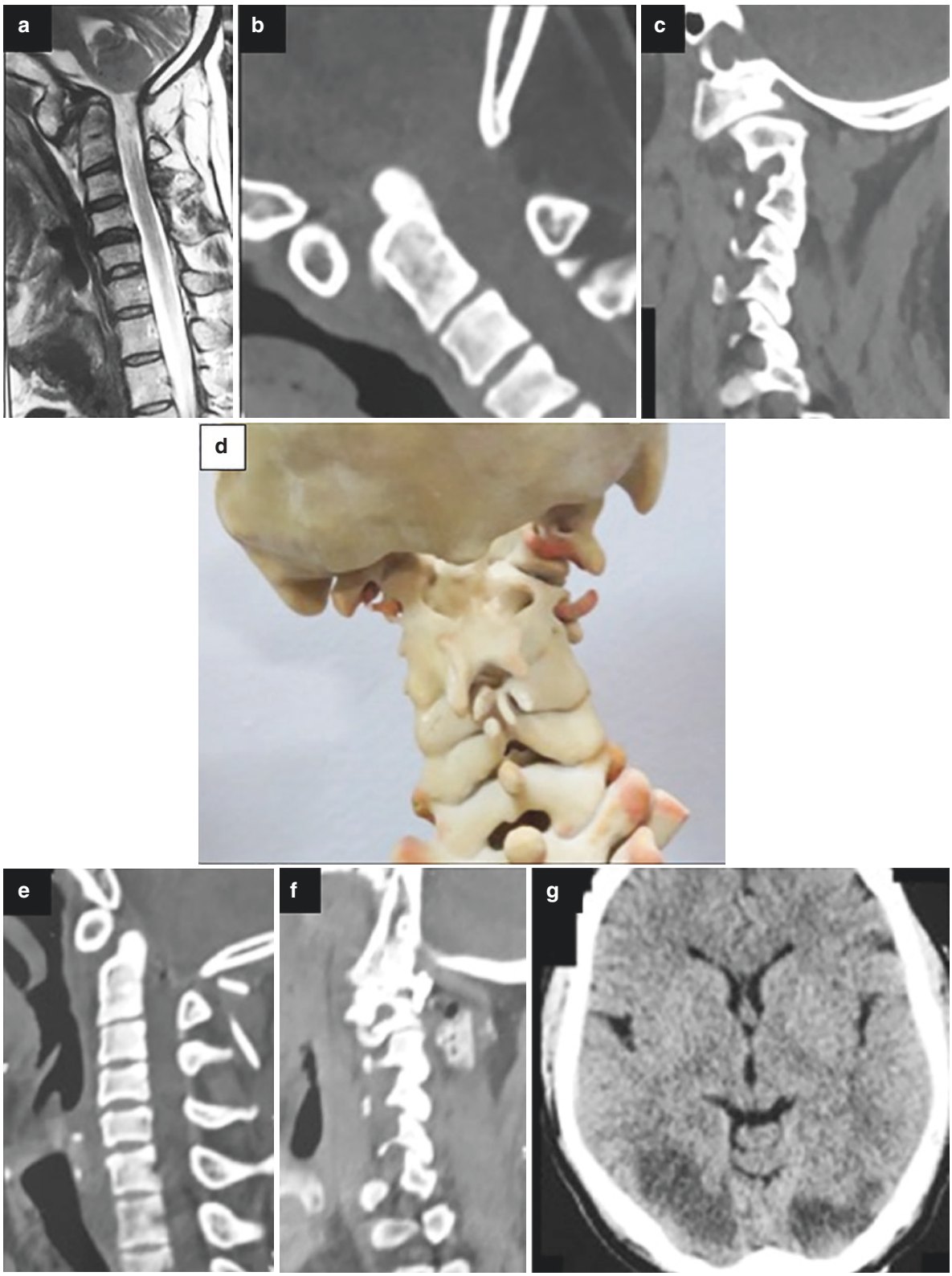

Fig. 7 Imaging findings in a 32-year-old man. Preoperative T2-weighted magnetic resonance imaging shows basilar invagination (**a**). Computed tomography (CT) with the head in flexion demonstrates basilar invagination, assimilation of the atlas, and atlantoaxial dislocation (**b**), along with Goel type 1 facet instability (**c**; sagittal cut through the facets). A three-dimensional model of the craniovertebral junction defines the abnormal course of the right vertebral artery on the inferior facet of the atlas (**d**). During surgery, there was an injury of the vertebral artery during dissection in the region of the atlantoaxial joint. Postoperative CT reveals the atlantoaxial fixation (**e**), the implant (**f**), and bilateral cerebral infarcts in the territory of both posterior cerebral arteries (**g**)

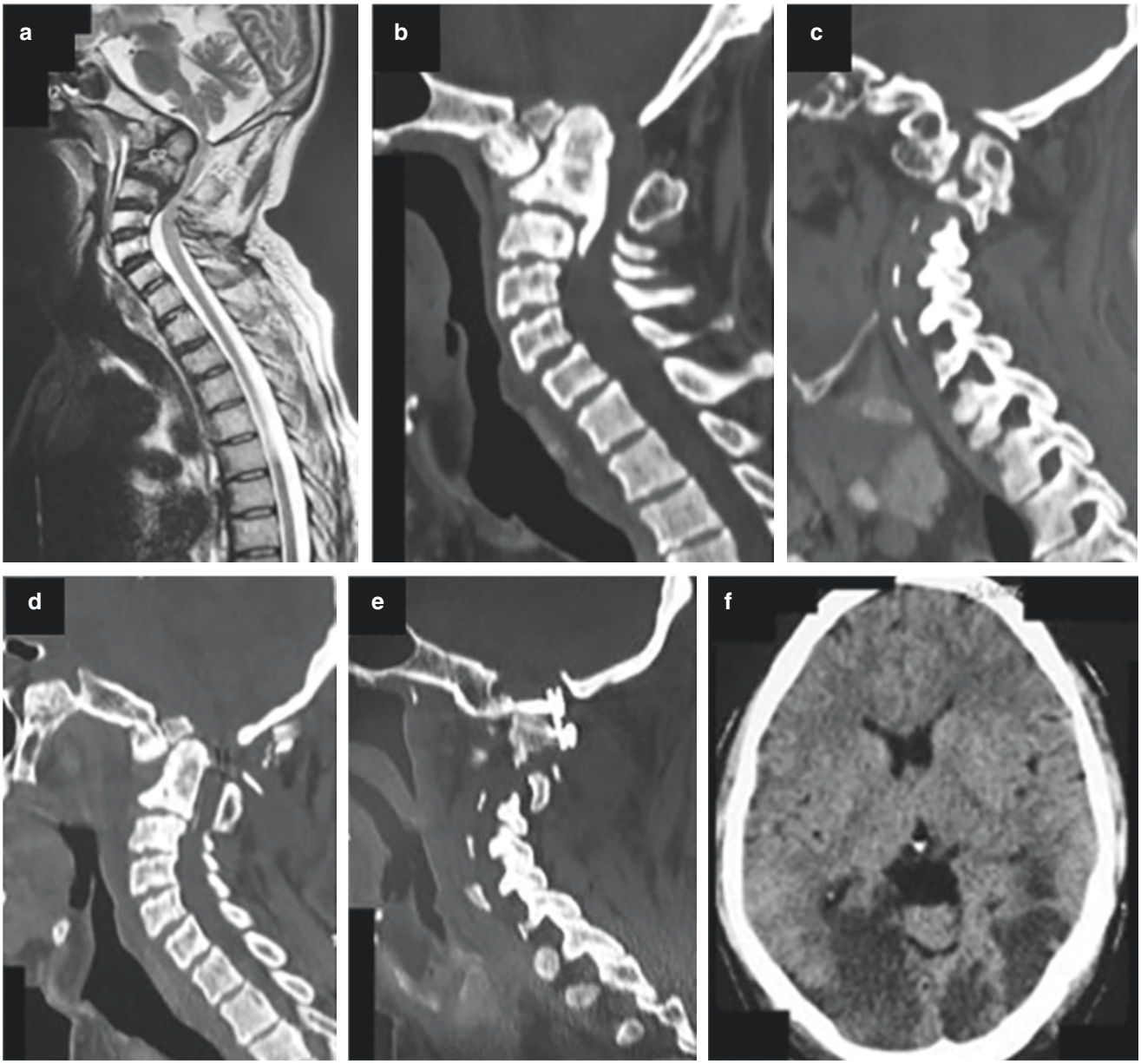

Fig. 8 Imaging findings in a 55-year-old man. Preoperative T2-weighted magnetic resonance imaging shows basilar invagination and spinal cord compression (**a**). Computed tomography (CT) demonstrates basilar invagination, assimilation of the atlas, and an ossified posterior longitudinal ligament in the region of the C2 and C3 vertebral bodies (**b**), along with a high-riding vertebral artery (**c**; sagittal cut through the facets). During surgery, there was an injury of the vertebral artery caused by screw insertion. Postoperative CT demonstrates craniovertebral realignment (**d**), the implant (**e**), and bilateral cerebral infarcts in the territory of both posterior cerebral arteries resulting in permanent blindness (**f**)

4. A single case of bilateral PCA infarct, leading to permanent bilateral blindness (Fig. 8).
5. An extensive posterior circulation infarct, leading to sudden death. Such large infarcts that lead to acute neurological worsening usually occur between 6 and 10 h after the surgical procedure complicated by VA injury.

Smaller infarcts are usually well tolerated by the patient. Partial visual loss is also well tolerated, and the visual field progressively improves over time. The author has observed that VA injury during screw insertion in C2 is usually better tolerated than an injury in the rostral course of the artery. Although the exact reason for this is unclear, it seems that

bleeding from the site of the C2 hole is rather quickly managed by screw insertion, while bleeding from other sites can take significant time to control.

Conclusion

The course of the VA on the inferior aspect of the superior facet of the axis makes it susceptible to damage during screw insertion in the adjacent lateral mass. The consequences of such an injury will depend on the adequacy of the collateral blood flow through other arteries supplying the brain. Quick decision-making for management of such complication is essential.

Conflict of Interest Statement The author has no conflict of interest concerning the reported materials or methods.

References

1. Goel A. Treatment of basilar invagination by atlantoaxial joint distraction and direct lateral mass fixation. J Neurosurg Spine. 2004;1:281–6.
2. Goel A, Laheri V. Plate and screw fixation for atlanto-axial subluxation. Acta Neurochir (Wien). 1994;129:47–53.
3. Goel A, Desai KI, Muzumdar DP. Atlantoaxial fixation using plate and screw method: a report of 160 treated patients. Neurosurgery. 2002;51:1351–7.
4. Cacciola F, Phalke U, Goel A. Vertebral artery in relationship to C1–C2 vertebrae: an anatomical study. Neurol India. 2004;52:178–84.
5. Goel A, Gupta S. Vertebral artery injury with transarticular screws [letter]. J Neurosurg 1999;90:376–377.
6. Gupta S, Goel A. Quantitative anatomy of the lateral masses of the atlas and axis vertebrae. Neurol India. 2000;48:120–5.
7. Paramore CG, Dickman CA, Sonntag VKH. The anatomical suitability of the C1–2 complex for transarticular screw fixation. J Neurosurg. 1996;85:221–4.
8. Wang S, Wang C, Liu Y, Yan M, Zhou H. Anomalous vertebral artery in craniovertebral junction with occipitalization of the atlas. Spine (Phila Pa 1976). 2009;34:2838–42.
9. Goel A, Gupta S, Laheri V. Congenital absence of posterior elements of axis: a report of two cases. Br J Neurosurg. 1999;13:459–61.
10. Goel A, Prasad A, Shah A, More S. C1–2 and C2–3 instability in the presence of hypoplastic posterior elements of C2 vertebra: report of 2 cases. World Neurosurg. 2018;110:604–8.
11. Goel A, Jankharia B, Shah A, Sathe P. Three-dimensional models: an emerging investigational revolution for craniovertebral junction surgery. J Neurosurg Spine. 2016;25:740–4.
12. Goel A. Caudally directed inferior facetal and transfacetal screws for C1–C2 and C1–2–3 fixation. World Neurosurg. 2017;100:236–43.
13. Goel A. Cervical ganglion 2 (CG2) neurectomy: a window to the atlantoaxial joint [comment]. World Neurosurg. 2012;78:78–9.

Complications of Anterior Cervical Discectomy and Fusion

Scott C. Robertson and Mason R. Ashley

Abstract

Anterior cervical discectomy and fusion (ACDF) is the most common surgery performed on the cervical spine, and the number of its cases has tripled over the last two decades. Although this intervention is typically safe and effective, it carries an inherent complication risk, which should not be underestimated. Improvements in surgical techniques and advances in interbody fusion devices and plating systems have certainly reduced the rate of postoperative morbidity, but despite such progress, surgeons need to beware consistently of the potential complications, inform the patient of their possibility, and have a management strategy as they develop. This review discusses postoperative morbidity encountered in recently reported large studies on ACDF and highlights the senior author's own single-surgeon experience with 2579 such procedures performed between 1998 and 2017. In his clinical series, which is the largest one reported to date, the overall complication rate was 7.0% (180 cases), and dysphagia (1.9% of cases), graft/hardware failures (1.3% of cases), and postoperative hematomas (0.9% of cases) were noted most frequently. Understanding of the risk and clinical impact of complications after ACDF is very important and every effort should be put on their possible avoidance and on appropriate management when they do occur.

Keywords

Anterior cervical discectomy and fusion · Cervical spine · Complication · Dysphagia · Nerve palsies · Postoperative hematoma · Spine hardware failure · Spine surgery · Surgical complications

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Introduction

Anterior cervical discectomy and fusion (ACDF) is the most common neck surgery performed in developed countries. The number of patients with cervical degenerative disease is expected to continue increasing as the population ages. The rate of ACDF surgeries is therefore expected to increase as well. This procedure is typically safe and effective, but carries an inherent risk [1–6]. Surgeons must beware of the potential complications and inform the patient of them. Appropriate surgical techniques should be practiced to keep adverse events to a minimum. When complications occur, surgeon should have a clear strategy for their management. The Association for Collaborative Spinal Research analyzed perioperative complications of cervical spine surgery in 1269 patients and identified 26 types of such unfavorable events, which can be classified as being (1) direct result of the intervention or (2) secondary morbidity, which may be encountered after any surgical procedure [3]. In addition, there have been several other large studies evaluating ACDF-related complications [1, 2, 4, 7–9]. This review also examines perioperative morbidity associated with ACDF and proposes methods to prevent and manage complications. It is primarily based on the senior author's single-surgeon series, which is the largest one reported to date, with specific look at complications directly related to the surgery, while the secondary morbidity highlighted in the Collaborative Spinal Research study [3] and other adverse events are shortly discussed as well.

Material and Methods

A total of 2579 cases of ACDF performed between 1998 and 2017 were evaluated retrospectively. The age of patients ranged from 18 to 90 years (mean 64.2 years). All of them were operated on by a single surgeon, who used a standard right-side anterior approach. Intraoperative nerve monitoring was utilized in most cases that involved the C4/5 level. Fusion was performed by the use of either a tricortical iliac

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_20

crest allograft or a polyether ether ketone (PEEK) cage filled with demineralized bone matrix (DBM) in the early part of the series. Anterior cervical plating was used in all cases. Over the last 6 years, we placed vancomycin powder in the wound prior to closing. Wound drain was not typically inserted in most cases. The vast majority of patients were discharged 12–36 h after surgery unless there were complications that prolonged length of the hospital stay.

All patients were followed up for a minimum of 3 months, with most seen at 6 months postoperatively. All patients were placed in a cervical orthosis for a minimum of 6 weeks, or for 12 weeks if three or more levels had been fused. Cervical X-rays were obtained immediately postoperatively and then at 6 weeks and 3 months. In cases of questionable pseudoarthrosis or graft/hardware failure, additional cervical X-rays were obtained at 6 months.

All patients were stratified into two age groups: 18–59 years and ≥60 years of age. We looked at the following most commonly reported complications directly related to the ACDF surgery: dysphagia, graft/hardware failure (in particular, that required reoperation), vascular injury, nerve palsy, dural tears, postoperative hematoma, infection, dysphonia, worsening neurologic condition postoperatively (myelopathy/radiculopathy), and esophageal tears. Only graft and hardware complications that required reoperation are reported herein. Any minor screw backout (<2 mm) that did not progress after 6 months and broken screws detected after 3 months were not included in this analysis. All symptomatic postoperative hematomas larger than 2.5 cm in width were noted, although reoperation for their evacuation was required in five patients only. A deteriorating neurologic condition was considered if the patient's radicular or myelopathic symptoms showed worsening immediately after surgery or during early postoperative period.

Results

The overall ACDF-related complication rate in our series was 7.0% (n = 180). Patients aged 18–59 years (n = 1598) had a lower complication rate (6.4%) than patients aged ≥60 years (n = 981; 7.8%) (Table 1), although the difference did not reach the level of statistical significance (P = 0.1744). As shown in Table 2, revision surgery (n = 52) and ACDF involving three or more fused levels (n = 471) carried a significantly higher rate of complications (P = 0.0163 and P < 0.0001, respectively). Specifically, the complication rate in revision surgery was roughly 2.5 times that in first-time surgery. Among all complications, dysphagia, graft/hardware failure, and postoperative hematomas were noted most frequently, which would be expected with a large number of multilevel ACDF surgeries in the presented series (Table 3).

Specific Complications

As shown in Table 4, the overall surgical complication rate and distribution of their types in our experience were in line with those in other recently reported large relevant studies [2–4].

Death: We had no deaths from surgery in our series. Each of the other comparable study [2–4] reported at least one death. Although it is a rare complication (occurring in 0.1–0.2% of cases), death from the ACDF surgery can happen, and this possibility must be discussed with the patient.

Dural Tears: Twelve of our patients (0.5%) experienced an inadvertent dural tear resulting in cerebrospinal fluid (CSF) leakage during the procedure. Three of these cases occurred during revision surgery. The others were noted in cases of significant degenerative disease with large bridging osteophytic bone spurs and an ossified posterior longitudinal ligament (OPLL) adherent to the dura, which was thinned out and tore during attempted removal of the adjacent bone. All of the CSF leaks were immediately identified and repaired with a Gelfoam® and fat graft sealed over with a fibrin glue. Additional fibrin glue was applied thereafter around the interbody graft and anterior plate upon their placement. Care was taken to make sure the interbody graft did not push the patch material into the spinal canal. A water-

Table 1 Age of patients and complication rates in the current anterior cervical discectomy and fusion series

Age (years)	Number of patients	Number of complications
18–59	1598	103 (6.4%)
≥60	981	77 (7.8%)

Table 2 Complication rates classified by surgical levels in the current anterior cervical discectomy and fusion series

Surgical level	Number of patients	Number of complications
First-time surgery		
1-level	1101	31 (2.8%)
2-level	957	71 (7.4%)
3-level	415	59 (14.2%)
4-level	54	11 (20.4%)
Revision surgery		
1-level	45	4 (8.9%)
2-level	5	2 (40.0%)
3-level	2	2 (100%)
Total	2579	180 (7.0%)

Table 3 Summary of surgical complications with regard to surgical levels in the current anterior cervical discectomy and fusion series

	1-level fusion	2-level fusion	3-level fusion	4-level fusion	Total
Number of patients	1146	962	417	54	2579
Number of complications					
Death	0	0	0	0	0
Dural tears	2	8	2	0	12 (0.5%)
Dysphagia at ≥6 weeks	8	20	15	5	48 (1.9%)
Dysphonia at ≥6 weeks	5	10	5	0	20 (0.8%)
Esophageal injury	0	2	1	0	3 (0.1%)
Graft/hardware failure/malposition	7	8	16	3	34 (1.3%)
Hematoma ≥2.5 cm in width	3	10[a]	10[b]	1	24[c] (0.9%)
Infection	7	8	4	1	20 (0.8%)
C5 nerve root palsy	2	5	6	1	14 (0.5%)
Neurologic deterioration postoperatively	1	2	2	0	5 (0.2%)
Vascular injury	0	0	0	0	0
Total	35	*73*	61	11	180 (7.0%)

[a]Three of these 10 hematomas necessitated reoperation
[b]Two of these 10 hematomas necessitated reoperation
[c]Five of these 24 hematomas necessitated reoperation

Table 4 Comparison of complications in the current anterior cervical discectomy and fusion series and other relevant studies

	Current series	Leckie et al. (2016) [3]	Nanda et al. (2014) [4]	Fountas et al. (2007) [2]
Number of patients	2579	936	1576	1015
Number of complications				
Death	0	2 (0.2%)	1 (0.1%)	1 (0.1%)
Dural tears	12 (0.5%)	4 (0.4%)	20 (1.3%)	5 (0.5%)
Dysphagia at ≥6 weeks	48 (1.9%)	14 (1.5%)	52 (3.3%)	97 (9.5%)
Dysphonia at ≥6 weeks	20 (0.8%)	4 (0.2%)	19 (1.2%)	32 (3.1%)
Esophageal injury	3 (0.1%)	0	1 (0.1%)	3 (0.3%)
Graft/hardware failure/malposition	34 (1.3%)	7 (0.7%)	14 (0.9%)	1 (0.1%)
Hematoma ≥2.5 cm in width	24[a] (0.9%)	2 (0.2%)	2 (0.1%)	57 (5.6%)
Infection	20 (0.8%)	5 (0.5%)	3 (0.2%)	1 (0.1%)
C5 nerve root palsy	14 (0.5%)	1 (0.1%)	NA	NA
Neurologic deterioration postoperatively	5 (0.2%)	4 (0.4%)	14 (0.9%)	2 (0.2%)
Vascular injury	0	0	0	0
Total	180 (7.0%)	43 (4.6%)	126 (8.0%)	199 (19.6%)

NA not available
[a]Five of these 24 hematomas necessitated reoperation

tight wound closure was attained without any additional drains. Conservative management of the CSF leak was performed postoperatively. No CSF diversion or re-exploration of the wound was required in any case. All of the leaks resolved without additional treatment by the time follow-up imaging was done at 6 weeks.

Dysphagia: Forty-eight of our patients (1.9%) experienced persistent dysphagia at 6 weeks postoperatively. In most of them, it resolved by 12 weeks, but eight patients continued to complain of moderate-to-severe symptoms. In three cases, hardware migration and backout was the cause, and revision surgery resolved the issue. In the other five, no surgical complication was identified, and these patients were referred for additional care and evaluation after swallowing studies were performed.

Dysphonia: Twenty of our patients (0.8%) experienced dysphonia or hoarseness in the postoperative period. The incidence of dysphonia was greater in multilevel cases than in a single-level ACDF, and the difference reached the borderline level of statistical significance (P = 0.0791). Three cases were associated with postoperative hematomas. In twelve patients, dysphonia resolved after 3 months. The other eight individuals were referred for additional otolaryngology evaluation and treatment; five of them were found to have a unilateral vocal cord paralysis, whereas three were lost to follow-up.

Esophageal Injury: Three patients (0.1%) in our series suffered an esophageal perforation. In one case, this complication was due to a chronic infectious discitis, which resulted in erosion of the esophageal wall and development of a perforation during intraoperative retraction. Two other cases of esophageal injury were anesthesia-related. In one of them, the metal stylet used within the endotracheal tube was found to have perforated the retropharyngeal space and esophageal wall. The other case occurred during emergent reintubation for an expanding postoperative hematoma causing airway compromise. The intubation was extremely difficult, with several failed attempts. Eventually, the hematoma was emergently evacuated to make the intubation easier. During evacuation of the hematoma, we found a perforation in the esophagus and exposure of the nasogastric tube. Primary repair of the esophagus was performed with assistance from an otolaryngologist. The wounds were copiously irrigated with bacitracin. A feeding tube was placed, and the patient was kept *nil per os* (NPO) for 6 weeks while receiving tube feeds, and was given antibiotics intravenously for 8 weeks. All of the patient's symptoms resolved by 3 months, and no signs of recurrent infection were noted.

Graft/Hardware Failure: Thirty-four patients (1.3%) developed a significant interbody graft or hardware complication. The majority of them were ≥60 years old and underwent multilevel fusions. In three cases, retropulsion of the interbody graft appeared, causing radiculopathy or myelopathy, which required revision surgery. Two cases of anterior graft migration and plate elevation occurred, which were also surgically revised. The remaining 29 patients had hardware failure (which usually involved screw backout and plate migration away from the spine) identified at their 6-week follow-up visit. Patients with symptoms of significant dysphagia or neck pain underwent surgical revision. In other cases, patients were followed up with serial X-rays for 6 months. Hardware that continued to migrate was removed and/or revised at 3 months. If the elevation of hardware was less than 3 mm and no its further migration was observed at 6 months, no revision surgery was performed.

Postoperative Hematoma: Only postoperative hematomas, which were ≥2.5 cm in width were included in this study. Twenty-four patients (0.9%) developed this complication. A number of the hematomas occurred after use of a PEEK cage without additional DBM added to fill it. After a change to use of tricortical allograft bone for interbody grafts, fewer postoperative hematomas were noted. Most patients with this complication were treated conservatively with pressure packs, steroids, and observation. Only five patients required surgery to evacuate hematomas because of airway compromise. Among them, three developed expanding symptomatic hematomas within the first 24 h after the intervention; they underwent emergent surgical exploration and hematoma evacuation. The other two patients developed large hematomas 5 days and 7 days (one case of each) after ACDF procedure. No clear vascular source of bleeding was identified during the reoperation. In two cases where a PEEK interbody cage was used without being filled with DBM, noticeable blood oozing was observed coming from the insertion screw hole on the cage. The cages were removed and filled with DBM and replaced. In all of these cases, patients had been on some form of antiplatelet/anticoagulation medication, which was stopped 7 days prior to surgery.

Infection: Twenty patients (0.8%) developed postoperative wound infections. In fourteen of them it was superficial and cleared with 10 days of oral antibiotic therapy. The other six patients underwent open wound irrigation and drainage with placement of a drain for 2 days. They received antibiotics intravenously for 6 weeks. None required any additional surgery or had any other symptoms at 6 weeks postoperatively. Three of the six patients who required wound drainage initially had small postoperative hematomas that later became infected. All but one patient who developed a wound infection after ACDF had type 2 diabetes and/or a previous spinal surgical infection.

C5 Nerve Root Palsy: Fourteen patients (0.5%) developed postoperative C5 nerve root palsies. In 11 of them, related symptoms were present immediately after surgery, whereas in 3 they developed a few days later. Eight C5 nerve palsies occurred on the left side and six on the right. Repeat magnetic resonance imaging (MRI) and X-rays were obtained to evaluate these patients for any surgical reason of the complication. In one case, we found some disc/fractured graft material compressing the C5 nerve root, and this patient was reoperated. No cause of the complication was identified in the other 13 individuals. They all received steroids for 3–5 days and aggressive physical therapy, including nerve stimulation, for 3–6 months after surgery. Eight patients recovered near-normal muscle function by 6 months, four recovered partial function, but two never demonstrated significant functional recovery even after 9 months. For avoidance of this complication, we adopted a perioperative protocol to monitor all C4/5 ACDF cases, which entailed initiation of the nerve/muscle monitoring before intubation and close blood pressure regulation, keeping the mean arterial pressure (MAP) greater than 80 mmHg throughout the procedure. Since that implementation, we have not experienced any new case of postoperative C5 nerve root palsy.

Neurologic Deterioration: Five patients (0.2%) experienced worsening of their preoperative neurologic symptoms. These did not include cases of the C5 nerve root palsy reported above. Patients with postoperative neurologic deterioration developed worsening myelopathy and, in some cases, neuropathic pain as a component of central cord syndrome. All of them had severe chronic spinal cord compression before surgery. Postoperative MRI was performed, but did not demonstrate compression of neural structures in any case, while all five patients had some degree of increased spinal cord signal intensity, and one had a small spinal cord hemorrhage. Conservative treatment with steroids and gabapentin was performed. All but one patient recovered back to

their preoperative neurologic baseline level within 6 months; the other patient still had not fully recovered at 12 months.

Vascular Complications: There were no vascular injuries to report.

Pseudoarthrosis: Although this was not a focus of this surgical complications study, we did have 198 patients (7.7%) with a surgical level of nonunion at 3 months and 78 patients (3.0%) at 6 months. Most of these patients had undergone multilevel fusions and were in "higher-risk" group, i.e., were older, presented with underlying comorbidities, including diabetes, and had a recent history of smoking. The type of interbody graft that was used did not seem to be a factor in the nonunion rate. Interestingly, most of the patients with pseudoarthrosis were asymptomatic with no reported neck pain. Twelve individuals developed disc herniations at adjacent levels, which became symptomatic and required surgery. During this reoperation, the nonfused level was revised and re-fused at the request of the patient.

Discussion

In patients undergoing ACDF, complications may occur at any time from the stage of preoperative preparation and anesthesia induction to the postoperative at-home recovery. Avoiding adverse events can best be achieved by thorough understanding of the pathology, appropriate selection of the surgical candidates, careful execution of the procedure, and patient participation in their postoperative education and care. In general, identifying higher-risk patients will allow the surgeon to be prepared for complications when they occur and possibly avoid a number of them. Herein we discuss some of the most common factors associated with the ACDF morbidity, although, certainly, do not pretend that this is an all-inclusive spectrum of possible perioperative complications in such cases.

Preoperative Considerations

Patient selection for ACDF is always important but cannot be controlled in all situations. Use of an anterior approach alone has been shown to carry the lowest rate of adverse events; when a posterior approach or a combined anterior/posterior approach is used, there is almost three times the risk of complications [3]. In concordance with previous reports, our study has confirmed that patients aged ≥60 years have a higher morbidity rate. Older individuals have increased pulmonary, cardiac, urologic, transfusion, and mental status complications, with an increased length of hospital stay [1, 4]. In addition, comorbidities such as hypoalbuminemia and diabetes have been shown to increase the risk of complications after ACDF [10]. Optimizing patients' nutritional status and getting appropriate medical clearance before intervention are important. Multilevel fusions and revision surgery both carry higher risks of complications, as was reconfirmed by our data presented herein. These risks should be conveyed to the patient, and the surgeon should be prepared for them.

The surgeon should confirm that all necessary materials and equipment are available to handle complications should they arise. The use of an operating microscope for ACDF procedure has been shown to improve safety, decrease bleeding, shorten the operative time, and reduce complications [11].

Anesthesia and Positioning

Airway swelling and obstruction resulting in prolonged intubation and/or a need for reintubation sometimes cannot be avoided. The incidence of postoperative airway compromise after ACDF has been reported to be as high as 14%. Anesthesia risk corresponding to grade >II according to an American Society of Anesthesiologists (ASA) physical status classification system, may carry a higher probability of airway complication in the perioperative period [12]. In such cases, most patients require only an additional overnight stay in an intensive care unit and can be weaned off the ventilator and extubated the next day. Addition of steroids to therapy can be useful. We try to keep our operative time and, correspondingly, the duration of wound retraction to a minimum. During longer procedures, we consider intermittent relaxing the retractors and give intraoperative steroids.

During induction of general anesthesia, cervical protective measures are significantly diminished and the compromised spinal cord is at risk of injury during forceful intubation. In-line manual traction and fiberoptic intubation should be used in cases where the spine is unstable or when the spinal cord is significantly compressed or injured.

Maintaining adequate blood pressure is crucial for spinal cord perfusion. Significant drops in blood pressure can occur during anesthesia induction and intubation, and can cause a significant reduction in the spinal cord blood flow, resulting in its ischemia and neurologic worsening. A decrease of 12% in spinal cord blood flow can cause paralysis [13]. We try to maintain a MAP >80 mmHg during the entire procedure.

Patient positioning is important to allow adequate surgical access while avoiding iatrogenic complications. Avoid excessive pressure on the eyes. Position the patient's arms at the side, and pad pressure points on the elbows, knees, and heels. Avoid excessive traction on the shoulders with tape or other mechanical devices to prevent brachial plexus and nerve root traction injuries.

Bone Graft Harvesting

Anterior iliac crest grafting is still commonly performed and used as an ACDF graft source. Common complications

include donor site pain, hematomas, iliac crest fractures, infections, and nerve damage. Proper location of the incision and use of a graft harvesting site 3 cm behind the anterior superior iliac spine are recommended. Minimize dissection and muscle stripping off the bone. Use bone wax or fill the donor site with bone void filler. Close the wound well to reduce hematoma and seroma formation.

The use of allograft bone and artificial cages (i.e., made of titanium or PEEK) has become popular in replacing autograft bone graft for ACDF. Fusion rates have been reported to be slightly lower using these alternative products, but not significantly lower. In our series with the application of only allograft bone or artificial cages, the fusion rate was comparable to those with the use of autograft bone reported elsewhere. The use of these alternative grafts has several advantages, including reduced operative time and no donor site complications.

Dural Tears

The risk of an inadvertent durotomy and CSF leakage in ACDF is generally low. Most reported cases occur in revision surgeries [2–4]. Risk factors include OPLL, dural thinning from chronic degenerative compression, significant neural foraminal narrowing from bone spurs, and old age of the patient. It is better to free the thinned-out ossification from its bony margins and to leave it attached, floating on the dura mater. Aggressively trying to remove adherent bone can cause dural tears.

Incidental intraoperative durotomies are usually seen immediately and should be repaired at that time. A primary suturing of the dural laceration is almost impossible in most cases. Fat or dural graft material can be used to patch the defect, followed by application of a fibrin sealant. The interbody graft can be placed, additional fibrin sealant is put around the bone void, and the plate then applied. A multilayer watertight wound closure is needed. Wound drains are not recommended. A lumbar drain is typically not needed. Re-exploration should be considered in cases of persistent CSF leakage, a fistula, or symptomatic nonresolving pseudomeningocele.

Dysphagia and Esophageal Injury

Dysphagia is the most commonly reported complication of ACDF. The etiology of dysphagia is multifactorial; it may be associated with the age of patient, traumatic intubation, excessive retraction of midline structures during surgery, hardware failure, and alteration of normal swallowing mechanisms. Preoperative screening for dysphagia should be performed, as surgery may exacerbate a minor pre-existing condition. In patients with significant preoperative symptoms, we recommend a swallowing evaluation and testing before intervention. Preoperative tracheal traction exercises to reduce the occurrence of dysphagia after surgery have been advocated [14]. Surgical techniques to avoid severe trauma to the soft tissues should be practiced. Specifically, excessive retraction of the pharyngeal/esophageal walls can cause their ischemic damage and mechanical distortion leading to dysphagia. Some studies suggest using thinner or zero-profile instrumentation to reduce the incidence of this complication [15, 16]. Of note, appearance or aggravation of dysphagia after ACDF can indicate hematoma formation, infection, pharyngeal plexus or superior laryngeal nerve injury, graft/plate dislodgement, or scar formation. Postoperative X-rays and MRI can identify some surgery-related problems that may require revision. Nevertheless, most cases of postoperative dysphagia after ACDF are transient and resolve by 2 weeks. An additional work-up including a swallowing study should be obtained for prominent symptoms, especially if they persist after 3 months.

Esophageal or pharyngeal tears are a rare complication of ACDF. Blunt finger dissection of the prevertebral region and esophagus is recommended. Careful placement of the retractor blades along the dissected longus colli muscle, and not into the esophagus, must be practiced. Also, avoid aggressive intubation with endotracheal metal stylets. Esophageal tears can be fatal and need to be addressed urgently. Injection of methylene blue directly into the esophagus to identify the site of perforation can be performed intraoperatively; proximal and distal blocking of the area in question with Foley catheters may improve the detection rate with this technique. Primary closure of the defect is required [17]. Use of additional muscle or fascial flaps over the site can strengthen the repair. The cervical wound should be washed out well, and a drain should be inserted for a few days. A feeding tube is placed, and the patient is kept NPO for 4–6 weeks while receiving tube feeds. Intravenous antibiotics should be given for 6–8 weeks, especially in instrumented cases. Additional imaging and swallowing studies may be required if symptoms still persist after 3 months.

Dysphonia/Recurrent Laryngeal Nerve Injury

Hoarseness after ACDF was usually reported in fewer than 3% of cases in the series we reviewed [1–4]. In most patients, this postoperative symptom is transient, lasting for 6–12 weeks, but in approximately 1% of cases it remains permanently and necessitates further evaluation. Damage of the recurrent laryngeal nerve is the most common cause of hoarseness; neuropraxia can result from overstretching, compression-related ischemia, adjacent soft tissue edema, or transection of the nerve. The risk of hoarseness appears to be greater in cases of multilevel ACDF. This could be explained by the added retraction time required to manage more surgical levels. Also, the traditional small horizontal skin incision

requires more retraction of soft tissues to achieve the exposure required to perform multilevel ACDF. We recommend extending the skin incision more toward the midline and undermining the skin to gain more exposure without having to perform a harder retraction. The risk of the recurrent laryngeal nerve injury also increases in cases of ACDF below C4. Other etiologies of postoperative hoarseness include direct vocal cord damage, superior laryngeal nerve injury, and laryngeal edema. Particularly, the endotracheal tube can damage the vocal cords or compress the lateral laryngeal wall, injuring the recurrent laryngeal nerve indirectly.

We found no increased risk of this complication with a right-side approach. Particularly, all of our revision surgeries were performed through the same incision on the right side, with no increased morbidity. In the case of a recurrent laryngeal nerve injury from a previous surgery, a same-side approach is specifically recommended. Careful blunt finger dissection around the medial prevertebral structures should be practiced. Proper retractor placement is important to avoid compression on the recurrent laryngeal nerve. Avoid excessive retraction medially on the tracheal/laryngeal structures and ligation of inferior thyroid vessels. During retraction, the endotracheal tube cuff should be released and its pressure should be adjusted to avoid vocal cord or lateral laryngeal wall injury.

Graft/Hardware Failure

Graft complications after ACDF are uncommon and have been seen in fewer than 1% of patients. Graft subsidence can occur more often in individuals with osteoporotic bone, but in general, migration of the graft usually results from its improper size. Any graft subsidence will transfer the compressive load to the anterior plate, leading to implant failure. Therefore, the graft must be of the right height and depth, and it is imperative to size, shape, and tap it into place appropriately. A larger-diameter graft provides a greater surface area to handle the structural load. Anterior plates can reduce the anterior extrusion of the graft. Posterior graft retropulsion can be prevented by using a slightly lordotic-shaped graft and by leaving a posterior lip during endplate preparation.

A number of graft materials are now being utilized, but none have proven to be superior to an autograft [6, 18, 19]. However, the number of complications associated with the graft donor site has pushed surgeons to use allograft bone and synthetic cages more frequently [6].

The advantages of anterior cervical plates are well known, and include initial stability, early mobilization of the patient, reduced graft migration risk, an improved fusion rate, and reduction of the external bracing duration after surgery. Complications associated with plates are relatively rare but include dysphagia and accelerated adjacent segment disc degeneration. Implant migration with screw backout is a more common problem, which is probably underreported in most studies. If <3 mm of screw backout is observed, it does not always require revision. The patient can be followed with serial X-ray examinations to ensure that no further screw backout progression has occurred. If this has happened or anterior plate elevation is revealed, revision surgery is indicated. Instrumentation complications are greater in older individuals and in cases of multilevel procedures. Particularly, long instrumented constructs in osteoporotic bone have a higher failure rate. Therefore, additional posterior support should be considered in older patients undergoing fusion at three or more levels. Careful placement of the hardware is important. Overangulation of screws can predispose them to backing out. Fixating the anterior plate to as many levels as possible helps reduce stress and screw pullout in longer plates. Dynamic plates have been designed to help reduce screw pullout and compensate for some subsidence that occurs [6]. Poorly positioned plates can accelerate adjacent segment disease. Both superior and inferior ends of the plate should be at a distance of at least 5 mm from adjacent endplates whenever possible. In multilevel fusions, multiple individual small plates placed at each level are less likely to pull out screws than longer plates. Until recently, individual anterior plates were too large to stack for multilevel fusions. New smaller plates and zero-profile devices allow this stacking to occur, reducing the need for implantation of longer plates.

Total disc replacement maintains motion, with a decreased rate of reoperations and lower reported incidence of adjacent segment disease [6, 20]. This surgical option should be considered in selected patients.

Postoperative Hematoma

Postoperative neck hematomas are a potentially life-threatening complication. Most of them occur within the first 24–48 h after surgery, but in some cases it can be delayed. Common causes include rupture of small vessels coagulated during dissection of the neck, bone endplate bleeding, epidural venous bleeding, distraction pin site bleeding, and unidentified inadvertent vessel damage during retraction. Obviously, patients who have coagulopathies or are on antiplatelet/anticoagulation medications have a higher risk of hemorrhagic complications. Meticulous tissue dissection is required always. All small bleeding vessels should be coagulated before wound closure. Avoid overaggressive endplate preparation, which can cause excessive bleeding. Plug all distraction screw holes with bone wax or Gelfoam® to prevent bleeding into the retropharyngeal space. Copious warm irrigation of the wound before closure will help with hemostasis and facilitate identification of the bleeding sites. Reduction of dead space and use of a thin layer of hemostatic material along the dissection plane can reduce the risk of hematoma formation. However, the necessity of the closed

wound drain insertion remains controversial. In any case, drains should be used only as an adjunct to meticulous intraoperative hemostasis.

Early detection should be the main focus of postoperative hematoma management. Most small superficial hematomas can be observed and treated conservatively. On the other hand, medical staff need to maintain a high index of suspicion for expanding hematomas. When patients report worsening neck pain, dysphagia, hoarseness, or breathing difficulties, close monitoring and emergent evacuation of the hematoma should be considered. In these cases, the airway can deteriorate quickly and intubation can become extremely difficult. Emergent revision of the wound and evacuation of the hematoma may be required at the bedside even before the patient can be intubated or taken to the operating room. A tracheostomy may be considered as a last resort.

Infection

The incidence of postoperative wound infections after ACDF is usually less than 2%. Their risk correlates with the duration of procedure and the surgical technique. Keeping the operative time to a minimum is important. Meticulous surgical technique directed at decrease of wound retraction, good hemostasis, reduction of dead spaces during closure, and frequent wound irrigation are necessary. Local application of vancomycin powder is also useful in reducing infections in long instrumented cases.

Most infections usually occur within 7–14 days postoperatively, but occasionally, they can present 3–4 weeks out from the surgery. Diabetic patients have a much higher rate of this complication. Many superficial wound infections can be treated with a short course (7–10 days) of oral antibiotics. For this purpose, we typically use cephalexin or dicloxacillin. Deeper wound infections, including abscesses and discitis, require open drainage with copious irrigation. We typically leave a drain in for 1–2 days and give all such patients intravenous antibiotics (mainly, vancomycin) for 6–8 weeks. We do not remove the hardware if the infection all appears to be in the prevertebral spaces. If there is disc space or epidural involvement on imaging, we remove all of the graft and hardware, clean the area out with copious antibiotic irrigation, and then insert new grafts and plates. Additional vancomycin powder is applied around the hardware and in the prevertebral space.

Nerve Root Injury/C5 Palsy

C5 nerve root palsy is the most frequently reported radiculopathy after ACDF. There is significant variation in the reported frequency of this complication but in most larger series its rate is less than 3%. Most cases present immediately postoperatively, but they can also manifest a few days after surgery. The etiology is still controversial, but most authors hypothesize that an ischemic component is involved. Other predisposing factors may include excessive traction, thermal injury from coagulation, and spinal cord migration. High signal intensity on preoperative T2-weighted MRI along the C3–C5 spinal cord segments, a C4/5 neural foraminal stenosis, and rotation of the spinal cord may be risk factors for development of C5 palsies after surgery [13]. Usefulness of the intraoperative nerve monitoring for preventing this complication is still controversial. Our experience has demonstrated that low blood pressure correlates well with loss of signals during intraoperative nerve/muscle monitoring, which are usually recovered when the blood pressure is increased. Therefore, we recommend keeping a MAP at >80 mmHg during intubation and throughout the procedure. Aggressive extension of the neck should be avoided, as it can reduce the neural foraminal diameter and compress the exiting nerve root and/or alter its vascularity. For the same reason, taping down or traction on the shoulders for intraoperative imaging should be done cautiously.

In symptomatic patients, postoperative MRI is needed to rule out nerve root compression, and if it is identified, a revision surgery should be performed. Other cases of C5 palsies can be treated conservatively, as most recover spontaneously by 6 months. Steroids may be considered but have not been proven to facilitate recovery. Physical therapy is recommended to prevent loss of shoulder mobility.

Neurologic Deterioration

Spinal cord injury during ACDF surgery is rare, but neurologic deterioration postoperatively is reported in some (<1%) cases. Injury can occur from excessive neck manipulation in the paralyzed patient during anesthesia, spinal cord ischemia, inadvertent spinal cord compression during disc/osteophyte removal with Kerrison rongeurs or drilling, or improper graft placement. Individuals with severe chronic spinal cord compression are at greatest risk. Intraoperative electrophysiologic monitoring is useful in high-risk patients for identifying early spinal cord injury. Increasing the blood pressure should be the first response when an intraoperative spinal cord/nerve signal loss occurs. Steroids can be used to reduce spinal cord edema. Postoperative MRI may demonstrate high signal intensity consistent with edema or even hemorrhage in the spinal cord, and rule out any compressive causes that may necessitate revision surgery. Hyperperfusion injury with loss of arterial autoregulation due to chronic spinal cord compression may be one explanation for postoperative myelopathy after ACDF. Recovery is variable; in our experience, most deficits resolve to at least the preoperative neurologic baseline level within 6 months.

Vascular Injury

Vascular injuries are rare during an anterior approach to the cervical spine and are seen more often in posterior cervical instrumentation cases. Careful dissection around the larger vessels is required. Staying within the natural avascular cleavage planes medial to the carotid sheath is imperative. Small bridging vessels should be tied off or coagulated if they prevent adequate exposure. Excessive retraction should be avoided, with attention to proper blade placement to prevent damage to blood vessels. To avoid vertebral artery injury, discectomy and foraminotomy should not be extended laterally past the uncinate process.

Other Complications

Other miscellaneous surgical complications include cervical sympathetic chain injury resulting in Horner's syndrome, thoracic duct transection with chylorrhea, and tracheal injuries. Most of these can be prevented with a detailed knowledge of the regional anatomy and application of a meticulous surgical technique.

Delayed Complications: Pseudoarthrosis

Pseudoarthrosis is a delayed complication of ACDF. Its incidence varies widely. Risk factors include older age of the patient, smoking, osteoporosis, use of nonsteroidal anti-inflammatory drugs, steroids, and antimetabolic agents, poor surgical technique, multilevel fusions, and concomitant collagen disorders or autoimmune diseases [21]. In concordance, in our experience a higher rates of pseudoarthrosis were noted in older patients and in cases of multilevel fusions. Preoperative radiographic findings of segmental motion and a greater T1 sagittal slope are also associated with an increased risk of pseudoarthrosis [22]. Newer biologic agents and bone growth stimulators may help increase fusion rates. In particular, use of bone morphogenetic proteins has been shown to be effective, but they cause serious complications when overdosed.

Secondary Complications

In the presented series, we have focused on the adverse events directly associated with ACDF. There are many other complications commonly seen with any surgery, not just attributed to cervical spine procedures [3]. Cardiac morbidity is one of the most frequently reported, but there is also high risk of respiratory complications caused by neck swelling, airway edema, and aspiration, which frequently lead to pneumonias. Patients with a myelopathy have more urologic complications, postoperative ileus, gastric reflux, and deep vein thromboses, especially in presence of significant spinal cord compression. Older patients are at greater risk of developing delirium from the use of narcotics, steroids, and general anesthesia, and the physician and family should be aware of this.

Conclusion

Nowadays, ACDF has become a safe and effective procedure. Nevertheless, a 10% postoperative complication rate is to be expected, while secondary adverse events associated with any surgical intervention will make the overall morbidity even higher. It definitely increases costs of treatment and duration of the hospital stay. In the current medical environment, when physicians and hospitals are penalized for adverse events, it is important to educate policy-makers and insurance companies on the inherent risk and natural causes of many complications associated with ACDF.

The incidence of adverse events will vary depending on the complexity of surgical cases and individual characteristics of patients seen in one's practice. Any surgeon should be prepared for common complications associated with ACDF and have a strategy to manage them. It is important to learn from ones` experience with complications and to make all necessary adjustments to reduce their recurrence. Presented single-surgeon series, which is the largest one reported to date, shows fewer complications than were noted in previously published smaller studies and analyses of grouped data. It may reflect an importance of the increased individual practical experience of any particular surgeon [4, 23].

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Cheung J, Luk K. Complications of anterior and posterior cervical spine surgery. Asian Spine J. 2016;10:385–400.
2. Fountas K, Kapsalaki E, Nikolakakos L, Smisson H, Johnston K, Grigorian A, Lee G, Robinson J. Anterior cervical discectomy and fusion associated complications. Spine (Phila Pa 1976). 2007;32:2310–7.
3. Leckie S, Yoon ST, Isaacs R, Radcliff K, Fessler R, Haid R, Traynelis V. Perioperative complications of cervical spine surgery: analysis of a prospectively gathered database through the Association for Collaborative Spinal Research. Global Spine J. 2016;6:640–9.
4. Nanda A, Sharma M, Sonig A, Ambekar S, Bollam P. Surgical complications of anterior cervical discectomy and fusion for cervical degenerative disease: a single surgeon's experience of 1,576 patients. World Neurosurg. 2014;82:1380–7.
5. Rahul Y, Siddharth C, Arvind C, Girjia PR. Post-operative complications in patients undergoing anterior cervical discectomy and fusion. J Neuroanaesth Crit Care. 2017;4:170–4.
6. Song KJ, Choi BY. Current concepts of anterior cervical discectomy and fusion: a review of literature. Asian Spine J. 2014;8:531–9.

7. Buerba R, Giles E, Webb M, Fu M, Gvozdyev B, Grauer J. Increased risk of complications after anterior cervical discectomy and fusion in the elderly: an analysis of 6253 patients in the American College of Surgeons National Surgical Quality Improvement Program database. Spine (Phila Pa 1976). 2014;39:2062–9.
8. Fu M, Gruskay J, Samual A, Sheha E, Derman P, Iyer S, Grauer J, Albert T. Outpatient anterior cervical discectomy and fusion is associated with fewer short-term complications in one- and two-level cases: a propensity-adjusted analysis. Spine (Phila Pa 1976). 2017;42:1044–9.
9. Gruskay J, Fu M, Basques B, Bohl D, Buerba R, Webb M, Grauer J. Factors affecting length of stay and complications after elective anterior cervical discectomy and fusion: a study of 2164 patients from the American College of Surgeons National Surgical Quality Improvement Project database (ACS NSQIP). Clin Spine Surg. 2016;29:34–42.
10. Fu M, Buerba R, Grauer J. Preoperative nutritional status as an adjunct predictor of major postoperative complications following anterior cervical discectomy and fusion. Clin Spine Surg. 2016;29:167–72.
11. Sun M, Kong L, Jiang Z, Liming L, Lu B. Microscope enhance the efficacy and safety of anterior cervical surgery for managing cervical ossification of the posterior longitudinal ligament. Med Sci Monit. 2017;23:3088–94.
12. Lim S, Carabini L, Kim R, Khanna R, Dahdaleh N. Evaluation of American Society of Anesthesiologists classification as 30-day morbidity predictor after single-level elective anterior cervical discectomy and fusion. Spine J. 2017;17:313–20.
13. Naito M, Owen J, Bridwell K, Sugioka Y. Effects of distraction on physiologic integrity of the spinal cord, spinal cord blood flow, and clinical status. Spine (Phila Pa 1976). 1992;17:1154–8.
14. Chaudhary S, Yu B, Pan F, Li X, Wang S, Shaikh I, Wu D. Manual preoperative tracheal retraction exercise decreases the occurrence of postoperative oropharyngeal dysphagia after anterior cervical discectomy and fusion. J Orthop Surg (Hong Kong). 2017;25(3): https://doi.org/10.1177/2309499017731446.
15. Basu S, Rathinavelu S. A prospective study of clinical and radiological outcomes of zero-profile cage screw implants for single-level anterior cervical discectomy and fusion: is segmental lordosis maintained at 2 years? Asian Spine J. 2017;11:264–71.
16. Wang Z, Zhu R, Yang H, Gan M, Zhang S, Shen M, Chen C, Yuan Q. The application of a zero-profile implant in anterior cervical discectomy and fusion. J Clin Neurosci. 2013;21:462–6.
17. Halani S, Baum G, Riley J, Pradilla G, Refai D, Rodts G, Ahmed F. Esophageal perforation after anterior cervical spine surgery: a systematic review of the literature. J Neurosurg Spine. 2016;25:285–91.
18. Yi J, Lee GW, Nam WD, Han K, Kim MH, Kang JW, Won J, Kim SW, Noh W, Yeom JS. A prospective randomized clinical trial comparing bone union rate following anterior cervical discectomy and fusion using a polyetheretherketone cage: hydroxyapatite/B--tricalcium phosphate mixture versus hydroxyapatite/demineralized bone matrix mixture. Asian Spine J. 2015;9:30–8.
19. Zadegan S, Abedi A, Jazayeri S, Vacarro A, Rahimi-Movaghar V. Demineralized bone matrix in anterior cervical discectomy and fusion: a systematic review. Eur Spine J. 2017;26:958–74.
20. Hisey M, Bae H, Davis R, Gaede S, Hoffman G, Kim K, Nunlet P, Peterson D, Rashbaum R, Stokes J, Ohnmeiss D. Prospective, randomized comparison of cervical total disk replacement versus anterior cervical fusion: results at 48 months follow-up. Clin Spine Surg. 2017;28:237–43.
21. Lee DH, Choatic JH, Jae H, Hwang CJ, Lee CS, Cho S, Kim C, Ha JK. What is the fate of pseudoarthrosis detected 1 year after anterior cervical discectomy and fusion? Spine (Phila Pa 1976). 2018;43:23–8.
22. Choi S, Cho J, Hwang C, Lee C, Gwak H, Lee D. Preoperative radiographic parameters to predict a higher pseudoarthrosis rate after anterior cervical discectomy and fusion. Spine (Phila Pa 1976). 2017;42:1772–8.
23. Mayo B, Massel D, Bohl D, Long W, Modi K, Singh K. Anterior cervical discectomy and fusion: the surgical learning curve. Spine (Phila Pa 1976). 2016;41:1580–5.

Wrong-Level Spine Surgery: Introduction of a Protocol for Avoidance of This Complication

James Paul Agolia and Ekkehard M. Kasper

Abstract

Wrong-level spine surgery, in which an operation is performed at a vertebral level different from the intended one, is a rare but serious complication with wide-ranging medical and legal effects. Although many protocols have been developed to prevent such a serious unfavorable event, the problem has not yet been eliminated. Research into the effectiveness of strategies to prevent wrong-level spine surgery is lacking. Herein, we describe a case of 44-year-old woman presented with neck pain and bilateral upper extremity weakness and numbness. Magnetic resonance imaging showed C5/6 and C6/7 disc herniations with spinal cord compression. The patient underwent anterior cervical discectomy and fusion; however, at the conclusion of the surgery, intraoperative radiographs showed that it was accomplished at C4/5 and C5/6—one level above the intended level. On the basis of this case and similar ones, a new protocol was developed that included implementation of a Spine Level Safety Checklist to document the reference point, the landmark, and the level of exposure that is marked on the intraoperative radiograph. Since implementation of this protocol, the incidence of wrong-level spine surgery at the senior author's institution has decreased from 4/7000 to 0/11,200. Adoption of this protocol by other centers is thus recommended to reduce the incidence of such complication.

Keywords

Anterior cervical discectomy and fusion · Cervical disc surgery · Cervical spine · Complication · Lumbar disc surgery · Spine Level Safety Checklist · Spine surgery · Universal Protocol · Wrong-level spine surgery

Introduction

Wrong-level spine surgery, in which operation is performed at the correct site but at the wrong vertebral level, is a rare but serious event in current neurosurgical practice [1, 2]. It is one subtype of the more general problem of wrong-site surgery, which encompasses wrong-procedure, wrong-patient, and wrong-site errors [3]. The medical, legal, and economic consequences of wrong-level spine surgery are considerable, since it fails to address the spinal pathology and will most likely not ameliorate the patient's symptoms [4]. Although most wrong-level spine surgeries may not lead to any new neurological deficit for the patient and may also not be aggravated by any complication, they may potentially lead to manifestations of failed back surgery syndrome [5, 6], as shown in a case series of 17,058 lumbar disc surgeries in which 24 wrong-level interventions did not resolve the patient's symptoms [4, 7–9]. Moreover, wrong-level procedure may cause postoperative tissue scarring that could impede future surgical approaches [4] and may lead to degenerative changes at spine levels that previously did not have any pathology [4, 10–13]. Thus, the medicolegal consequences of wrong-level spine surgery can be profound [7, 14].

Although professional organizations have defined wrong-level spine surgery as a "never" event [15], it does occur regularly, albeit very rarely. Several studies have attempted to estimate the occurrence rate of wrong-level spine surgery. In a retrospective case series of 530 lumbar microdiscectomy operations, Williams [16] reported a 0.6% incidence of missed disc pathology due to intervention at the wrong level. In a different case series, Roberts [9] reported a wrong-level surgery rate of

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_21

0.14%. On the basis of a survey of Canadian neurosurgeons, Jhawar et al. [17] generated estimates of a wrong-level lumbar surgery rate of 0.045% and a corresponding wrong-level cervical surgery rate of 0.068%. Mody et al. [4] surveyed members of the American Academy of Neurological Surgeons and reported that such an unfavorable event has a prevalence of 0.03%. More recently, James et al. [18] reported a 0.041% wrong-site surgery rate among spine surgeons surveyed during applications for board certification. Approximately 50% of spine surgeons have performed wrong-level spine surgery at least once during their careers [19]. It must be noted, though, that these retrospective studies are limited by potential for recall bias, underreporting, and subjective reporting by the participating surgeon only, and it is likely that these numbers underestimate the true prevalence of wrong-level spine surgery.

Many causes of wrong-level surgery have been suggested in the literature, though studies generally rely on the participating surgeon to report the specific or potential causes of the error. The limited exposure of microsurgical approaches in itself presents unique challenges that may result in a "counting" level error. For example, an increasing overhang of lamina as the surgeon moves cephalad may result in identification of the wrong disc space, or a marking needle on a surgical flat film may be inserted too high with respect to the disc space, causing the surgeon to be directed into the disc space one level higher than intended [20]. In interviews with a small number of neurosurgeons who identified themselves as having committed wrong-level errors, Mitchell et al. [21] identified missed safety checks and distracting circumstances as major factors. Failure to take intraoperative X-rays, misinterpretation of available intraoperative films, and unusual patient anatomy have also been reported as factors leading to wrong-level surgery [17]. It appears that more experienced surgeons may have a somewhat lower risk of exposing the wrong level [22]. Patient-related factors that seem to confer an increased risk of wrong-level lumbar discectomy include age greater than 55 years and an intended surgical level above L5/S1 [23].

In response to growing awareness of the problem of wrong-site surgery, professional societies and government agencies have created guidelines and enacted protocols to prevent this problem from occurring [15, 24–27]. These include the Joint Commission's Universal Protocol [26] and the North American Spine Society's "Sign, Mark, and X-Ray" program [25], which stipulate completion of a preoperative verification checklist, site marking, a time-out before start of surgery, and intraoperative imaging to verify the level. However, the effects of these guidelines and procedures have not been well studied, and they have not been shown to eliminate the incidence of wrong-level error [2]. Multiple institution-specific protocols attempting to prevent such complication have been developed as well. These protocols generally include additional checks of the operative level, some form of intraoperative imaging, or a combination of both [4, 17, 21]. Several techniques to identify the correct spinal level have been proposed, including intraoperative fluoroscopy with placement of a wire in the cephalad spinous process [5], fiducial marker placement [28, 29], placement of an angiography coil in the pedicle during the interventional radiology procedure [30], and sterile spinal needle insertion into the transverse process under fluoroscopy [31]. Since all of these measures have not been able to abolish the problem, more research is needed to determine the effectiveness of different protocols and techniques in preventing wrong-level spine surgery. The senior author's institution developed a new protocol for preventing wrong-level spine surgery, which is outlined following the case presentation below.

Case Report

A 44-year-old woman presented to the clinic with severe neck pain, episodic bilateral upper extremity numbness, and subjective muscle weakness. Her past medical history was significant only for hypothyroidism and significant obesity (body mass index 39.9). She worked as a teacher and was married with two children, and she was referred to the senior author because a family member worked in the same hospital's preoperative anesthesia care unit. On examination, she had weakness in the C6 distribution and numbness of her shoulders and the first three fingers of both hands. The deep tendon reflexes were 3+ in the upper extremities, and she had a positive Lhermitte sign, a positive Hoffmann sign, and a negative Babinski sign. She exhibited slight spastic paraparesis, but her gait was normal.

Imaging had been conducted at a different hospital. Magnetic resonance imaging (Fig. 1) showed a large disc herniation at C5/6 and a smaller disc herniation at C6/7, with spinal cord compression and T2 hyperintensity in the spinal cord proper at these levels. The patient was diagnosed with compressive cervical myelopathy due to disc extrusions at these levels, and elective anterior cervical discectomy and fusion (ACDF) at C5/6 and C6/7 was planned.

The patient was admitted to the hospital, and urgent surgery was scheduled on the add-on list and was performed at 10 p.m. The operation was done in accordance with all aspects of the Universal Protocol and standard procedures [25, 26]. An intraoperative cross-table lateral cervical spine radiograph (Fig. 2a) was taken with radiopaque markers in place. The two-level ACDF itself was uneventful. However, at closure, a second radiograph was obtained (Fig. 2b). This showed that the ACDF had been performed at C4/5 and C5/6—one level above the intended level.

Reasons for Surgery at the Wrong Level

Several factors that may have contributed to the wrong-level error in this particular case were identified by the attending surgeon. First, the operation was done at night, when he was likely somewhat fatigued (although, subjectively, he did not feel that way). Second, the patient's body habitus made it

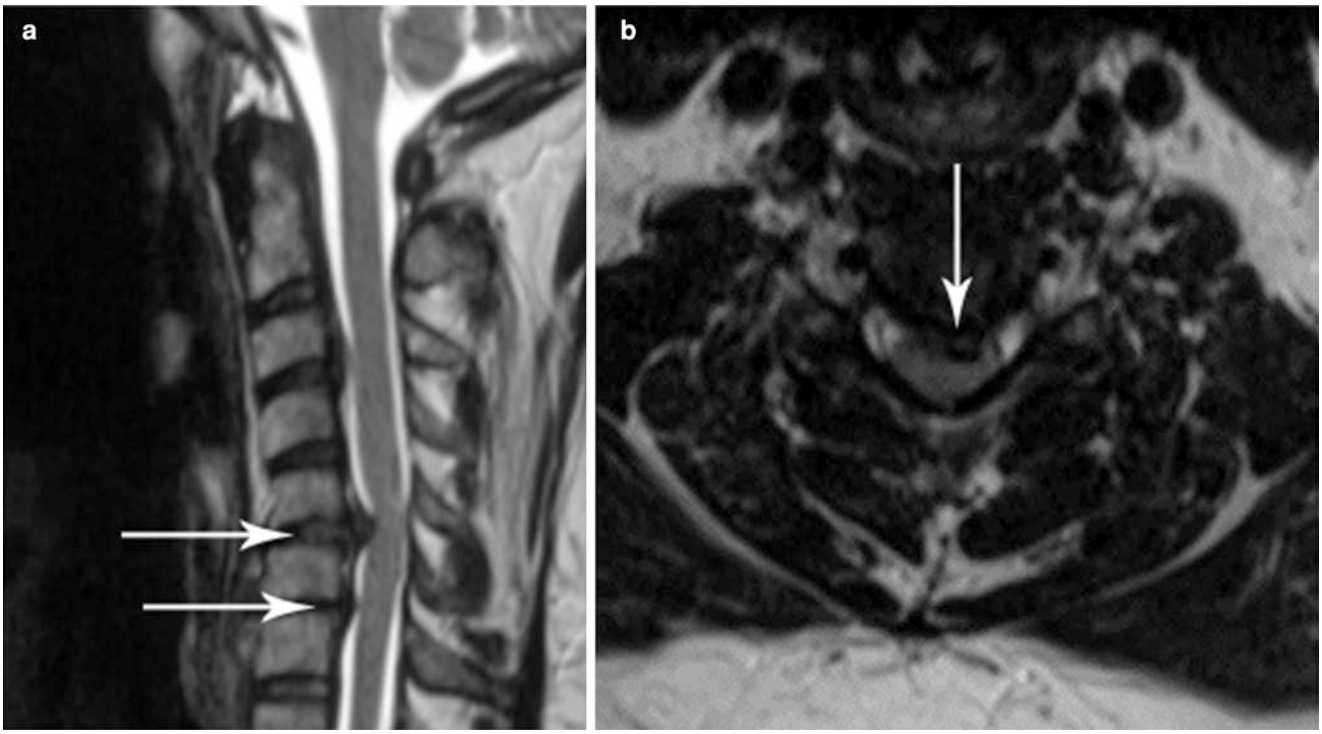

Fig. 1 Imaging at the patient's initial presentation. Sagittal T2-weighted magnetic resonance imaging (MRI) of the cervical and thoracic spine showed a large disc herniation at C5/6 and a smaller disc herniation at C6/7, as indicated by arrows (**a**). Axial T2-weighted MRI of the cervical spine at C5/6 level again showed a large disc herniation (*arrow*) with compression of the spinal cord (**b**)

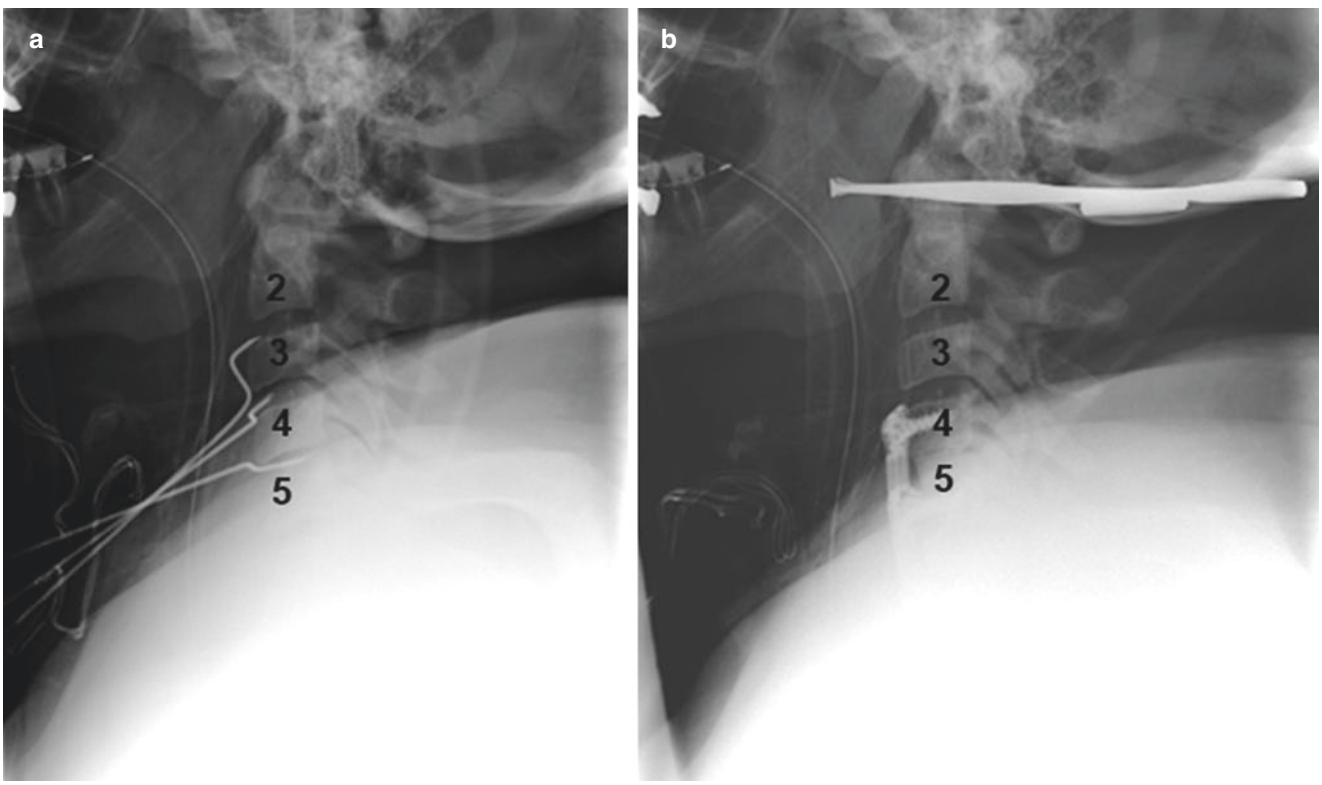

Fig. 2 Intraoperative radiographs. A cross-table lateral intraoperative localizing radiograph shows spinal needles in the C2/3, C3/4, and C4/5 interspaces (**a**). Because of the patient's body habitus, short neck, large shoulders, and submental cyst, it was not possible to visualize the C5/6 and C6/7 levels, where anterior cervical discectomy and fusion (ACDF) was intended to be performed. A cross-table lateral intraoperative radiograph taken at the time of closure shows that ACDF was performed at C4/5 and C5/6 instead of at the intended levels of C5/6 and C6/7 (**b**)

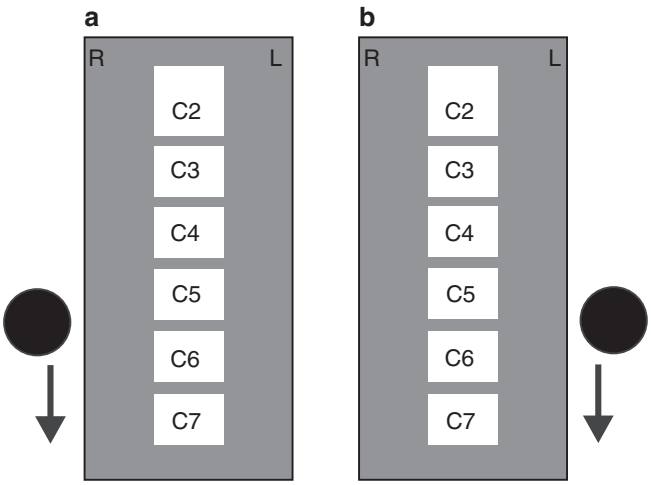

Fig. 3 The surgeon switching sides is a factor in wrong-level spine surgery. The surgeon began this anterior cervical discectomy and fusion (ACDF) on the patient's right side (**a**). If he was performing ACDF at C5/6, the next level for discectomy (C6/C7) would be to his *right* (*black arrow*). However, during the operation, the surgeon switched to the patient's left side (**b**). In this new position, the next level for discectomy (C6/7) would be to his *left* (*black arrow*). Switching sides during the procedure could thus be a potential source of miscounting error, leading to ACDF at the wrong level

difficult to externally identify or palpate any landmarks in relation to the jugular notch; here, the attending surgeon was not able to clearly localize the C6/7 level. Third, he changed his own side (position) when performing the dissection, moving from the patient's right side to the patient's left side. This relative movement created an opportunity for miscounting vertebrae: when correctly identifying a disc level at C5/6, the next surgical level at C6/7 would be to the surgeon's *right* when he was standing on the patient's right side, but it would be to his *left* when he was standing on the patient's left side (Fig. 3). Fourth, although intraoperative radiographs were obtained before the actual ACDF was performed and then again at closure, no repeat intraoperative films were taken to confirm the levels during the surgery. Fifth, the final intraoperative X-ray was performed only after closure had already been achieved and was not reviewed with the entire operative team to check and confirm the respective levels.

Postoperative Management of Wrong-Level Error

After the wrong-level surgery was identified in the operating room, several steps were taken to manage this medical error. Most importantly, a confidential peer was contacted to rapidly review the process of disclosure and identify what additional hospital resources would need to be utilized. Within 30 min of the conclusion of the surgery, the miscounting error was formally disclosed to the patient's family. The attending surgeon told the family that the surgery had been performed at the middle level (at C5/6) as planned, but that the surgery had also been mistakenly performed one level above it (at C4/5) instead of one level below it (at C6/7) as planned. This process of disclosing the adverse event immediately to the family occurred in accordance with Massachusetts law. The risk management, quality assurance, and patient outreach teams were notified at once on the same night, and the event was classified as a serious reportable event (SRE) and disclosed to the Department of Surgery and the Massachusetts Department of Health (DPH), as required by state law [32].

In this case, the patient exhibited full resolution of all neurological signs and symptoms by postoperative day 3, and her postoperative course was otherwise uneventful. This resolution of her symptoms suggested that all of the patient's preoperative clinical manifestations were caused by the afflicted C5/6 level and not by the C6/7 level, which had also been identified as abnormal (although to a lesser degree than the adjacent level). Given that she made a full recovery, this patient did not pursue legal action, and her family has continued to refer other members to the attending surgeon for care.

As three similar wrong-level surgeries (i.e., SRE) had occurred at the senior author's institution, the decision was made by the DPH to review all spine surgery cases at that hospital over a 5-year period. The hospital's quality assurance team also hired an external consultant to implement a DPH-mandated plan to prevent similar SRE from happening again.

Development of a New Protocol to Prevent Wrong-Level Surgery

As a result, a new protocol was implemented as a supplement to the already existing Universal Protocol. All steps of this protocol are documented using the Spine Level Safety Checklist (Fig. 4), a form created in the patient's electronic medical record (EMR). The circulating nurse and attending surgeon fill out their respective parts of the checklist. All preoperative marking and repeat intraoperative films are saved in the EMR with this form. Any exceptions to this procedure are required to be documented in the EMR. The new protocol encompasses three key steps: preoperative, intraoperative, and postoperative.

Preoperative Steps

Before the operation, if there are any abnormalities (such as transitional vertebrae), the attending surgeon is encouraged to review the images with an attending radiologist to define common terminology. If the original imaging does not visualize reliable landmarks adequately, the imaging should be repeated to obtain a proper counting sequence with relevant landmarks clearly visible. Before the patient is brought into the operating suite, the attending surgeon must personally meet and physically mark the patient with a resistant marker pen in the preoperative area. The Universal Protocol is followed completely, including the patient sign-in and prepro-

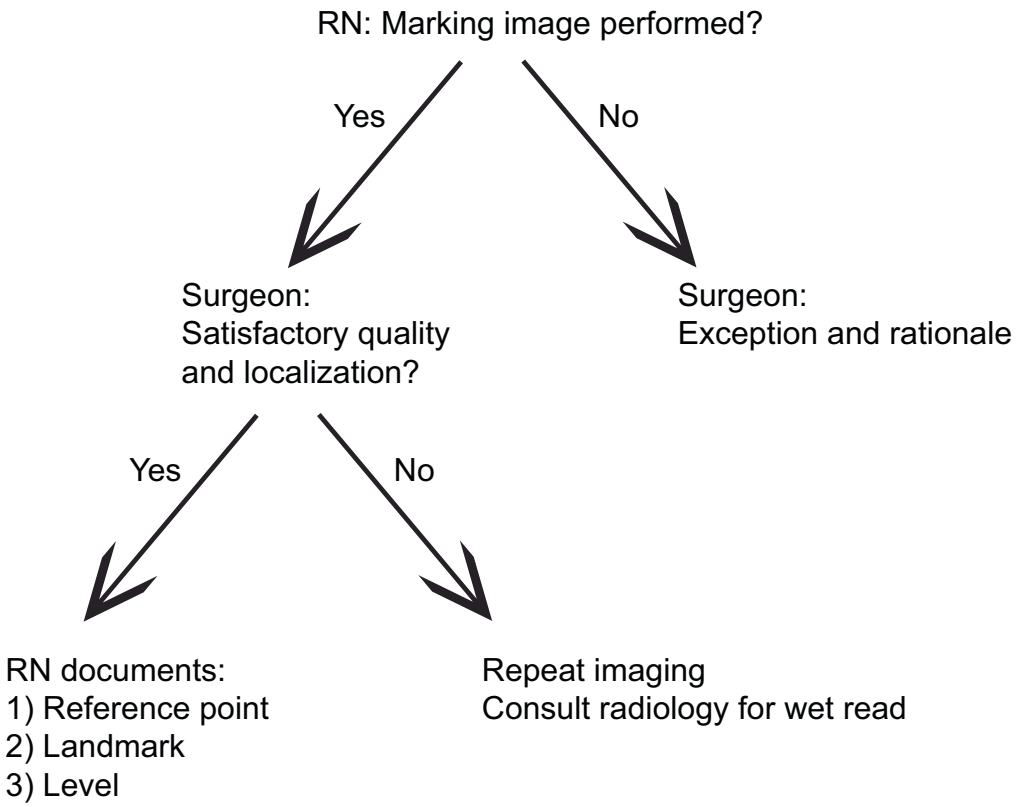

Fig. 4 The Spine Level Safety Checklist, developed and implemented as part of a new institutional protocol to prevent wrong-level spine surgery. During the operation, the circulating nurse documents in the electronic medical record whether or not an intraoperative marking radiograph is taken. If a radiograph is not taken, the attending surgeon must document the reason. If a radiograph is taken, the attending surgeon must personally review it and dictate to the circulating nurse whether it is of sufficient quality and whether it has adequately localized the operative level. If not, a repeat marking film should be taken and a radiologist should be contacted for a wet read. Once an adequate marking film has been obtained and reviewed, the surgeon dictates to the circulating nurse the reference point being used for counting vertebral levels (e.g., the base of the skull for cervical procedures), the landmark on the radiograph used to mark the level of exposure (e.g., the disc space, pedicle, spinous process), and the level that is marked on the radiograph. The circulating nurse then signs the checklist. Following the end of the operation, the attending surgeon completes and signs his or her portion of the checklist. *RN* Recording nurse

cedure time-out. Preoperative radiographs can then be taken. According to the Spine Level Safety Checklist [25, 26], preliminary localization radiography is encouraged to precisely place the incision and troubleshoot problems with X-ray penetration before a sterile field is created.

If, despite these precautions, landmarks cannot be found in the preoperative imaging, preoperative permanent markers should be placed to localize the correct level exactly.

Intraoperative Steps

The most striking aspect of the new protocol is that intraoperative marking films must be taken, and this should be repeated during the operation. The marking film must be obtained with a fixed marker of the site and at the level of the intervention, and it must be done prior to any disc removal or hardware insertion. If a marking film is not taken, the surgeon must document the reasons for such an exception to the protocol. With the exception of thoracic spine surgeries, the marking images must include reliable landmarks, such as the bottom of the skull or the odontoid process for cervical spine procedures and the sacrum for lumbar procedures. Other landmarks can be used and must be verbally confirmed with other team members (usually the circulating nurse).

The circulating nurse documents the spine-marking process in the Spine Level Safety Checklist while the attending surgeon verbalizes all parts of the checklist. For marking film documentation, the nurse checks the box for "Yes" if a marking film was obtained and the box for "N/A" if no marking film was taken, with the attending surgeon documenting the reason it was not performed. Of note, the attending surgeon must personally place the marker and interpret the marking films; delegation to another member of the operating team, such as a resident physician, is not permitted during this step. If there is any uncertainty in interpretation of the films, the imaging should be repeated and, again, an attending radiologist should be consulted for an intraoperative wet read. After the marking film is taken and interpreted, the fixed marker is replaced with a stitch or a bone bite. In cases treated with minimally invasive techniques, additional requirements must be met. First, marking films must be taken when the retractor is placed in the final position at each operative site. Second, a marking image for each level and side, with landmarks visible, must be obtained.

Postoperative Steps

Following the operation, the attending surgeon personally completes and signs his or her portion of the Spine Level Safety Checklist. All intraoperative marking films must be saved in the EMR. In addition to the above protocol, an educational module on wrong-level spine surgery has been created and mandated for health care providers participating in spine operations.

Effectiveness of the New Protocol

In the 5-year period prior to the implementation of the new protocol, the senior author's institution had four cases of wrong-level spine surgery. Since about 1400 spine surgery cases are performed at this center annually, it amounted to an approximate error rate of 4/7000. Since implementation of the new protocol in 2008, there have been no cases of wrong-level spine surgery, which translates into an error rate of 0/11,200. Given these numbers, we strongly encourage other centers to follow our suggestion and to implement the said protocol.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Anonymous. Patient safety first alert—implementing a correct site surgery policy and procedure. AORN J. 2002;76:785–8.
2. DeVine J, Chutkan N, Norvell DC, Dettori JR. Avoiding wrong site surgery: a systematic review. Spine. 2010;35:S28–36.
3. The Joint Commission. Sentinel event policy; 2017. https://www.jointcommission.org/sentinel_event_policy_and_procedures/. Accessed 11 Apr 2018.
4. Mody MG, Nourbakhsh A, Stahl DL, Gibbs M, Alfawareh M, Garges KJ. The prevalence of wrong level surgery among spine surgeons. Spine. 2008;33:194–8.
5. Irace C, Corona C. How to avoid wrong-level and wrong-side errors in lumbar microdiscectomy. J Neurosurg Spine. 2010;12:660–5.
6. Onesti ST. Failed back syndrome. Neurologist. 2004;10:259–64.
7. Goodkin R, Laska LL. Wrong disc space level surgery: medicolegal implications. Surg Neurol. 2004;61:323–42.
8. Roberts M. Complications of lumbar disc surgery. In: Hardy RW Jr, editor. Lumbar disc disease. 2nd ed. New York: Raven Press; 1993. p. 161–70.
9. Roberts MP. Complications of lumbar disc surgery. Spinal Surg. 1988;2:13–9.
10. Eck JC, Humphreys SC, Lim T-H, Jeong ST, Kim JG, Hodges SD, An HS. Biomechanical study on the effect of cervical spine fusion on adjacent-level intradiscal pressure and segmental motion. Spine. 2002;27:2431–4.
11. Hilibrand AS, Carlson GD, Palumbo MA, Jones PK, Bohlman HH. Radiculopathy and myelopathy at segments adjacent to the site of a previous anterior cervical arthrodesis. J Bone Joint Surg Am. 1999;81:519–28.
12. Lopez-Espina CG, Amirouche F, Havalad V. Multilevel cervical fusion and its effect on disc degeneration and osteophyte formation. Spine. 2006;31:972–98.
13. Willson MC, Ross JS. Postoperative spine complications. Neuroimaging Clin N Am. 2014;24:305–26.
14. Fager CA. Malpractice issues in neurological surgery. Surg Neurol. 2006;65:416–21.
15. Agency for Healthcare Research and Quality. Wrong-site, wrong-procedure, and wrong-patient surgery. 2017. https://psnet.ahrq.gov/primers/primer/18/wrong-site-wrong-procedure-and-wrong-patient-surgery. Accessed 11 Apr 2018.
16. Williams RW. Microlumbar discectomy: a conservative surgical approach to the virgin lumbar herniated disc. Spine. 1978;3:175–82.
17. Jhawar BS, Mitsis D, Duggal N. Wrong-sided and wrong-level neurosurgery: a national survey. J Neurosurg Spine. 2007;7:467–72.
18. James MA, Seiler JG III, Harrast JJ, Emery SE, Hurwitz S. The occurrence of wrong-site surgery self-reported by candidates for certification by the American Board of Orthopaedic Surgery. J Bone Joint Surg Am. 2012;94(1):e2.
19. Groff MW, Heller JE, Potts EA, Mummaneni PV, Shaffrey CI, Smith JS. A survey-based study of wrong-level lumbar spine surgery: the scope of the problem and current practices in place to help avoid these errors. World Neurosurg. 2013;79:585–92.
20. McCulloch JA. Complications (adverse effects). In: McCulloch JA, editor. Principles of microsurgery for lumbar disc disease. New York: Raven Press; 1989. p. 225–38.
21. Mitchell P, Nicholson C, Jenkins A. Side errors in neurosurgery. Acta Neurochir (Wien). 2006;148:1289–92.
22. Wiese M, Kr½mer J, Bernsmann K, Willburger RE. The related outcome and complication rate in primary lumbar microscopic disc surgery depending on the surgeon's experience: comparative studies. Spine J. 2004;4:550–6.
23. Ammerman JM, Ammerman MD, Dambrosia J, Ammerman BJ. A prospective evaluation of the role for intraoperative X-ray in lumbar discectomy: predictors of incorrect level exposure. Surg Neurol. 2006;66:470–4.
24. American Academy of Orthopaedic Surgeons. Information statement: surgical site and procedure confirmation. 2015. chrome-https://www.aaos.org/globalassets/about/bylaws-library/information-statements/1043-surgical-site-and-procedure-confirmation.pdf. Accessed 11 Apr 2018.
25. North American Spine Society. Sign, mark, and X-ray: prevention of wrong-site spinal surgery. 2014. https://www.spine.org/Portals/0/Documents/ResearchClinicalCare/SMAX2014Revision.pdf. Accessed 11 Apr 2018.
26. The Joint Commission. Universal protocol; 2018. https://www.jointcommission.org/standards_information/up.aspx. Accessed 11 Apr 2018.
27. The Joint Commission. Universal protocol for preventing wrong site, wrong procedure, wrong person surgery. Oakbrook Terrace: The Joint Commission; 2003.
28. Madaelil TP, Long JR, Wallace AN, Baker JC, Ray WZ, Santiago P, Buchowski J, Zebala LP, Jennings JW. Preoperative fiducial marker placement in the thoracic spine. Spine. 2017;42:E624–8.
29. Marichal DA, Barnett DW, Meler JD, Layton KF. Fiducial marker placement for intraoperative spine localization. J Vasc Interv Radiol. 2011;22:95–7.
30. Reitman CA. Pearls: wrong-level surgery prevention. Clin Orthop Relat Res. 2016;474:636–9.
31. Chin KR, Seale J, Cumming V. Avoidance of wrong-level thoracic spine surgery using sterile spinal needles: a technical report. Clin Spine Surg. 2017;30:E54–8.
32. Massachusetts Legislature. Reporting about healthcare-associated infections and serious reportable events, and serious adverse drug events; charges or reimbursement for resulting services prohibited. Massachusetts general law, Chapter 305 of the acts of 2008. General laws, part I, title XVI, chapter 111, section 51H. https://malegislature.gov/Laws/GeneralLaws/PartI/TitleXVI/Chapter111/Section51H. Accessed 15 Apr 2018.

Vascular Injury During Lumbar Disc Surgery: Case Report

Anne-Sophie Mehdorn, Matthias Mehdorn, and H. Maximilian Mehdorn

Abstract

A retroperitoneal organ injury—vascular injury or solid organ injury—that occurs during lumbar disc surgery needs to be dealt with adequately, because otherwise it could result in a poor (or, even, fatal) outcome of a "simple" procedure. Vascular injuries require special attention from the neurosurgical side (think of the possibility!) and cooperation between neurosurgeons and abdominal/vascular surgeons. In the presented case of a very obese female patient, a bite injury of the aorta during L3/4 disc surgery led to delayed intra-abdominal hemorrhage, which then required an emergency abdominal operation followed by major thromboembolic complication, and ultimately resulted in amputation of the patient's healthy leg. Pitfalls in intraoperative diagnosis and postoperative care are discussed, along with related medicolegal issues.

Keywords

Endovascular repair · Lumbar disc surgery · Vascular injury · Vascular surgery

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Introduction

A retroperitoneal organ injury—vascular injury or solid organ injury—that occurs during lumbar disc surgery needs to be dealt with adequately, because otherwise it could result in a poor outcome of a "simple" procedure. In particular, vascular injuries require special attention from the neurosurgical side (think of the possibility!) and cooperation between neurosurgeons and abdominal/vascular surgeons. Herein, we present the case of a very obese female patient in whom a bite injury of the aorta during L3/4 disc surgery led to delayed intra-abdominal hemorrhage, which then required an emergency abdominal operation followed by major thromboembolic complication.

Case Report

In 1970, when the senior author (HMM) first came into contact with neurosurgery as a medical student at the University Clinics of Zürich in Switzerland, under the guidance of Prof. Hugo Krayenbühl, and was allowed to scrub in a few cases, he was amazed to see a panel in the dressing room, saying "*Cave aortam uretheremque*" ("Watch out for the aorta and ureter"). This warning guided him through his later residency and further on in his professional career.

In 1985, this senior surgeon—who, at that time, was still a younger member of staff—operated on an obese female patient with an acute severe deficit of the left quadriceps muscle due to a herniated L3/4 disc. The operation was done on a national holiday because the patient was in severe pain and had an increasing neurological deficit. The surgery started at around 10:00 a.m. and went uneventfully except for a sensation of lack of anterior resistance at the level of the anterior part of the annulus fibrosus/anterior longitudinal ligament complex during cleaning of the disc space. No particular blood loss was seen in the surgical field, and the anesthesiologist noted no special problems. For safety reasons, the patient was transferred to the

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_22

intensive care unit, where she received continued monitoring of her blood pressure and heart rate variability (HRV), and hemoglobin (Hb) control. Consultation was sought from a general surgeon, who, because of a busy emergency surgical schedule on the national holiday, was unable to review the patient in person and thus could only give advice, by telephone, to observe her carefully.

Over the subsequent hours, a slight decline in Hb level was seen, while the HRV remained stable. The abdominal surgeon recommended measuring the circumference of the abdomen, which was found unchanged within the limits of measurement accuracy. At around 5 p.m. (approximately 5 hours after the end of the lumbar disc surgery), the patient went into severe shock, with a further Hb decline, leading to emergency exploratory laparotomy without further diagnostic steps for an acute abdomen by the general surgery department. Intraoperative findings revealed a bite injury of the aorta at the L3/4 level, adjacent to the operated disc space, which was repaired successfully after removal of a major intra- and retroperitoneal hematoma.

After abdominal surgery, the patient recovered promptly and initially showed a normal clinical course, but 3 days later, swelling and ischemia of the previously healthy right leg were noted. Regrettably, the surgical repair of the aorta had resulted in thromboembolic occlusion of the right femoral artery, which led to amputation because of the severity of the ischemic event. The previously symptomatic left leg showed only little improvement after the disc surgery; therefore, the patient was functionally paraplegic and bedridden, and remained so for the next few months despite in-hospital rehabilitation.

The patient and her family went to court, through a two-level ruling, but their case against the senior author's clinic was dismissed in both instances. It was judged that the incidence of such complications was 1–2 per 10,000 lumbar disc surgeries, that the patient had been correctly informed well ahead of the intervention, and that all actions were taken appropriately.

Nevertheless, it is a very bad feeling for a surgeon to sit opposite a former patient (whom he wanted to care for, by all means) who is now in a wheelchair and is bringing a case to court.

Discussion

The first lesson that may be learned from such a simple case is to look even more closely at the anatomy, as demonstrated by computed tomography (CT) or magnetic resonance imaging (MRI), with particular attention to vascular/spinal column contact.

Anatomical Considerations

The abdominal aorta is situated retroperitoneally, slightly on the left anterior side of the spine, in direct contact with the anterior longitudinal ligament and thus in indirect contact with the vertebral bodies and the annulus fibrosus of the lumbar discs. In healthy adults, the aortic diameter is 2.5–3 cm. In the lumbar region, four paired arteries (arteriae lumbales), feeding the lumbar discs and muscles, branch from the aorta before it separates into the two common iliac arteries at the level of L4. Additionally, the median sacral artery descends from the abdominal aorta, slightly cranial of the aortic bifurcation, supplying blood to the vertebral bodies of L4 and L5 and adjacent discs, as well as the sacral and coccygeal region. The vena cava inferior is very close to the spine as well, being situated on the right side of the vertebral column, entailing a risk of more subtle damage due to thinner vessel walls. However, interindividual variations exist and age-dependent changes may occur, which warrant special attention in the event of surgery [1].

Site and Type of Injury and Its Prevention

The most common vascular injury in lumbar disc surgery is laceration of the left common iliac artery because of its immediate proximity to the annulus fibrosus of L4/5 and L5/S1 intervertebral discs [2–4]. The second most common iatrogenic complication is formation of an arteriovenous fistula (AVF) [1]. Injuries of the right common iliac artery and of other vessels have been reported as well [5]. Removal of as much disc material as possible—which was the standard philosophy at the time when our presented patient was operated on—may lead to inadvertent perforation of the annulus fibrosus and the anterior longitudinal ligament, particularly when they are soft and bulging anteriorly. It also needs to be noted that approximately 11% of patients have anterior ligamentous defects, rendering them very vulnerable to surgical perforation into the retroperitoneal space [6, 7]. Previous inflammation of the vessel wall and arteriosclerosis may result in tissue adherence and exacerbate the risk of vascular injury [5]. This may also occur more easily when one has the mouth of the rongeur open while taking the bite and does not fully account for the resistance of the tissue. Additionally, use of rongeurs with shafts of various nonstandardized lengths may further increase the risk of disorientation of the surgeon with respect to the operative field depth.

Clinical manifestations of the intraoperative vascular injury depends on its size. Laceration of the aortic wall (which is remarkably thick) caused by a "simple bite" or a scratch may not be obvious right from the first moment, particularly if no blood is observed in the narrow disc space. It is only in the case of a major vascular injury that it might present in the form of massive intraoperative hemorrhage, with drops in Hb level and/or blood pressure. Minor arterial bleeding may become evident only later on after the surgery and present itself with a less dramatic course but with the same symptoms, as was the case in the patient reported herein. During lumbar spine surgery, iatrogenic

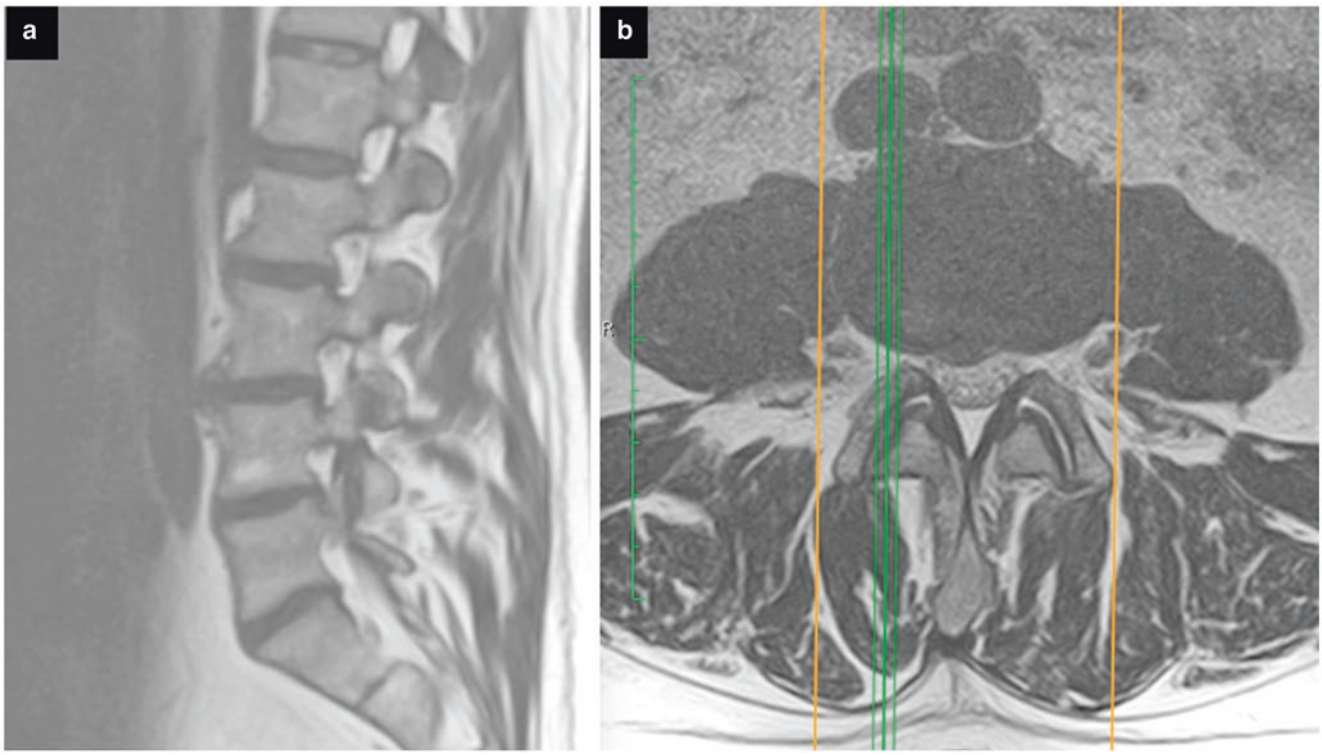

Fig. 1 Standard lumbar magnetic resonance imaging in a sagittal paramedian view (**a**) and in an axial view at the level of L3/4 (**b**) demonstrate anterior disc protrusion close to the vena cava inferior

lacerations of the vena cava inferior and the common iliac vein may happen as well, and represent 9.3% and 23.3% of vascular injuries, respectively [8, 9]. Because the blood pressure is lower in the venous system, the manifestation of bleeding may be less obvious, and patients may not present with the full range of corresponding symptoms that appear in arterial injuries, leading to a delay in diagnosis [5]. Often, a hematoma develops after venous injury and blocks further bleeding, which resolves the problem temporary, and the complication is not detected until later [1].

Obviously, retro- or intraperitoneal hemorrhage caused by vascular injury during spine surgery may be life-threatening, and mortality rates of up to 13% (and even up to 50%) have been reported in the past, depending on the extent of the laceration, the time to diagnosis, and the action that is taken [6, 8, 10, 11]. Fortunately, with modern diagnostic tools and better awareness of this type of complication, mortality rates in more recent times have dropped, and vascular injury after lumbar disc surgery is less likely to be fatal these days [1]. In a German cooperative study of more than 68,000 patients who underwent lumbar disc surgery, abdominal bleeding caused by vascular injury occurred in 0.045% of cases [12], whereas other authors have reported its incidence rates of between 0.01% and 0.17% [3, 5]. In particular, laceration of the aorta has been mainly happened during surgery for an L3/4 intervertebral disc prolapse, and reportedly occurred in up to 4.7% of such cases [9, 11].

Besides intraoperative safety measures, prevention of these complications requires knowledge of individual patient anatomy as visualized by preoperative CT or MRI, which should be examined very carefully with regard to the spatial relation of the intervertebral disc bulging and anteriorly located vessels (Fig. 1). Appropriate technical parameters of imaging are of crucial importance; for example, overdone fat suppression may occasionally obscure visualization of vessels in the retroperitoneal space. Furthermore, additional risk factors for vascular injuries during lumbar disc surgery should be considered, including the patient's constitution, pre-existing defects in the annulus fibrosus, and the state of the anterior longitudinal ligament, all of which may impact the local tissue tightness and hardness.

Of note, vascular injuries are not the only ones reported during lumbar disc surgery. Inadvertent damage of other intraperitoneal (bowel or pancreas) or retroperitoneal (urinary tract, bladder, or ureter) anatomical structures can occasionally occur as well [6, 13].

Immediate Management and Further Diagnostic Steps

In cases of major vascular injury, patients may present with typical symptoms of shock and will need to be stabilized immediately. This may occur during the postoperative course or even

during surgery. Hence, the procedure needs to be interrupted in these cases, and the patient needs to be stabilized first [10, 11].

In contrast, occult bleeding may just manifest minor hypotension or a small drop in Hb level, which may be corrected by stabilization of the intravascular volume or blood transfusion [10]. Other unspecific symptoms—such as abdominal pain or distension, as well as back pain or vomiting—may be easily attributed to the surgery performed previously [10, 14, 15]. It should be also considered that retro- and intraperitoneal spaces are both having a large capacity for accumulation of sizable blood volumes, and patients may seem relatively stable because of tamponade of the bleeding point [16, 17]. A pseudoaneurysm or AVF may present later on with typical clinical signs, including a "machinery" murmur on local auscultation, heart failure, tinnitus, or pain in various locations, such as the back, the abdomen, or the inguinal region [1]. Sometimes, such AVF may occur without clinical signs, be without immediate clinical signifance and only diagnosed on the long-term follow-up examination after the surgery [1, 6].

Clinical observation of a patient after a vascular injury may have happened is of primary importance but certainly not enough; nowadays, the slightest suspicion of the anterior longitudinal ligament perforation and penetration into the retroperitoneal space should prompt the surgeon to order emergency CT—preferably contrast-enhanced biphasic CT of the region of interest, which offers the possibility of showing active bleeding from arterial or venous vessels by contrast leakage [11]. The advantage of this procedure is its fast performance and immediate interpretation of the results. On the other hand, in this situation imaging findings cannot direct specific therapeutic actions; moreover, the contrast leakage may be detectable only if a bleeding rate is sufficiently high.

While CT angiography (CTA) would be preferred diagnostic modality in urgent and unclear clinical situations (similar to those observed in our patient), if one is really sure there is intra-abdominal bleeding and considers possible emergency intervention, catheter angiography may be performed [16]. In fact, for a long time, this was the diagnostic gold standard [1]. Although this technique is far more time-consuming and invasive than biphasic CT with CTA, it provides a possibility for endovascular intervention to resolve the problem within the same session.

Management of Complications

In any case in which vascular injury is suspected, the patient should be monitored closely and a vascular surgeon should be informed even if no extravasation of blood has been noted. If, however, retroperitoneal extravasation is evident, the vascular surgeon should be informed immediately about this emergency situation, should review the patient in person to decide on further treatment, and needs to be asked for an opinion as to whether emergency surgery is needed. It is the obligation and responsibility of the neurosurgeon who has performed the particular lumbar disc surgery to stay with the patient until everything is settled. As a side issue, it is also interesting to see, from a neurosurgical perspective, the detail of intra-abdominal injury that has been caused, when the patient is undergoing laparotomy or endovascular treatment.

When blood leakage has been detected, management of this unfortunate complication will depend on its severity, since it could result in lethal consequences [10]. Time is precious, and action should not be delayed [10]. Given recent successful developments in interventional radiology, angiographic placement of endovascular stent grafts may be another possibility for treatment to cover the vascular defect [3, 8, 11, 16, 17], especially if open surgery is contraindicated because of previous abdominal operation and expected adhesions, or if the risk of general anesthesia is too high in this particular patient [2, 16, 17]. Endovascular procedures have proven to be quite successful if carried out correctly [2]. In the case of a smaller vessel injury, coiling may also be an option if there are enough collateral vessels to perfuse the region of interest [3]. However, this depends on the availability of the service; a trained interventional radiologist may not be rapidly available everywhere. Sometimes, it might be easier to consult a vascular surgeon, who might either just suture the defect if its size and location allow this, or, in more severe cases, resect the injured part of the vessel after removal of the adherent hematoma and replace it with a venous or stent graft [4, 11, 13, 17]. All interventions themselves carry risks of further complications [3]. In rare cases, conservative treatment under intensive monitoring is warranted and may be an option if the patient's condition remains stable [18].

Thrombosis

In the event of vascular injury, the human organism is naturally reacts by producing a blood clot in order to close the laceration, potentially resulting in thrombosis of the affected vessel or an AVF [1]. However, rupture or breaking apart of the thrombus, can cause embolism of distant vessels and blockage of the arterial blood flow leading to ischemic complications. It may have fatal consequences, especially in elderly patients with morphological changes in the vessel walls. If not detected at an early stage, thromboembolism may cause complete occlusion of adjacent or distant vessels, as happened in our patient and subsequently resulted in the loss of an appendage. In addition, deep vein thrombosis or a pulmonary embolism may negatively impact the further clinical course. In case of a patent foramen ovale (also know as foramen Botalli) a cerebral stroke

may even occur. Of note, use of foreign material for securing a vascular laceration is associated with a higher risk of thrombosis. Hence, the possible need for anticoagulation therapy should be taken into consideration but needs to be balanced against the risk of additional bleeding.

Summary and Conclusion

The basis of every surgery is a comprehensive anatomical knowledge [3]. Preoperative images should be examined precisely to establish the depth and extent of the intervertebral disc defect and space in order to avoid intraoperative vascular injuries [19]. Use of magnifying glasses or operating microscope helps to prevent surgical errors by providing a better view of the operative field [8]. Further, depth-marking of surgical instruments and intraoperative imaging (including vascular contrast enhancement) in cases of uncertainty have been recommended in order to avoid related complications [5]. Yet, it is mandatory to perform surgery carefully, and not to violate the borders of the operative field by applying an excessive force on the surgical instruments in the event of difficulty [5, 6]. Since vascular injuries can occasionally happen during lumbar disc surgery, informed consent should be obtained in advance of the intervention, with an emphasis on their possibility and related consequences.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Szolar DH, Preidler KW, Steiner H, Riepl T, Flaschka G, Stiskal M, Moelleken S, Norman D. Vascular complications in lumbar disk surgery: report of four cases. Neuroradiology. 1996;38:521–5.
2. Canaud L, Hireche K, Joyeux F, D'Annoville T, Berthet JP, Marty-Ané C, Alric P. Endovascular repair of aorto-iliac artery injuries after lumbar-spine surgery. Eur J Vasc Endovasc Surg. 2011;42:167–71.
3. Hart JP, Wallis F, Kenny B, O'Sullivan B, Burke PE, Grace PA. Endovascular exclusion of iliac artery to iliac vein fistula after lumbar disk surgery. J Vasc Surg. 2003;37:1091–3.
4. Horacio Alvarez J, Cazarez JC, Hernandez A. An alternative repair of major vascular injury inflicted during lumbar disk surgery. Surgery. 1987;101:505–7.
5. Goodkin R, Laska LL. Vascular and visceral injuries associated with lumbar disc surgery: medicolegal implications. Surg Neurol. 1998;49:358–72.
6. Grumme T, Kolodziejczyk D, editors. Komplikationen in der Neurochirurgie, Bd 1: Wirbelsäulenchirurgie. Blackwell Wissenschafts: Schmerzchirurgie und Nervenchirurgie. Berlin; 1994.
7. Schmidt RC, Pöll W. Anterior lumbar disc herniations [in German]. Arch Orthop Trauma Surg. 1978;92:59–62.
8. Tsai YD, Yu PC, Lee TC, Chen HS, Wang SH, Kuo YL. Superior rectal artery injury following lumbar disc surgery. J Neurosurg. 2001;95(1 Suppl Spine):108–10.
9. van Zitteren M, Fan B, Lohle PN, de Nie JC, de Waal MJ, Vriens PW, Heyligers JM. A shift toward endovascular repair for vascular complications in lumbar disc surgery during the last decade. Ann Vasc Surg. 2013;27:810–9.
10. Altun G, Hemsinli D, Kutanis D, Gazioglu G. Silent killer: a scalpel in the aortic wall after spinal surgery. Neurol Neurochir Pol. 2016;50:294–6.
11. Busardò FP, Frati P, Carbone I, Pugnetti P, Fineschi V. Iatrogenic left common iliac artery and vein perforation during lumbar discectomy: a fatal case. Forensic Sci Int. 2015;246:e7–11.
12. Wildförster U. Intraoperative complications in lumbar intervertebral disk operations. Cooperative study of the Spinal Study Group of the German Society of Neurosurgery [in German]. Neurochirurgia (Stuttg). 1991;34:53–6.
13. Jue-Denis P, Kieffer E, Benhamou M, Le-Thoai H, Richard T, Natali J. Injuries to abdominal vessels after surgery of disk herniation [in French]. Rev Chir Orthop Reparatrice Appar Mot. 1984;70:141–5.
14. Kakkos SK, Shepard AD. Delayed presentation of aortic injury by pedicle screws: report of two cases and review of the literature. J Vasc Surg. 2008;47:1074–82.
15. Sugimoto Y, Tanaka M, Gobara H, Misawa H, Kunisada T, Ozaki T. Management of lumbar artery injury related to pedicle screw insertion. Acta Med Okayama. 2013;67:113–6.
16. Uei H, Tokuhashi Y, Oshima M, Miyake Y. Vascular injury following microendoscopic lumbar discectomy treated with stent graft placement. J Neurosurg Spine. 2014;20:67–70.
17. Zhou W, Bush RL, Terramani TT, Lin PH, Lumsden AB. Treatment options of iatrogenic pelvic vein injuries: conventional operative versus endovascular approach—case reports. Vasc Endovascular Surg. 2004;38:569–73.
18. Umeda A, Saeki N, Matsumoto C, Nakao M, Kawamoto M. Abdominal aortic injury during vertebroplasty. Spine (Phila Pa 1976). 2015;40:E439–41.
19. Yip SL, Woo SB, Kwok TK, Mak KH. Nightmare of lumbar diskectomy: aorta laceration. Spine (Phila Pa 1976). 2011;36:E1758–60.

Managing Complications Related to Peripheral Nerve Surgery: Selected Illustrative Cases

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Abstract

Peripheral nerve surgery mostly involves elective procedures; thus, the associated complications are of great clinical, social, and medicolegal importance. Apart from the general perioperative morbidity, complications during interventions on peripheral nerves are extremely rare. However, iatrogenic peripheral nerve injuries during unrelated surgical procedures performed by those not specialised in peripheral nerve surgery remain the most significant group of complications, accounting for up to approximately 17% of all cases. The aims of this review are to provide better insight into the multifaceted nature of complications related to peripheral nerve surgery—from the perspective of their causes, treatment, and outcome—and to raise surgeons' awareness of the risks of such morbidity. It should be emphasized that intraoperative complications in peripheral nerve surgery are largely "surgeon-related" rather than "surgery-related"; therefore, they have great potential to be avoided.

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Keywords

Complication · Peripheral nerve surgery · Preventive measures

Introduction

Peripheral nerve (PN) surgery mostly involves elective procedures; thus, the associated complications are of great clinical, social, and medicolegal importance [1]. The related morbidity in such cases is generally divided into three major groups [2]: (1) general perioperative complications not specifically linked to PN surgery, (2) intraoperative complications during PN surgery, and (3) nerve-related complications occurring as a result of iatrogenic injuries during surgeries where PN are not the targeted pathology. Russell and Kline [3, 4] previously performed a comprehensive analysis of possible complications during PN surgery and provided detailed guidance on how to avoid them. The present review is aimed at providing better insight into the multifaceted nature of complications related to PN surgery—from the perspective of their causes, treatment, and outcome—and raising surgeons' awareness of the risks of such morbidity. In addition, we present selected illustrative cases based on the experience of the Department of Peripheral Nerve Surgery at the Clinic for Neurosurgery, University Clinical Center of Serbia (Belgrade, Serbia). Since general perioperative complications are not specifically related to PN surgery, our discussion is mainly directed at intraoperative and iatrogenic complications, highlighting the interaction between them.

General Perioperative Complications

General perioperative complications after PN surgery are classified on the basis of their degree, as follows [5]:

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_23

- Minor (e.g., localized wound infection, dehiscence, or seroma): These can be managed in an outpatient clinic.
- Intermediate (e.g., extensive dehiscence, infection, hematoma/seroma, or deep vein thrombosis): In such cases, patients usually require readmission.
- Major (e.g., myocardial infarction, cerebrovascular event, pulmonary embolism, injury of a functionally important adjacent anatomical structure, or limb loss): These require specific treatment and may potentially lead to a lethal outcome.

Intraoperative Complications During Peripheral Nerve Surgery

Direct complications occurring during the course of PN surgery are very rare and reportedly have never occurred at some experienced and specialized treatment centers [3, 5]. Therefore, when they do occur, such surgery-related morbidity may be better described as "surgeon-related," which indicates its overlap with intraoperative iatrogenic PN injuries.

Excision of Peripheral Nerve Tumors

Surgical excision of PN tumors (such as a malignant PN sheath tumor [MPNST]) or neoplasms involving adjacent PN represents a rather specific clinical scenario. To reduce the risk of complications in such cases, the "first, do no harm" principle can be considered—i.e., incomplete resection of the mass lesion with functional preservation of the PN. However, such a strategy definitely increases the risk of tumor recurrence; thus, it should be carefully weighed against the tumor biology, and the outcome may be determined by several independent factors [2].

Iatrogenic Injuries of Peripheral Nerves

Iatrogenic PN injuries during unrelated surgical procedures are the most significant group of complications and account for approximately 17% of all PN injuries [6, 7]. With regard to the cause, such cases may be divided into four major types [1]: (1) injection or needle injuries, (2) radiation-induced, (3) pressure and traction injuries related to positioning during anesthesia, and (4) direct intraoperative injuries. The latter mostly occur when the relatively small nerves are not visualized or when they are mistakenly identified as vessels. In such cases, the most common mechanisms and types of PN injuries include partial or complete transection; stretching, contusion, or compression; coagulation with bipolar forceps; and inadvertent excision along with the target pathology.

The risk of iatrogenic intraoperative PN injuries obviously varies, depending on the body area where the surgery is undertaken, with the greatest concerns pertaining to those regions where PN lie superficially and/or are exposed during the procedure [1]. Table 1 provides an overview of PN at risk in different body regions and the mechanisms of their injury. Surgical procedures carrying the highest risks of iatrogenic intraoperative PN injuries include osteosynthesis, lymph node biopsy, varicose vein excision, and inguinal hernia repair [1, 6, 8]. Of note, all such interventions are performed by specialists other than neurosurgeons.

Table 1 Nerves at risk in different body regions and mechanisms of their injury

Nerve at risk	Region	Mechanism of injury
Spinal accessory nerve	Posterior triangle of the neck	Injection or needle injury; Radiation-induced injury
Radial nerve	Lateral upper arm	Injection or needle injury
Ulnar, radial, and median nerves	Elbow level	Positioning during anesthesia; Hematoma secondary to phlebotomy
Median nerve	Carpal tunnel and distal wrist	Direct intraoperative damage
Ilioinguinal and genitofemoral nerves and their branches	Groin	Direct intraoperative damage
Sciatic nerve	Buttock	Injection or needle injury
Tibial and peroneal nerves	Popliteal region	Direct intraoperative damage
Peroneal nerve	Head of the fibula	Positioning during anesthesia

Selected Illustrative Cases

The following five clinical cases have been selected to illustrate the range of potential complications during PN surgery from the perspective of their causes, treatment, and outcome. To better highlight the particular clinical problems and their consequences, these cases are referred to as an adverse event, mistreatment, an oversight, permanent damage, and a nightmare.

Adverse Event

The term "adverse event" refers to an indirect PN lesion that occurs during an unrelated surgical procedure [9]. In our experience, such complications are hardly preventable, but there are definite options for their treatment, and the outcome is typically good, with the possible presence of more or less significant residual symptoms but without major related disability [10].

Illustrative Case: A 38-year-old man was referred to our department because of severe burning pain at the level of the

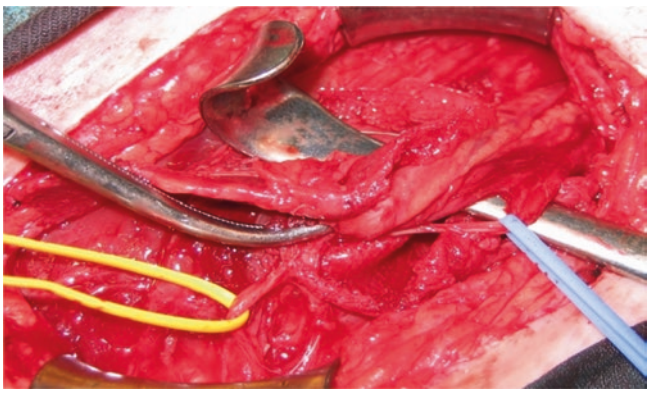

Fig. 1 Right femoral nerve entrapped in fibrous tissue as an adverse event after surgical repair of an inguinal hernia

upper inner right thigh and the scrotum on the right side, which had persisted for 11 months following a previous operation for an inguinal hernia. His score on the Numeric Pain Rating Scale (NPRS), which is composed of 11 points ranging from 0 (no pain at all) to 10 (the worst imaginable pain), was 10. Magnetic resonance imaging (MRI) and ultrasonography did not reveal any abnormalities in the affected body region.

Considering his pain severity, surgical treatment was performed. Intraoperatively, a lesion of the ilioinguinal and genitofemoral nerves was identified, and neurectomy was done. Immediately after the surgery, a reduction in his pain was noted, with a decrease in the NPRS score to 2.

The patient experienced relief from pain during the two subsequent years, but he then visited our center again, complaining of reappearance of severe burning pain at the level of the anterior and inner right thigh, which had an NPRS score of 9. In addition, definite weakness of both right thigh flexion and right lower leg extension were revealed during his examination. Electromyoneurography (EMNG) indicated a lesion in the continuity of the right femoral nerve.

The patient underwent surgery once again. Intraoperatively, excessive fibrosis was noted, and external neurolysis of the right femoral nerve was performed (Fig. 1). Two years after the last surgery, the patient had no motor deficit but still had pain at the level of the anterior and inner right thigh, with an NPRS score of 4. He is still being followed up at our clinic.

Mistreatment

Complications referred to as mistreatment are caused by inexperienced surgeons with insufficient knowledge and lack of intraoperative meticulousness and attention. Such cases may be related to superficial and nonsystematic preoperative planning, lack of intraoperative monitoring, the presence of PN anatomical variations, and inappropriate application of the "first, do no harm" principle. The outcome in mistreated patients may be variable, and it depends on the physician's reaction to the unsatisfactory recovery and on the timing of the affected individual's referral to an experienced/subspecialized PN surgeon [10].

Illustrative Case: A 40-year-old woman visited our department, complaining of loss of sensation in the right median nerve distribution and loss of power in the flexor pollicis longus, the flexor digitorum profundus of the second and third fingers, the flexor digitorum superficialis, the opponens pollicis, and the abductor pollicis brevis muscles. These deficits were linked to previous surgery for a schwannoma of the median nerve at the level of the upper right arm, which had been conducted at another institution 5 months earlier. MRI revealed fusiform soft tissue expansion in the postoperative region.

Surgical treatment was performed. During the operation, contused and edematous fascicles of the median nerve with tumor remnants were identified (Fig. 2). Intraoperative monitoring indicated that this affected a 9-cm-long segment of the median nerve was completely nonfunctional. It was therefore resected, and graft repair with the contralateral sural nerve was done. In addition, transfer of the radial nerve branch to the extensor carpi radialis brevis to the anterior interosseous nerve, transfer of the supinator motor branch to the median nerve branch to the flexor digitorum superficialis, transfer of the ulnar nerve branch to the abductor digiti minimi to the thenar motor branch of the median nerve, and transfer of the terminal branches of the superficial radial nerve at the level of the proximal phalanx of the thumb and index finger to the terminal sensitive branches of the median nerve at the same level were performed.

By the time of the 1.5-year postoperative follow-up examination, the patient had regained sensation in the distal phalanx of the thumb and index finger on the palmar side. The strength in all reinnervated muscles scored 4 out of 5 on the Medical Research Council (MRC) Muscle Power Scale.

Oversight

Oversight complications occur when PN are located in the vicinity of targeted structures and have not been identified (particularly if they are of small caliber), which may easily lead to direct intraoperative lesions of nerves and their branches. In addition, in such cases, adjacent PN may be affected by infection of the surgical wound or by postoperative hematomas or seromas with a compressive effect. Specifically, after implantation procedures, PN injury may be caused by implant-related compression and/or persistent toxic effects of the implanted material, which may be rather prolonged; therefore, just the presence of an implant may importantly hinder satisfactory functional recovery [10].

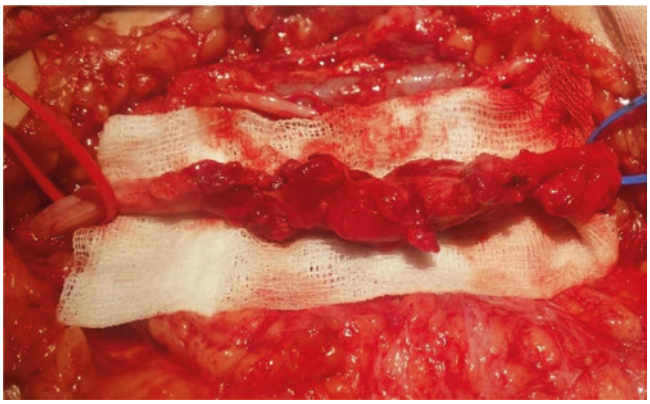

Fig. 2 Contused and edematous fascicles of the right median nerve with tumor remnants as a result of mistreatment at another institution

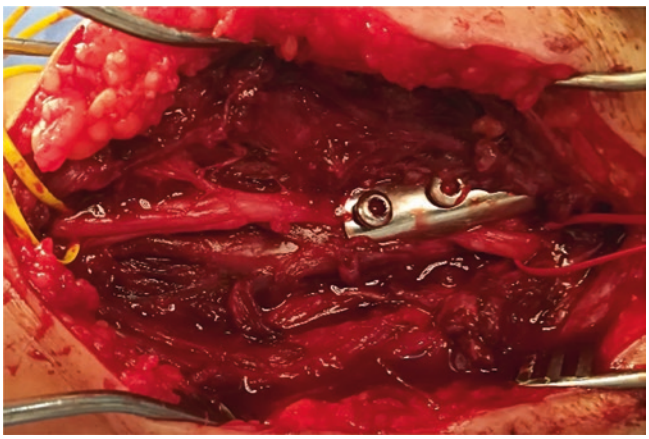

Fig. 3 Left radial nerve entrapped between the osteosynthesis plate and the bone as a result of an oversight during previous surgery for a humerus fracture

Illustrative Case: A 58-year-old woman was referred to our institution because of pain in her left hand, which had lasted for 4 months following a previous operation for a fracture of the left humerus. She had been injured by a fall and undergone emergency osteosynthesis by an orthopedic surgeon. There was no neurological deficit before that operation. Upon examination, she was unable to perform active finger and wrist extension, and she had hypoesthesia and paresthesia over the first web space dorsally. X-ray examination showed correct positioning of the osteosynthesis plate and humerus. Only physiological findings were noted on MRI. EMNG indicated a moderate radial nerve lesion at the level of the radial groove of the humerus.

The patient underwent surgical treatment. Intraoperatively, the radial nerve was found to be entrapped between the osteosynthesis plate and the bone (Fig. 3). The nerve was released; it was edematous and contused, and the epineurium was disrupted in the previously entrapped part. The injured epifascicular epineurium was removed circumferentially from the area of the lesion, and the scarred interfascicular epineurium was also excised.

The patient was discharged on the second postoperative day, with a recommendation to undertake physical therapy. Subsequently, within 8 months after her last surgery, she regained nearly the full amount of movement of her wrist and finger extension.

Permanent Damage

Permanent damage of PN can occur in mistreated patients or those with intraoperative injuries, particularly when a significant amount of time elapses before the affected individual is referred to an experienced/subspecialized PN surgeon. From our experience, belated visits to a specialized PN surgery center in such cases are frequently related to the following interconnected factors: (1) the pride of the treating physician and their hesitancy to admit to a personal mistake; (2) too prolonged a wait for spontaneous recovery, even when the treating physician is suspicious or aware of the nerve damage he or she has inadvertently caused.

Illustrative Case: A 32-year-old man was admitted to our department with a left claw hand deformity and a continuous tingling sensation in the medial half of the fourth and fifth fingers. Nine months earlier, during a fight, he had sustained a cutting injury with a knife on the distal part of the left forearm, and was operated on by a hand surgeon at a regional medical center. According to the medical information about that surgery, direct suturing of the ulnar nerve was performed. However, the ultrasonography done at our clinic showed that the ulnar nerve was discontinuous, and electrophysiological examination revealed a block in the sensory and motor conduction of the ulnar nerve and denervation potential in the intrinsic muscles of the hand.

The patient underwent a reoperation. It was revealed during this surgery that the ulnar nerve had been inadvertently sutured to the flexor tendon and vice versa (Fig. 4). After a detailed revision, a 2-cm defect of the ulnar nerve was noted; thus, grafting with an allograft (NeuraGen® Nerve Guide; Integra LifeSciences, Princeton, NJ, USA) was performed. Attempted direct suturing of the flexor tendon was, unfortunately, unsuccessful because the tension on the suture line was too strong.

One year after the last operation, the patient felt minor numbness in the fourth and fifth fingers, and the claw hand deformity had not resolved. He was therefore referred for palliative orthopedic treatment.

Nightmare

Nightmare complications can be encountered even by the most experienced surgeons who perform state-of-the-art interventions. It often causes feelings of confusion and help-

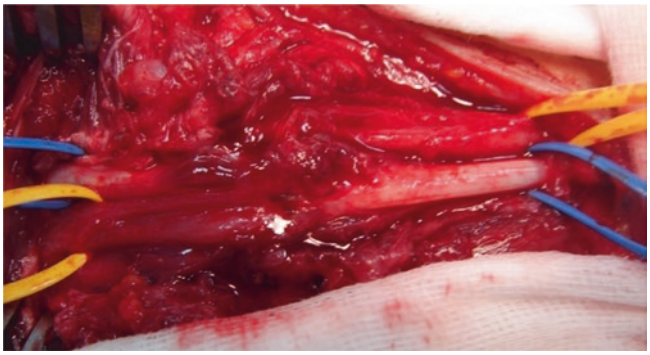

Fig. 4 Left ulnar nerve sutured to the flexor tendon and vice versa during previous surgery, resulting in permanent damage following belated referral to a specialized peripheral nerve surgery center

lessness, which are arising naturally in cases where the patient's condition is getting worse despite adequate, well-planned, and technically perfect execution of the procedure (or even a series of procedures), resulting in an inevitably unsatisfactory outcome, which becomes a nightmare for both the patient and the surgeon.

Illustrative Case: A 37-year-old man, who had been operated on for the right-side cubital tunnel syndrome 6 months earlier at another institution, visited our department with complaints of numbness and pain at the level of the medial part of the right forearm and the wrist. During the clinical examination, hypotrophy of the hypothenar and interosseal muscles, along with impaired abduction and adduction of the fingers on the right hand, were revealed. MRI of the cervical spine and brachial plexus showed a tumor of the right lower trunk with no signs of propagation into the spinal canal. EMNG demonstrated signs of cubital tunnel syndrome and radiculopathy of the C8 and T1 spinal roots on the right side.

Supraclavicular exploration of the brachial plexus and a tumor biopsy were performed. The histopathological diagnosis was a diffuse intraneural neurofibroma.

The patient recovered well after the surgery, with no additional neurological deficit. However, 6 months later, he came back to our clinic because of worsening of his previous symptoms. At that time, MRI of the cervical spine and brachial plexus did not demonstrate any additional changes, but EMNG indicated worsening of the previous findings at the level of the right cubital tunnel. MRI of the right elbow showed signs of ulnar nerve compression by fibrous tissue.

The patient was operated on once again for the cubital tunnel syndrome. Intraoperatively, the ulnar nerve was found to be compressed by the surrounding scar tissue; therefore, decompression, nerve liberation, and anteroposition were done.

Initially, the patient demonstrated a good postoperative recovery. However, 3 months later, he came to us again with signs of deterioration and complaints of pain and numbness in his whole right arm. Examination revealed incapacity for abduction and adduction of the fingers on the right hand, along with paraparesis (he could not walk without help). Repeat MRI of the cervical spine showed tumor growth with propagation into the spinal canal.

The patient was operated on once again, undergoing extirpation of the neoplastically changed C8 and T1 roots, the lower trunk, and its anterior and posterior branches; laminoplasty of C7, T1, and T2; and removal of the spinal part of the tumor, which was found to be located completely intradurally. At this time, the histopathological diagnosis was MPNST.

After surgery, the patient initially recovered well and regained the ability to walk on his own. However, 2 months later, he returned to our center and was now paraplegic. MRI of the cervical spine showed recurrence of the tumor in the spinal canal.

Surgery was done again. Laminectomy of C7, T1, and T2 was performed, along with extirpation of the tumor, which, by this time, was located only extradurally without an intradural component. Histopathological examination reconfirmed the diagnosis of MPNST.

After the last surgery, the condition of the patient did not change. He was treated with adjuvant radiotherapy, chemotherapy, and physical therapy but died 3 months later.

Preventive Measures for Complication Avoidance

Complications related to operations for various PN pathologies are an important issue in their surgical treatment. For prevention of such morbidity, surgeons must have perfect knowledge of the anatomy of the related body region. For all interventions performed in the vicinity of major PN, intraoperative use of a nerve stimulator is mandatory [2, 3].

The timing of a reconstructive procedure and the technique used are two crucial factors for effective functional recovery after surgical treatment for the PN damage. In addition, these are the only factors that the treating physician can actually influence (unlike other prognostic factors, such as the type of the affected nerve, the level of the injury, the severity of the damage, and the age of the patient). Therefore, the importance of the role of the treating physician in timely recognition, treatment, and/or referral of a patient with complications related to PN surgery to a specialized PN surgery center or an experienced/subspecialized PN surgeon cannot be overemphasized.

If PN damage is noticed during surgery, it should be repaired either during the same procedure or within 2–3 weeks. If a neurological deficit is noticed after an operation, the patient should be referred for physical treatment, and detailed clinical assessment—including neurological, neuro-

radiological, and neurophysiological examinations—should be done [1]. If these examinations demonstrate complete separation of the nerve or a neuroma-in-continuity, immediate surgical treatment is indicated [6]. In other cases, if no improvement is observed within 3 months postoperatively, repeat surgery aimed at nerve repair should be seriously considered.

In cases of inadvertent PN injury during unrelated surgery, it is mandatory to perform an operation aimed at nerve repair no later than at 6 months after the previous intervention, since the success rate of nerve reconstruction decreases dramatically with a longer delay [10].

Patients with traumatic PN injuries should be referred to a specialized PN surgery center or an experienced/subspecialized PN surgeon for diagnosis and treatment; this allows correct clinical assessment and selection of the appropriate management strategy. Surgical procedures that can be performed for PN repair include external and internal neurolysis, nerve transplantation, nerve transfer, and neuroma resection [7]. The choice is based on detailed evaluation of the patient's condition, including clinical assessment (anamnesis, general and neurological examinations), radiological evaluation (X-ray, computed tomography, MRI), electrophysiological evaluation (EMNG, somatosensory evoked potentials), evaluation during surgery with use of intraoperative neurophysiological monitoring, and postoperative evaluation with thorough monitoring of symptoms and signs related to the condition (e.g., pain or motor, sensory, or cosmetic deficits).

Conclusion

Patients with complications related to PN surgery deserve to be treated in the best possible manner, in accordance with contemporary guidelines, because their quality of life may be seriously affected by mistreatment. As illustrated by the selected cases presented herein, our experience demonstrates that intraoperative complications in PN surgery are largely "surgeon-related" rather than "surgery-related". Therefore, raising awareness of their prevention, diagnosis, and management is essential and definitely merits more systematic attention in the future.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Rasulić L, Savić A, Vitošević F, Samardžić M, Živković B, Mićović M, Baščarević V, Puzović V, Joksimović B, Novakovic N, Lepić M, Mandić-Rajčević S. Iatrogenic peripheral nerve injuries—surgical treatment and outcome: 10 years' experience. World Neurosurg. 2017;103:841–51, e1–6.
2. Kitagawa RS, Kim S-D, Kim DH. Complications of peripheral nerve surgery. In: Benzel EC, editor. Spine surgery: techniques, complication avoidance, and management. 3rd ed. Philadelphia: Elsevier Saunders; 2012. p. 1307–16.
3. Russell SM, Kline DG. Complication avoidance in peripheral nerve surgery: preoperative evaluation of nerve injuries and brachial plexus exploration—part 1. Neurosurgery. 2006;59(4 Suppl Operative):ONS441–8.
4. Russell SM, Kline DG. Complication avoidance in peripheral nerve surgery: injuries, entrapments, and tumors of the extremities—part 2. Neurosurgery. 2006;59(4 Suppl Operative):ONS449–57.
5. Ducic I, Hill L, Maher P, Al-Attar A. Perioperative complications in patients undergoing peripheral nerve surgery. Ann Plast Surg. 2011;66:69–72.
6. Antoniadis G, Kretschmer T, Pedro MT, König RW, Heinen CP, Richter HP. Iatrogenic nerve injuries: prevalence, diagnosis and treatment. Dtsch Arztebl Int. 2014;111:273–9.
7. Kretschmer T, Antoniadis G, Braun V, Rath SA, Richter HP. Evaluation of iatrogenic lesions in 722 surgically treated cases of peripheral nerve trauma. J Neurosurg. 2001;94:905–12.
8. Rasulic L, Cinara I, Samardzic M, Savic A, Zivkovic B, Vitosevic F, Micovic M, Bascarevic V, Puzovic V, Mandic-Rajcevic S. Nerve injuries of the upper extremity associated with vascular trauma—surgical treatment and outcome. Neurosurg Rev. 2017;40:241–9.
9. Ducic I, Zakaria HM, Felder JM 3rd, Arnspiger S. Abdominoplasty-related nerve injuries: systematic review and treatment options. Aesthet Surg J. 2014;34:284–97.
10. Rasulić L, Savić A, Živković B, Vitošević F, Mićović M, Baščarević V, Puzović V, Novaković N, Lepić M, Samardžić M, Mandić-Rajčević S. Outcome after brachial plexus injury surgery and impact on quality of life. Acta Neurochir (Wien). 2017;159:1257–64.

Radiotherapy-Induced Neurocognitive Dysfunction in Brain Tumor Survivors: Burden and Rehabilitation

Rakesh Jalali and Priyamvada Maitre

Abstract

Radiotherapy-induced neurocognitive dysfunction after cranial irradiation has an incidence of 40–100%. It may affect both children and adults, and represents a significant burden not only on ill individuals and their caregivers but also on the health care system and society in general. Multiple patient-, tumor-, and treatment-related factors may contribute to development of this complication, but its pathophysiological mechanisms are still not understood clearly. It is hoped that introduction of more advanced techniques for conformal irradiation, optimized dosimetry, and specific prophylactic measures will decrease the risk of neurocognitive decline in brain tumor survivors in the future.

Keywords

Brain tumor · Brain tumor survivors · Complication · Fractionated radiotherapy · Neurocognitive dysfunction · Neuro-oncology · Outcome · Radiotherapy-induced dysfunction · Treatment

Introduction

Neurocognitive dysfunction is one of the most recognized and researched concerns in brain tumor survivors. With advances in diagnosis and treatment, survival of patients with central nervous system (CNS) neoplasms is increasing in both incidence and duration [1]. Overall survival (OS) at 10 years in cases of pediatric brain tumors and adult low-grade/benign tumors is about 70% [2]; therefore, preservation of cognition and its attendant effects are extremely important in this population. Patients with high-grade gliomas (HGG) with favorable molecular profiles are also showing improved survival, and a median OS duration of 14 years has been reported in cases of anaplastic oligodendrogliomas [3, 4]. These long-term survivors have to face the prospect of lifelong treatment-related late adverse effects, of which neurocognitive decline is one of the most arduous. Even short-term survivors of HGG experience significant cognitive dysfunction, which can severely impair their quality of life (QOL).

Burden of Radiotherapy-Induced Neurocognitive Dysfunction

Numerous studies have reported a near universal incidence of tumor- and/or treatment-related cognitive dysfunction in brain tumor survivors, with rates varying from 40% to 100% [5–7]. The true incidence is probably higher than the rates of physical disabilities, given the challenges in assessment of neurocognition. Anatomical imaging may help in evaluating treatment-related changes in brain regions that are important for cognition, but the complexity of dysfunction may not always correlate with a specific lesion or location. The pervasive spectrum of neurocognitive dysfunction includes declines in the intelligence quotient (IQ), processing speed, working memory, attention, executive functioning, affect, and personality, as well as neurobehavioral slowing and dementia. It is a difficult task to evaluate each facet in its entirety; hence, the incidence and severity of dysfunction depend on *what*, *when*, and *in whom* we perform the assessment.

A decline in neurocognition as a late sequela of cranial fractionated radiotherapy (FRT) has been recognized for decades. Universal use of cranial FRT in posterior fossa tumors, such as medulloblastomas and ependymomas, has

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_24

been recognized as a cause of significant cognitive dysfunction in long-term survivors. An increased risk of dementia after craniospinal irradiation (CSI) in medulloblastoma patients less than 2 years of age was reported by Bloom et al. [8] as far back as 1969. In patients with posterior fossa tumors receiving CSI with 23.4 Gy and a focal boost of 32.4 Gy, significant declines were reported in the Full Scale IQ (FSIQ; −4.3 points/year), verbal IQ (−4.2 points/year), and nonverbal IQ (−4.0 points/year) [9]. Results from the Childhood Cancer Survivor Study (CCSS), the largest study in pediatric cancer survivors, showed that brain tumor survivors had significantly worse neurocognition than their siblings or non-CNS cancer survivors [5]. The severity of impairment was greater if the patients had received cranial FRT, with a worse score after total brain irradiation than after partial brain irradiation [5]. A progressive neurocognitive decline has also been observed after focal FRT in long-term survivors of low-grade gliomas (LGG). In comparison with LGG patients who did not receive FRT, these survivors reported significantly worse attention, executive functioning, and information processing irrespective of the FRT fraction size [10]. In our experience of low-grade/benign brain tumors treated with an advanced conformal stereotactic RT (SRT) technique, one-third of patients showed a >10% decline in the FSIQ from the baseline. Patient age <15 years at the time of irradiation and higher dose delivery to the left temporal lobe were significant factors influencing the FSIQ decline [11].

Chronic progressive neurocognitive impairment in childhood brain tumor survivors severely hampers their academic outcomes. The memory and attention domains are the worst affected, leading to poor exam scores, repetition of school grades, frequent absenteeism, and increased dropouts. Overall educational attainment in brain tumor survivors treated with cranial FRT can be as low as 30–40% of the average attainment in the general population [12]. In a French study of long-term survivors of medulloblastoma, about one-fourth of the patients required special schooling [13]. In the CCSS cohort, CNS cancer survivors were 18 times more likely to use a special education service than their siblings, and the odds and duration of use were even greater in those who received cranial FRT. They were also much less likely to finish high school than their siblings; however, use of special education services was able to mitigate this risk to a significant extent [14, 15]. This fact highlights the need for specialized academic environments for these survivors to allow them to achieve their optimum potential. Lack of such resources places survivors at risk of permanent socioeconomic dependency. Less access to higher education, a higher likelihood of unemployment, a lower annual income, and poor interpersonal relationships have been recognized as being associated with a prior history of cranial FRT, higher radiation dose delivery to the temporal or frontal lobes, and a consequent late neurocognitive decline [16].

Neurocognitive deficits also have a significant impact on the overall health-related QOL (HRQOL) of survivors, as shown by studies in patients with glial tumors. In a recent study conducted by the European Organization for Research and Treatment of Cancer (EORTC), survivors of LGG with posttreatment cognitive impairment reported worse physical functioning, visual disorders, and worse overall HRQOL [17]. With increasing recognition of the importance of patient-reported outcomes (PRO) in brain tumor research, reliable assessment of HRQOL is required. Studies in patients affected by LGG or HGG show that their self-reporting of HRQOL differs significantly from proxy-reported ratings in the presence of significant cognitive impairment, in contrast to good concordance of patient–proxy reporting in cognitively preserved subgroups [17, 18]. In HGG, this incongruence is likely due to patients' inability to self-report their problems, as well as proxies' different perspectives and understanding of the patients' cognitive impairment.

Pathophysiology

Development of FRT-induced neurocognitive dysfunction is dependent on dynamic and complex cellular interactions in the brain, which are not yet very clearly understood. Cell death within populations of neurons, oligodendrocytes, or endothelial cells, and secondary effects such as damage to microvasculature and myelin (due to oxidative stress) have been hypothesized as possible causes [19, 20]. An altered microenvironment of neural precursor cells in the hippocampus, leading to defects in proliferation and differentiation of neural progenitor cells after irradiation, has also been linked to cognitive dysfunction [21]. Advances in imaging have led to identification of a decrease in the volume of brain tissue, particularly that of cerebral white matter, in patients showing a decline in IQ after receiving cranial FRT [22]. Extensive research in pediatric brain tumor survivors at St. Jude Children's Research Hospital (Memphis, TN, USA) showed that loss of volume of normal-appearing white matter correlated with deficits in attention and IQ, a history of cranial FRT, and the dose of FRT received [23–25]. Use of diffusion tensor imaging (DTI) in medulloblastoma survivors showed that loss of myelin integrity in white matter, as revealed by fractional anisotropy maps, correlated with worse academic performance [26]. FRT-induced vasculopathies, such as moyamoya syndrome, have also been linked to progressive dementia due to recurrent ischemic and hemorrhagic strokes [27]. It is now being recognized that subtle CNS changes induced within 6 months of cranial FRT evolve into chronic progressive decline in neurocognition, and early interventions may potentially arrest the development of permanent deficits [28].

Patient-Related and Tumor-Related Factors

Multiple patient- and tumor-related factors have been identified as contributory to development of neurocognitive dysfunction after FRT. Even before commencement of treatment, a heavier burden of impaired cognition is associated with a brain tumor than with diagnosis of any other malignancy. A Swiss case–control study found measurable pretreatment cognitive deficits in one of 5 children diagnosed with a brain tumor but in only one of 25 children diagnosed with an extracranial malignancies [29]. In that study, no significant difference was observed in the baseline IQ among pediatric patients diagnosed with cranial versus extracranial tumors [29]. However, an investigation at Tata Memorial Centre (Mumbai, India) revealed that two-thirds of children and young adults diagnosed with low-grade/benign brain tumors had a less-than-average IQ score prior to advanced conformal SRT [30]. Worse pretreatment cognition status expectedly predicts poor posttreatment cognitive function, but children with higher baseline IQ score may also be susceptible to its steep decline after therapy [9]. Other patient-related factors, such as younger age at diagnosis and at the time of FRT, genetic syndromes, and socioeconomic status have also been shown to be important [6, 9, 27, 31, 32]. Optimum neurocognitive functioning may also be hampered by the presence of comorbidities (such as seizures, endocrinopathies, developmental disorders, etc.). Coexisting auditory and visual impairment have also been shown to be associated with poor verbal reasoning, lower intelligence, and overall worse academic and social functioning [6, 33]. Intellectual functioning is also influenced significantly by the presence of family support and higher socioeconomic status [31]. Children diagnosed with brain tumors recorded higher IQ scores, emotional adjustment, and adaptive functioning when they lived in two-parent households of higher socioeconomic status [34].

Normal cognition is a complex function, which is dependent on the integrity of a wide neural network. The high prevalence rates of neurocognitive deficits at the time of brain tumor diagnosis indicate the disruptive effect of the neoplasm presence itself, regardless of the lesion type or location. However, the extent of its impact on cognition may also be affected by the lesion location, histopathological type and grade, and by the duration of the disease [6, 35]. Left-side tumors and those infiltrating the hippocampus are associated with worse neurocognitive function [36]. Tumor-induced cranial nerve palsies, seizures, and hydrocephalus requiring shunt placement have been linked to reduced IQ scores, nonverbal intellectual functioning, and academic skills [37, 38]. Analysis of long-term neurocognitive outcomes in the CCSS cohort has shown worse functioning associated with hearing impairment (in cases of posterior fossa tumors) and seizure disorders (in cases of temporal region tumors) [35]. Progression or recurrence of the neoplasm can exacerbate existing deficits and cause worsening of cognitive function.

Treatment-Related Factors

Studies have shown that before they even start FRT, the majority of patients with low-grade/benign brain tumors have significant pre-existing neurocognitive dysfunction, which could be tumor-related or surgery-related [11, 39]. The type of surgery, number of surgical procedures, extent of resection, and postoperative complications can also have long-term impacts on intellectual functioning. After surgery, a decline in neurocognitive functioning (especially in language skills) has been widely observed. Hence, surgical resection in the eloquent cortex of the frontal and temporal regions has been associated with greater deficits [40]. The left and right temporal lobes have traditionally been assigned dominant roles in verbal and nonverbal language skills, respectively, but significant pervasive lingual deficits have been reported after surgery irrespective of its laterality [41]. Postoperative cerebellar mutism syndrome can affect up to one-third of patients after surgical resection of posterior fossa tumors, resulting in moderate to severely diminished speech, ataxia, hypotonia, and irritability. These symptoms may be only partially reversible, resulting in residual motor and nonmotor impairments and neurocognitive deficits in significant numbers of survivors [42]. The impact of improvements in surgical techniques in reducing the incidence rates or the extents of these disabilities is under evaluation [43]. In low-grade/benign tumors, surgical resection is often the mainstay of treatment. However, the extent of surgical resection and repeated interventions for local recurrences of these mass lesions (e.g., craniopharyngioma) have been associated with significantly impaired neurocognition in long-term survivors [44]. Various other adjuvant and supportive treatment options—such as use of systemic or intrathecal chemotherapy, insertion of the cerebrospinal fluid shunts for hydrocephalus, and use of antiepileptic drugs and corticosteroids—also contribute significantly to neurocognitive function both before and after FRT [5, 27]. Use of intrathecal methotrexate was reported to be associated with a greater need for special education services in the CCSS cohort [15]. In pediatric LGG, use of chemotherapy to delay FRT itself was associated with a worse verbal learning outcome [45]. FRT-sparing platinum-based chemotherapy regimens cause significant hearing loss, with hearing aids being required in up to one-third of survivors [46].

With regard to FRT itself, neurocognitive decline in survivors has shown significant correlations with the radiation dose and the volume and location of the treated brain tissue. In patients with posterior fossa tumors, declines in the FSIQ score and verbal comprehension were linked to the extent of

FRT (involved-field irradiation of just the posterior fossa versus CSI) and the dose of CSI (0 Gy versus 25 Gy versus 35 Gy) [47]. Another study in patients with medulloblastoma compared intellectual outcomes in patients receiving standard or reduced-dose CSI, followed by a boost delivered to the entire posterior fossa or only to the tumor bed [48]. Expectedly, the best scores were seen in the group with the least dose–volume of irradiated brain, i.e., patients who received reduced-dose CSI with a tumor bed boost [48]. In a study of childhood CNS germ cell tumors, patients receiving FRT delivered to the ventricles showed better neurocognitive outcomes than those receiving CSI [49]. The radiation dose per fraction may also be a factor in late neurocognitive toxicity. Evidence shows that neurocognitive dysfunction can occur at a fraction size less than 2 Gy, which was traditionally considered "safe" [10]. Use of hyperfractionated CSI (delivering a dose of 1 Gy per fraction instead of the conventional 1.8–2 Gy) in both average-risk and standard-risk medulloblastomas has shown better preservation of neurocognition without increasing the risk of relapse [50, 51].

Radiation dose delivery to the frontal and temporal lobes has emerged as a predictive factor in late neurocognitive decline. Using equivalent uniform dose (EUD) modeling, it was found that delivery of a higher radiation dose to the orbitofrontal brain regions and temporal lobe affected working memory and was associated with a decline in the processing speed, respectively [52]. Overall, the impact of declines in memory and executive functioning was seen in the form of poor sociodemographic outcomes in the CCSS cohort. Delivery of cranial FRT doses ≥30 Gy and ≥50 Gy to the temporal or frontal lobe was associated with a higher unemployment rate (relative risk [RR] 1.7), and delivery of ≥50 Gy to the posterior fossa was associated with a lower annual household income (RR 2.1) [53]. Treatment in which >43.2 Gy was delivered to >13% of the temporal lobe volume was associated with an FSIQ decline >10% in our series of advanced conformal SRT for low-grade/benign brain tumors [11]. A recent longitudinal case–control study observed effects of cranial FRT on cerebral growth and intellectual outcomes [54]. A lower FRT dose and greater cerebral volume were seen to be associated with a better vocabulary. A slower rate of cerebral volume growth and smaller right frontal and right temporal lobe volumes were seen in patients than in healthy individuals [54]. This may explain the observation that slowing of IQ growth after cranial FRT is caused by impaired ability to learn new skills rather than by loss of previously acquired information [55].

Being the seat of memory and learning, the hippocampus is particularly vulnerable to radiation dose–dependent neurocognitive decline [56, 57]. The subgranular zone of the hippocampus is a niche site for neural progenitor cells, which have self-renewal ability and play an important role in late neurocognitive sequelae [58]. Volume loss has been observed in both hippocampi within 2–3 years after cranial FRT [59]. In one study, delivery of a radiation dose >7.3 Gy in fractions of 2 Gy to 40% of bilateral hippocampi was associated with impaired long-term list-learning delayed recall [57]. Another study showed a 20% risk of a decline in memory if the dose received by 50% of bilateral hippocampi exceeded 22 Gy [60]. Better understanding of such treatment-related factors has spurred further research on judicious use of advanced irradiation techniques to minimize long-term cognitive sequelae in survivors.

Advances in Treatment That Minimize the Risks of Neurocognitive Dysfunction

Modern treatment protocols for most pediatric tumors include cranial or neuraxial FRT (including CSI) for improving local control, despite known neurocognitive morbidity. In brain metastases, whole-brain radiation therapy (WBRT) is associated with considerable neurocognitive deficits. Hence, tissue-sparing conformal FRT techniques have been investigated intensively in recent decades in order to minimize such complications. Intensity-modulated radiation therapy (IMRT) and conformal SRT spare considerably more healthy tissue than conventional irradiation techniques and have been used extensively in pediatric patients with low-grade/benign brain tumors to minimize the doses delivered to critical structures [57, 61]. Better long-term neurocognitive and neuroendocrine functional outcomes have been observed with conformal SRT than with conventional FRT in such cases, without compromising survival [62]. Sparing of the hippocampus by use of conformal irradiation can reduce the risk of neurocognitive dysfunction as well. This was demonstrated in patients with brain metastases treated with hippocampal-avoidance WBRT in a phase II study [63]. Restriction of the maximum radiation dose delivered to the hippocampus to <16 Gy and the dose delivered to 100% of the hippocampus to <9 Gy was associated with significant memory preservation in comparison with a historical cohort [63]. In a series of patients with low-grade/benign tumors treated with conformal SRT, restriction of the mean radiation dose delivered to the left hippocampus to ≤30 Gy predicted favorable long-term FSIQ and performance IQ scores [62]. Intensive research is under way to evaluate the hippocampus sparing by use of various conformal irradiation techniques during management of both metastatic and primary brain tumors, as well as prophylactic cranial irradiation [64]. A dosimetric study compared IMRT delivered using a high-definition multileaf collimator, forward planning conformal SRT, and helical tomotherapy in irradiation of low-grade/benign tumors [61]. While all three techniques effectively spared the left hippocampus, the dose delivered to the contralateral hippocampus tended to be lowest with the use of tomotherapy for eccentrically located mass lesions [61]. Another

study of focal FRT for HGG showed that the integral dose delivered to healthy brain tissue was lower with conventional IMRT than with helical tomotherapy–based IMRT when no selective sparing of the hippocampus, limbic circuit, or neural stem cell niches was planned [65]. However, the integral dose delivered to healthy brain tissue was much lower with both techniques when selective sparing of these structures was used [65]. These advanced techniques of radiation delivery have now become part of routine clinical practice during treatment of low-grade/benign brain tumors for avoidance of neurocognitive impairment, especially in pediatric patients, who are expected to have long survival. In addition, in newly diagnosed brain metastases, stereotactic radiosurgery (SRS) has now emerged as an acceptable alternative to WBRT for better preservation of learning and memory functions [66]. However, enthusiastic implementation of these highly conformal techniques in high-grade brain tumors has also given rise to new controversies. From one side, neural progenitor cell niches within the brain are capable of self-repair in response to radiation injury; hence, sparing of the hippocampal niche is important to preserve cognitive functions. On the other hand, the self-renewal ability of another such niche in the subventricular zone has now been associated with the tumor repopulation in HGG [58]. In fact, delivery of a higher radiation dose to this zone could potentially even improve OS in patients with glioblastoma [67]. Therefore, a balanced approach toward emerging technological advances should be adopted to minimize late effects without compromising clinical outcomes.

In patients with medulloblastoma, where CSI is often indispensable, a reduction in the neuraxial radiation dose from 36 Gy to 23.6 Gy and a reduction of the posterior fossa dose to 55.8 Gy have been associated with better preservation of cognitive functions [48, 52, 68]. The recent molecular subgrouping of medulloblastoma on the basis of risk stratification has significant potential for personalization of therapy [69]. De-escalation of aggressive treatment has become possible in patients with a favorable molecular profile (such as WNT-activated neoplasms) in terms of a decreased extent of surgical resection, a reduction in the dose of CSI to 15–18 Gy, and minimization of chemotherapy use during CSI [70, 71]. Evidence has already emerged of better preservation of intellectual functioning after reduced-dose CSI with a tumor bed boost rather than a boost delivered to the entire posterior fossa [48, 72].

Particle beam therapy is now being used in pediatric brain tumors to reduce the radiation dose delivered to healthy tissues beyond the borders of the lesion. With proton therapy, too, delivery of a higher maximum dose to the left temporal lobe correlated with a decline in performance IQ and FSIQ, showing a drop of 1 point in FSIQ for every 5-Gy increase in the maximum dose delivered to the left temporal lobe [73]. More effective sparing of small anatomical structures (such as the hippocampus and cochlea) with proton therapy and restriction of the volume of healthy brain tissue receiving low-dose radiation were associated with superior neurocognitive outcomes in a dose–cognitive effects modeling study [74]. Emerging clinical outcome data after use of proton therapy in pediatric and adult patients with brain tumors show achievement of lower dose delivery to healthy brain tissue and stable cognitive function after irradiation [75–77], but evidence of benefit is yet to be established in randomized studies.

Advanced imaging techniques such as DTI and blood oxygen level–dependent (BOLD) functional magnetic resonance imaging (MRI) have led to identification of new "organs at risk," which are being taken into account in FRT planning. DTI and functional MRI are now being integrated with SRS and IMRT to help restrict radiation dose delivery to the corticospinal and optic tracts in order to reduce late morbidities [78–80].

Cognitive Rehabilitation

Cognitive rehabilitation strategies have focused on improving attention and memory in brain tumor survivors, as these deficits account for up to 70% of functional academic impairments. The results of such a cognitive remediation therapy of 4–5 months duration, tested in a phase III randomized study in brain tumor survivors, showed improved attention and academic achievement [81]. However, such intensive programs may not be feasible or practical in resource-limited clinical settings. A shorter 15-week intervention designed to improve general cognition, memory, and attention showed improvements in social skills, reading and writing skills, and problem-solving ability [82]. Cognitive remediation therapies may not always be institution-based, since pilot studies also reporting improved attention and memory with the use of home-based computerized programs [83]. A randomized study of a cognitive rehabilitation program showed improved subjective cognitive functioning immediately posttreatment and better verbal memory and attention at 6-month follow-up [84]. The realization that such therapeutic strategies can have significant impacts on academic and social outcomes in long-term survivors of brain tumors is of paramount importance to both clinicians and health policy workers.

Pharmacotherapy

One of the main mechanisms of radiation injury in the CNS is vasculopathy affecting the brain microvasculature, which can lead to hemodynamic insufficiency, ischemic stroke, and progressive dementia [28]. Hence, drugs used for treatment of vascular dementia can potentially reduce radiation-induced neurocognitive dysfunction.

Memantine is an antagonist of the *N*-methyl-D-aspartate (NMDA) receptor, which is involved in learning and mem-

ory. Its neuroprotective effect on prevention of vascular dementia was tested in a double-blind placebo-controlled trial by the Radiation Therapy Oncology Group (RTOG 0614) [85]. In comparison with patients in the placebo study arm, those in the memantine study arm showed a significantly longer time to cognitive decline and better outcomes in terms of executive functions, processing speed, and delayed recognition domains at 24 weeks after WBRT [85]. Memantine was well tolerated, with no major toxicities, but improvement in the primary endpoint of delayed recall could not be conclusively proved.

Other pharmacological interventions have also been chiefly aimed at memory and attention deficits in brain tumor survivors, and CNS stimulants used to treat attention deficit–hyperactivity disorder (ADHD) have been tried with some success. Methylphenidate (MPH), a mixed dopaminergic–noradrenergic agonist, was tested in a randomized double-blind study, and improvement in sustained attention was reported with a single dose of MPH in pediatric brain tumor survivors [86]. A 1-year course of MPH treatment also showed beneficial effects on sustained attention, concentration, reaction time, classroom behavior, and social behavior in survivors of CNS tumors and leukemia [87]. Similar beneficial effects on fatigue, mood, executive functions, and general QOL were observed in brain tumor survivors treated with another CNS stimulant, modafinil [88]. An acetylcholinesterase inhibitor, donepezil, has been also evaluated in both children and adults with irradiated brain tumors, and some success in improving memory, mood, and concentration was demonstrated [89, 90]. In a phase III randomized placebo-controlled study performed in brain tumor patients undergoing cranial FRT, donepezil showed modest improvements in attention, immediate and delayed recall, visuomotor skills, motor speed, and dexterity, especially in individuals with greater pretreatment cognitive impairment [91].

Social Support

Neurocognitive dysfunction places a significant social burden on survivors and their caregivers. The family is the first and foremost support system when increasing deficits limit the social skills of ill persons. Studies show that positive family interactions can potentially moderate the severity of such cognitive impairment [92]. Among survivors of cancer at all sites, brain tumor survivors have the lowest scores on social independence measures, and the role of family in helping to cope with social demands is critical [15, 93]. Mothers are generally the primary caregivers, but availability of both parents has been linked to higher 4-year IQ scores in pediatric patients [34]. Studies exploring the ways in which neurocognition and emotional HRQOL of brain tumor survivors are linked to family functioning have highlighted the significant impact of familial support on the long-term social QOL of patients [92].

Support in the academic environment is equally important in mitigating the impact of neurocognitive impairment on the educational outcomes of patients treated for brain tumor. Significant communication gaps, curtailed capacity for social expression, physical and cognitive deficits, behavioral stress, and frequent absenteeism are some of the issues that impact the interactions of pediatric cancer survivors with their peers and educators. Lack of a sensitive school environment and social withdrawal of affected individuals being misconstrued as lack of motivation to learn can actually encourage early dropouts and consequently worse educational and employment outcomes [15]. An ideal structured academic program with support from an interdisciplinary team of educators, counselors, psychologists, and pediatric oncology specialists is rarely feasible in reality. However, empathy and sensitivity on the part of educators toward the cognitive issues faced by brain tumor survivors can go a long way toward helping them cope better. A positive learning atmosphere is achievable even with simple adjustments, such as oral/practical assessments, multiple-choice exam formats, preferential seating in classrooms, and use of learning aids. Educational and behavioral training efforts have to be reinforced in order to achieve optimal educational performance in these young individuals coping with serious disease.

Conclusion

Treatment-induced neurocognitive dysfunction after irradiation of brain tumors may affect both pediatric and adult patients, and it represents a significant burden not only on them and their caregivers but also on the health care system and society in general. There are sincere hopes that better understanding of the risk factors and pathophysiology of adverse radiation-induced effects on neuronal tissue—as well as development of more advanced techniques for conformal FRT, optimized dosimetry, and specific prophylactic measures—will decrease the risk of neurocognitive decline in brain tumor survivors in the future.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

References

1. Papathoma P, Thomopoulos TP, Karalexi MA, Ryzhov A, Zborovskaya A, Dimitrova N, Zivkovic S, Eser S, Antunes L, Sekerija M, Zagar T, Bastos J, Demetriou A, Cozma R, Coza D, Bouka E, Dessypris N, Kantzanou M, Kanavidis P, Dana H, Hatzipantelis E, Moschovi M, Polychronopoulou S, Pourtsidis A,

Stiakaki E, Papakonstantinou E, Oikonomou K, Sgouros S, Vakis A, Zountsas B, Bourgioti C, Kelekis N, Prassopoulos P, Choreftaki T, Papadopoulos S, Stefanaki K, Strantzia K, Cardis E, Steliarova-Foucher E, Petridou ET. Childhood central nervous system tumours: incidence and time trends in 13 Southern and Eastern European cancer registries. Eur J Cancer. 2015;51:1444–55.
2. Armstrong GT, Chen Y, Yasui Y, Leisenring W, Gibson TM, Mertens AC, Stovall M, Oeffinger KC, Bhatia S, Krull KR, Nathan PC, Neglia JP, Green DM, Hudson MM, Robison LL. Reduction in late mortality among 5-year survivors of childhood cancer. N Engl J Med. 2016;374:833–42.
3. Cairncross G, Wang M, Shaw E, Jenkins R, Brachman D, Buckner J, Fink K, Souhami L, Laperriere N, Curran W, Mehta M. Phase III trial of chemoradiotherapy for anaplastic oligodendroglioma: long-term results of RTOG 9402. J Clin Oncol. 2013;31:337–43.
4. Labussière M, Boisselier B, Mokhtari K, Di Stefano AL, Rahimian A, Rossetto M, Ciccarino P, Saulnier O, Paterra R, Marie Y, Finocchiaro G, Sanson M. Combined analysis of TERT, EGFR, and IDH status defines distinct prognostic glioblastoma classes. Neurology. 2014;83:1200–6.
5. Ellenberg L, Liu Q, Gioia G, Yasui Y, Packer RJ, Mertens A, Donaldson SS, Stovall M, Kadan-Lottick N, Armstrong G, Robison LL, Zeltzer LK. Neurocognitive status in long-term survivors of childhood CNS malignancies: a report from the Childhood Cancer Survivor Study. Neuropsychology. 2009;23:705–17.
6. Ullrich NJ, Embry L. Neurocognitive dysfunction in survivors of childhood brain tumors. Semin Pediatr Neurol. 2012;19:35–42.
7. Robinson KE, Kuttesch JF, Champion JE, Andreotti CF, Hipp DW, Bettis A, Barnwell A, Compas BE. A quantitative meta-analysis of neurocognitive sequelae in survivors of pediatric brain tumors. Pediatr Blood Cancer. 2010;55:525–31.
8. Bloom HJ, Wallace EN, Henk JM. The treatment and prognosis of medulloblastoma in children. A study of 82 verified cases. Am J Roentgenol Radium Ther Nucl Med. 1969;105:43–62.
9. Ris MD, Packer R, Goldwein J, Jones-Wallace D, Boyett JM. Intellectual outcome after reduced-dose radiation therapy plus adjuvant chemotherapy for medulloblastoma: a Children's Cancer Group study. J Clin Oncol. 2001;19:3470–6.
10. Douw L, Klein M, Fagel SS, van den Heuvel J, Taphoorn MJ, Aaronson NK, Postma TJ, Vandertop WP, Mooij JJ, Boerman RH, Beute GN, Sluimer JD, Slotman BJ, Reijneveld JC, Heimans JJ. Cognitive and radiological effects of radiotherapy in patients with low-grade glioma: long-term follow-up. Lancet Neurol. 2009;8:810–8.
11. Jalali R, Mallick I, Dutta D, Goswami S, Gupta T, Munshi A, Deshpande D, Sarin R. Factors influencing neurocognitive outcomes in young patients with benign and low-grade brain tumors treated with stereotactic conformal radiotherapy. Int J Radiat Oncol Biol Phys. 2010;77:974–9.
12. Lancashire ER, Frobisher C, Reulen RC, Winter DL, Glaser A, Hawkins MM. Educational attainment among adult survivors of childhood cancer in Great Britain: a population-based cohort study. J Natl Cancer Inst. 2010;102:254–70.
13. Frange P, Alapetite C, Gaboriaud G, Bours D, Zucker JM, Zerah M, Brisse H, Chevignard M, Mosseri V, Bouffet E, Doz F. From childhood to adulthood: long-term outcome of medulloblastoma patients. The Institut Curie experience (1980–2000). J Neurooncol. 2009;95:271–9.
14. Mitby PA, Robison LL, Whitton JA, Zevon MA, Gibbs IC, Tersak JM, Meadows AT, Stovall M, Zeltzer LK, Mertens AC. Utilization of special education services and educational attainment among long-term survivors of childhood cancer: a report from the Childhood Cancer Survivor Study. Cancer. 2003;97:1115–26.
15. Gurney JG, Krull KR, Kadan-Lottick N, Nicholson HS, Nathan PC, Zebrack B, Tersak JM, Ness KK. Social outcomes in the Childhood Cancer Survivor Study cohort. J Clin Oncol. 2009;27:2390–5.
16. Gupta P, Jalali R. Long-term survivors of childhood brain tumors: impact on general health and quality of life. Curr Neurol Neurosci Rep. 2017;17(12):99.
17. Ediebah DE, Reijneveld JC, Taphoorn MJ, Coens C, Zikos E, Aaronson NK, Heimans JJ, Bottomley A, Klein M. Impact of neurocognitive deficits on patient–proxy agreement regarding health-related quality of life in low-grade glioma patients. Qual Life Res. 2017;26:869–80.
18. Giesinger JM, Golser M, Erharter A, Kemmler G, Schauer-Maurer G, Stockhammer G, Muigg A, Hutterer M, Rumpold G, Holzner B. Do neurooncological patients and their significant others agree on quality of life ratings? Health Qual Life Outcomes. 2009;7:87.
19. Hopewell JW, van der Kogel AJ. Pathophysiological mechanisms leading to the development of late radiation-induced damage to the central nervous system. Front Radiat Ther Oncol. 1999;33:265–75.
20. Tofilon PJ, Fike JR. The radioresponse of the central nervous system: a dynamic process. Radiat Res. 2000;153(4):357–70.
21. Monje ML, Mizumatsu S, Fike JR, Palmer TD. Irradiation induces neural precursor-cell dysfunction. Nat Med. 2002;8:955–62.
22. Reddick WE, Mulhern RK, Elkin TD, Glass JO, Merchant TE, Langston JW. A hybrid neural network analysis of subtle brain volume differences in children surviving brain tumors. Magn Reson Imaging. 1998;16:413–21.
23. Mulhern RK, Merchant TE, Gajjar A, Reddick WE, Kun LE. Late neurocognitive sequelae in survivors of brain tumours in childhood. Lancet Oncol. 2004;5:399–408.
24. Mulhern RK, White HA, Glass JO, Kun LE, Leigh L, Thompson SJ, Reddick WE. Attentional functioning and white matter integrity among survivors of malignant brain tumors of childhood. J Int Neuropsychol Soc. 2004;10:180–9.
25. Reddick WE, White HA, Glass JO, Wheeler GC, Thompson SJ, Gajjar A, Leigh L, Mulhern RK. Developmental model relating white matter volume to neurocognitive deficits in pediatric brain tumor survivors. Cancer. 2003;97:2512–9.
26. Khong PL, Kwong DL, Chan GC, Sham JS, Chan FL, Ooi GC. Diffusion-tensor imaging for the detection and quantification of treatment-induced white matter injury in children with medulloblastoma: a pilot study. AJNR Am J Neuroradiol. 2003;24:734–40.
27. Duffner PK. Risk factors for cognitive decline in children treated for brain tumors. Eur J Paediatr Neurol. 2010;14(2):106–15.
28. Makale MT, McDonald CR, Hattangadi-Gluth JA, Kesari S. Mechanisms of radiotherapy-associated cognitive disability in patients with brain tumours. Nat Rev Neurol. 2017;13:52–64.
29. Margelisch K, Studer M, Ritter BC, Steinlin M, Leibundgut K, Heinks T. Cognitive dysfunction in children with brain tumors at diagnosis. Pediatr Blood Cancer. 2015;62:1805–12.
30. Jalali R, Goswami S, Sarin R, More N, Siddha M, Kamble R. Neuropsychological status in children and young adults with benign and low-grade brain tumors treated prospectively with focal stereotactic conformal radiotherapy. Int J Radiat Oncol Biol Phys. 2006;66(4 Suppl):S14–9.
31. Butler RW, Fairclough DL, Katz ER, Kazak AE, Noll RB, Thompson RD, Sahler OJ. Intellectual functioning and multidimensional attentional processes in long-term survivors of a central nervous system related pediatric malignancy. Life Sci. 2013;93:611–6.
32. Reddick WE, Taghipour DJ, Glass JO, Ashford J, Xiong X, Wu S, Bonner M, Khan RB, Conklin HM. Prognostic factors that increase the risk for reduced white matter volumes and deficits in attention and learning for survivors of childhood cancers. Pediatr Blood Cancer. 2014;61:1074–9.
33. Brinkman TM, Bass JK, Li Z, Ness KK, Gajjar A, Pappo AS, Armstrong GT, Merchant TE, Srivastava DK, Robison LL, Hudson

MM, Gurney JG. Treatment-induced hearing loss and adult social outcomes in survivors of childhood CNS and non-CNS solid tumors: results from the St. Jude Lifetime Cohort Study. Cancer. 2015;121:4053–61.
34. Carlson-Green B, Morris RD, Krawiecki N. Family and illness predictors of outcome in pediatric brain tumors. J Pediatr Psychol. 1995;20:769–84.
35. Packer RJ, Gurney JG, Punyko JA, Donaldson SS, Inskip PD, Stovall M, Yasui Y, Mertens AC, Sklar CA, Nicholson HS, Zeltzer LK, Neglia JP, Robison LL. Long-term neurologic and neurosensory sequelae in adult survivors of a childhood brain tumor: childhood cancer survivor study. J Clin Oncol. 2003;21:3255–61.
36. Bodensohn R, Corradini S, Ganswindt U, Hofmaier J, Schnell O, Belka C, Niyazi M. A prospective study on neurocognitive effects after primary radiotherapy in high-grade glioma patients. Int J Clin Oncol. 2016;21:642–50.
37. Reimers TS, Ehrenfels S, Mortensen EL, Schmiegelow M, Sønderkaer S, Carstensen H, Schmiegelow K, Müller J. Cognitive deficits in long-term survivors of childhood brain tumors: identification of predictive factors. Med Pediatr Oncol. 2003;40:26–34.
38. Hardy KK, Bonner MJ, Willard VW, Watral MA, Gururangan S. Hydrocephalus as a possible additional contributor to cognitive outcome in survivors of pediatric medulloblastoma. Psychooncology. 2008;17:1157–61.
39. Carpentieri SC, Waber DP, Pomeroy SL, Scott RM, Goumnerova LC, Kieran MW, Billett AL, Tarbell NJ. Neuropsychological functioning after surgery in children treated for brain tumor. Neurosurgery. 2003;52:1348–57.
40. Satoer D, Visch-Brink E, Dirven C, Vincent A. Glioma surgery in eloquent areas: can we preserve cognition? Acta Neurochir. 2016;158:35–50.
41. Noll KR, Weinberg JS, Ziu M, Benveniste RJ, Suki D, Wefel JS. Neurocognitive changes associated with surgical resection of left and right temporal lobe glioma. Neurosurgery. 2015;77:777–85.
42. Robertson PL, Muraszko KM, Holmes EJ, Sposto R, Packer RJ, Gajjar A, Dias MS, Allen JC. Incidence and severity of postoperative cerebellar mutism syndrome in children with medulloblastoma: a prospective study by the Children's Oncology Group. J Neurosurg. 2006;105(6 Suppl Pediatrics):444–51.
43. Wibroe M, Cappelen J, Castor C, Clausen N, Grillner P, Gudrunardottir T, Gupta R, Gustavsson B, Heyman M, Holm S, Karppinen A, Klausen C, Lönnqvist T, Mathiasen R, Nilsson P, Nysom K, Persson K, Rask O, Schmiegelow K, Sehested A, Thomassen H, Tonning-Olsson I, Zetterqvist B, Juhler M. Cerebellar mutism syndrome in children with brain tumours of the posterior fossa. BMC Cancer. 2017;17:439.
44. Steinbok P. Craniopharyngioma in children: long-term outcomes. Neurol Med Chir (Tokyo). 2015;55:722–6.
45. Di Pinto M, Conklin HM, Li C, Merchant TE. Learning and memory following conformal radiation therapy for pediatric craniopharyngioma and low-grade glioma. Int J Radiat Oncol Biol Phys. 2012;84:e363–9.
46. Orgel E, Jain S, Ji L, Pollick L, Si S, Finlay J, Freyer DR. Hearing loss among survivors of childhood brain tumors treated with an irradiation-sparing approach. Pediatr Blood Cancer. 2012;58:953–8.
47. Grill J, Renaux VK, Bulteau C, Viguier D, Levy-Piebois C, Sainte-Rose C, Dellatolas G, Raquin MA, Jambaqué I, Kalifa C. Long-term intellectual outcome in children with posterior fossa tumors according to radiation doses and volumes. Int J Radiat Oncol Biol Phys. 1999;45:137–45.
48. Moxon-Emre I, Bouffet E, Taylor MD, Laperriere N, Scantlebury N, Law N, Spiegler BJ, Malkin D, Janzen L, Mabbott D. Impact of craniospinal dose, boost volume, and neurologic complications on intellectual outcome in patients with medulloblastoma. J Clin Oncol. 2014;32:1760–8.
49. Mabbott DJ, Monsalves E, Spiegler BJ, Bartels U, Janzen L, Guger S, Laperriere N, Andrews N, Bouffet E. Longitudinal evaluation of neurocognitive function after treatment for central nervous system germ cell tumors in childhood. Cancer. 2011;117:5402–11.
50. Gupta T, Jalali R, Goswami S, Nair V, Moiyadi A, Epari S, Sarin R. Early clinical outcomes demonstrate preserved cognitive function in children with average-risk medulloblastoma when treated with hyperfractionated radiation therapy. Int J Radiat Oncol Biol Phys. 2012;83:1534–40.
51. Carrie C, Grill J, Figarella-Branger D, Bernier V, Padovani L, Habrand JL, Benhassel M, Mege M, Mahé M, Quetin P, Maire JP, Baron MH, Clavere P, Chapet S, Maingon P, Alapetite C, Claude L, Laprie A, Dussart S. Online quality control, hyperfractionated radiotherapy alone and reduced boost volume for standard risk medulloblastoma: long-term results of MSFOP 98. J Clin Oncol. 2009;27:1879–83.
52. Doger de Speville E, Robert C, Perez-Guevara M, Grigis A, Bolle S, Pinaud C, Dufour C, Beaudré A, Kieffer V, Longaud A, Grill J, Valteau-Couanet D, Deutsch E, Lefkopoulos D, Chiron C, Hertz-Pannier L, Noulhiane M. Relationships between regional radiation doses and cognitive decline in children treated with cranio-spinal irradiation for posterior fossa tumors. Front. Oncologia. 2017;7:166.
53. Armstrong GT, Liu Q, Yasui Y, Huang S, Ness KK, Leisenring W, Hudson MM, Donaldson SS, King AA, Stovall M, Krull KR, Robison LL, Packer RJ. Long-term outcomes among adult survivors of childhood central nervous system malignancies in the Childhood Cancer Survivor Study. J Natl Cancer Inst. 2009;101:946–58.
54. Agbahiwe H, Rashid A, Horska A, Mahone EM, Lin D, McNutt T, Cohen K, Redmond K, Wharam M, Terezakis S. A prospective study of cerebral, frontal lobe, and temporal lobe volumes and neuropsychological performance in children with primary brain tumors treated with cranial radiation. Cancer. 2017;123:161–8.
55. Palmer SL, Goloubeva O, Reddick WE, Glass JO, Gajjar A, Kun L, Merchant TE, Mulhern RK. Patterns of intellectual development among survivors of pediatric medulloblastoma: a longitudinal analysis. J Clin Oncol. 2001;19:2302–8.
56. Farjam R, Pramanik P, Aryal MP, Srinivasan A, Chapman CH, Tsien CI, Lawrence TS, Cao Y. A radiation-induced hippocampal vascular injury surrogate marker predicts late neurocognitive dysfunction. Int J Radiat Oncol Biol Phys. 2015;93:908–15.
57. Gondi V, Hermann BP, Mehta MP, Tomé WA. Hippocampal dosimetry predicts neurocognitive function impairment after fractionated stereotactic radiotherapy for benign or low-grade adult brain tumors. Int J Radiat Oncol Biol Phys. 2012;83:e487–93.
58. Kut C, Janson RK. New considerations in radiation treatment planning for brain tumors: neural progenitor cell–containing niches. Semin Radiat Oncol. 2014;24:265–72.
59. Nagel BJ, Palmer SL, Reddick WE, Glass JO, Helton KJ, Wu S, Xiong X, Kun LE, Gajjar A, Mulhern RK. Abnormal hippocampal development in children with medulloblastoma treated with risk-adapted irradiation. AJNR Am J Neuroradiol. 2004;25:1575–82.
60. Ma TM, Grimm J, McIntyre R, Anderson-Keightly H, Kleinberg LR, Hales RK, Moore J, Vannorsdall T, Redmond KJ. A prospective evaluation of hippocampal radiation dose volume effects and memory deficits following cranial irradiation. Radiother Oncol. 2017;125:234–40.
61. Kothavade V, Jamema SV, Gupta T, Pungavkar S, Upasani M, Juvekar S, Jalali R. Which is the most optimal technique to spare hippocampus?-Dosimetric comparisons of SCRT, IMRT, and tomotherapy. J Cancer Res Ther. 2015;11:358–63.
62. Jalali R, Gupta T, Goda JS, Goswami S, Shah N, Dutta D, Krishna U, Deodhar J, Menon P, Kannan S, Sarin R. Efficacy of stereotactic conformal radiotherapy vs conventional radiotherapy on benign and low-grade brain tumors: a randomized clinical trial. JAMA Oncol. 2017;3:1368–76.

63. Gondi V, Pugh SL, Tome WA, Caine C, Corn B, Kanner A, Rowley H, Kundapur V, DeNittis A, Greenspoon JN, Konski AA, Bauman GS, Shah S, Shi W, Wendland M, Kachnic L, Mehta MP. Preservation of memory with conformal avoidance of the hippocampal neural stem-cell compartment during whole-brain radiotherapy for brain metastases (RTOG 0933): a phase II multi-institutional trial. J Clin Oncol. 2014;32:3810–6.
64. Kazda T, Jancalek R, Pospisil P, Sevela O, Prochazka T, Vrzal M, Burkon P, Slavik M, Hynkova L, Slampa P, Laack NN. Why and how to spare the hippocampus during brain radiotherapy: the developing role of hippocampal avoidance in cranial radiotherapy. Radiat Oncol. 2014;9:139.
65. Marsh JC, Ziel GE, Diaz AZ, Wendt JA, Gobole R, Turian JV. Integral dose delivered to normal brain with conventional intensity-modulated radiotherapy (IMRT) and helical tomotherapy IMRT during partial brain radiotherapy for high-grade gliomas with and without selective sparing of the hippocampus, limbic circuit and neural stem cell compartment. J Med Imaging Radiat Oncol. 2013;57:378–83.
66. Chang EL, Wefel JS, Hess KR, Allen PK, Lang FF, Kornguth DG, Arbuckle RB, Swint JM, Shiu AS, Maor MH, Meyers CA. Neurocognition in patients with brain metastases treated with radiosurgery or radiosurgery plus whole-brain irradiation: a randomised controlled trial. Lancet Oncol. 2009;10:1037–44.
67. Lee P, Eppinga W, Lagerwaard F, Cloughesy T, Slotman B, Nghiemphu PL, Wang PC, Kupelian P, Agazaryan N, Demarco J, Selch MT, Steinberg M, Kang JJ. Evaluation of high ipsilateral subventricular zone radiation therapy dose in glioblastoma: a pooled analysis. Int J Radiat Oncol Biol Phys. 2013;86:609–15.
68. Merchant TE, Kun LE, Krasin MJ, Wallace D, Chintagumpala MM, Woo SY, Ashley DM, Sexton M, Kellie SJ, Ahern V, Gajjar A. Multi-institution prospective trial of reduced-dose craniospinal irradiation (23.4 Gy) followed by conformal posterior fossa (36 Gy) and primary site irradiation (55.8 Gy) and dose-intensive chemotherapy for average-risk medulloblastoma. Int J Radiat Oncol Biol Phys. 2008;70:782–7.
69. Ramaswamy V, Remke M, Bouffet E, Bailey S, Clifford SC, Doz F, Kool M, Dufour C, Vassal G, Milde T, Witt O, von Hoff K, Pietsch T, Northcott PA, Gajjar A, Robinson GW, Padovani L, André N, Massimino M, Pizer B, Packer R, Rutkowski S, Pfister SM, Taylor MD, Pomeroy SL. Risk stratification of childhood medulloblastoma in the molecular era: the current consensus. Acta Neuropathol. 2016;131:821–31.
70. Thompson EM, Hielscher T, Bouffet E, Remke M, Luu B, Gururangan S, McLendon RE, Bigner DD, Lipp ES, Perreault S, Cho YJ, Grant G, Kim SK, Lee JY, Rao AAN, Giannini C, Li KKW, Ng HK, Yao Y, Kumabe T, Tominaga T, Grajkowska WA, Perek-Polnik M, Low DCY, Seow WT, Chang KTE, Mora J, Pollack IF, Hamilton RL, Leary S, Moore AS, Ingram WJ, Hallahan AR, Jouvet A, Fèvre-Montange M, Vasiljevic A, Faure-Conter C, Shofuda T, Kagawa N, Hashimoto N, Jabado N, Weil AG, Gayden T, Wataya T, Shalaby T, Grotzer M, Zitterbart K, Sterba J, Kren L, Hortobágyi T, Klekner A, László B, Pócza T, Hauser P, Schüller U, Jung S, Jang WY, French PJ, Kros JM, van Veelen MC, Massimi L, Leonard JR, Rubin JB, Vibhakar R, Chambless LB, Cooper MK, Thompson RC, Faria CC, Carvalho A, Nunes S, Pimentel J, Fan X, Muraszko KM, López-Aguilar E, Lyden D, Garzia L, Shih DJH, Kijima N, Schneider C, Adamski J, Northcott PA, Kool M, Jones DTW, Chan JA, Nikolic A, Garre ML, Van Meir EG, Osuka S, Olson JJ, Jahangiri A, Castro BA, Gupta N, Weiss WA, Moxon-Emre I, Mabbott DJ, Lassaletta A, Hawkins CE, Tabori U, Drake J, Kulkarni A, Dirks P, Rutka JT, Korshunov A, Pfister SM, Packer RJ, Ramaswamy V, Taylor MD. Prognostic value of medulloblastoma extent of resection after accounting for molecular subgroup: a retrospective integrated clinical and molecular analysis. Lancet Oncol. 2016;17:484–95.
71. Archer TC, Mahoney EL, Pomeroy SL. Medulloblastoma: molecular classification–based personal therapeutics. Neurotherapeutics. 2017;14:265–73.
72. Moxon-Emre I, Taylor MD, Bouffet E, Hardy K, Campen CJ, Malkin D, Hawkins C, Laperriere N, Ramaswamy V, Bartels U, Scantlebury N, Janzen L, Law N, Walsh KS, Mabbott DJ. Intellectual outcome in molecular subgroups of medulloblastoma. J Clin Oncol. 2016;34:4161–70.
73. Zureick AH, Pulsifer M, Niemierko A, Nichols AJ, Paganetti H, Grassberger C, Fullerton BC, Khan F, Tarbell NJ, MacDonald S, Yock TI. Elevated proton radiation therapy dose to left temporal lobe or whole-brain correlates with decline in full-scale IQ components for pediatric CNS tumor survivors. Int J Radiat Oncol Biol Phys. 2016;96(2 Suppl):S120.
74. Merchant TE, Hua CH, Shukla H, Ying X, Nill S, Oelfke U. Proton versus photon radiotherapy for common pediatric brain tumors: comparison of models of dose characteristics and their relationship to cognitive function. Pediatr Blood Cancer. 2008;51:110–7.
75. Shih HA, Sherman JC, Nachtigall LB, Colvin MK, Fullerton BC, Daartz J, Winrich BK, Batchelor TT, Thornton LT, Mancuso SM, Saums MK, Oh KS, Curry WT, Loeffler JS, Yeap BY. Proton therapy for low-grade gliomas: results from a prospective trial. Cancer. 2015;121:1712–9.
76. Sherman JC, Colvin MK, Mancuso SM, Batchelor TT, Oh KS, Loeffler JS, Yeap BY, Shih HA. Neurocognitive effects of proton radiation therapy in adults with low-grade glioma. J Neurooncol. 2016;126:157–64.
77. Pulsifer MB, Sethi RV, Kuhlthau KA, MacDonald SM, Tarbell NJ, Yock TI. Early cognitive outcomes following proton radiation in pediatric patients with brain and central nervous system tumors. Int J Radiat Oncol Biol Phys. 2015;93:400–7.
78. Koga T, Shin M, Maruyama K, Kamada K, Ota T, Itoh D, Kunii N, Ino K, Aoki S, Masutani Y, Igaki H, Onoe T, Saito N. Integration of corticospinal tractography reduces motor complications after radiosurgery. Int J Radiat Oncol Biol Phys. 2012;83:129–33.
79. Pantelis E, Papadakis N, Verigos K, Stathochristopoulou I, Antypas C, Lekas L, Tzouras A, Georgiou E, Salvaras N. Integration of functional MRI and white matter tractography in stereotactic radiosurgery clinical practice. Int J Radiat Oncol Biol Phys. 2010;78:257–67.
80. Igaki H, Sakumi A, Mukasa A, Saito K, Kunimatsu A, Masutani Y, Hanakita S, Ino K, Haga A, Nakagawa K, Ohtomo K. Corticospinal tract–sparing intensity-modulated radiotherapy treatment planning. Rep Pract Oncol Radiother. 2014;19:310–6.
81. Butler RW, Copeland DR, Fairclough DL, Mulhern RK, Katz ER, Kazak AE, Noll RB, Patel SK, Sahler OJ. A multicenter, randomized clinical trial of a cognitive remediation program for childhood survivors of a pediatric malignancy. J Consult Clin Psychol. 2008;76:367–78.
82. Patel SK, Katz ER, Richardson R, Rimmer M, Kilian S. Cognitive and problem solving training in children with cancer: a pilot project. J Pediatr Hematol Oncol. 2009;31:670–7.
83. Hardy KK, Willard VW, Bonner MJ. Computerized cognitive training in survivors of childhood cancer: a pilot study. J Pediatr Oncol Nurs. 2011;28:27–33.
84. Gehring K, Sitskoorn MM, Gundy CM, Sikkes SA, Klein M, Postma TJ, van den Bent MJ, Beute GN, Enting RH, Kappelle AC, Boogerd W, Veninga T, Twijnstra A, Boerman DH, Taphoorn MJ, Aaronson NK. Cognitive rehabilitation in patients with gliomas: a randomized, controlled trial. J Clin Oncol. 2009;27:3712–22.
85. Brown PD, Pugh S, Laack NN, Wefel JS, Khuntia D, Meyers C, Choucair A, Fox S, Suh JH, Roberge D, Kavadi V, Bentzen SM, Mehta MP, Watkins-Bruner D. Memantine for the prevention of cognitive dysfunction in patients receiving whole-brain radiotherapy: a randomized, double-blind, placebo-controlled trial. Neuro Oncol. 2013;15:1429–37.

86. Thompson SJ, Leigh L, Christensen R, Xiong X, Kun LE, Heideman RL, Reddick WE, Gajjar A, Merchant T, Pui CH, Hudson MM, Mulhern RK. Immediate neurocognitive effects of methylphenidate on learning-impaired survivors of childhood cancer. J Clin Oncol. 2001;19:1802–8.
87. Conklin HM, Reddick WE, Ashford J, Ogg S, Howard SC, Morris EB, Brown R, Bonner M, Christensen R, Wu S, Xiong X, Khan RB. Long-term efficacy of methylphenidate in enhancing attention regulation, social skills, and academic abilities of childhood cancer survivors. J Clin Oncol. 2010;28:4465–72.
88. Gehring K, Patwardhan SY, Collins R, Groves MD, Etzel CJ, Meyers CA, Wefel JS. A randomized trial on the efficacy of methylphenidate and modafinil for improving cognitive functioning and symptoms in patients with a primary brain tumor. J Neurooncol. 2012;107:165–74.
89. Shaw EG, Rosdhal R, D'Agostino RB Jr, Lovato J, Naughton MJ, Robbins ME, Rapp SR. Phase II study of donepezil in irradiated brain tumor patients: effect on cognitive function, mood, and quality of life. J Clin Oncol. 2006;24:1415–20.
90. Castellino SM, Tooze JA, Flowers L, Hill DF, McMullen KP, Shaw EG, Parsons SK. Toxicity and efficacy of the acetylcholinesterase (AChe) inhibitor donepezil in childhood brain tumor survivors: a pilot study. Pediatr Blood Cancer. 2012;59:540–7.
91. Rapp SR, Case LD, Peiffer A, Naughton MM, Chan MD, Stieber VW, Moore DF Jr, Falchuk SC, Piephoff JV, Edenfield WJ, Giguere JK, Loghin ME, Shaw EG. Donepezil for irradiated brain tumor survivors: a phase III randomized placebo-controlled clinical trial. J Clin Oncol. 2015;33:1653–9.
92. Hocking MC, Hobbie WL, Deatrick JA, Hardie TL, Barakat LP. Family functioning mediates the association between neurocognitive functioning and health-related quality of life in young adult survivors of childhood brain tumors. J Adolesc Young Adult Oncol. 2015;4:18–25.
93. Hobbie WL, Ogle S, Reilly M, Barakat L, Lucas MS, Ginsberg JP, Fisher MJ, Volpe EM, Deatrick JA. Adolescent and young adult survivors of childhood brain tumors: life after treatment in their own words. Cancer Nurs. 2016;39:134–43.

The Hawthorne Effect: Quality and Outcomes in Neurosurgery

Anil Pande and Siddhartha Ghosh

Abstract

Measure something, and it gets better—this is what is called as the Hawthorne effect (also known as the observer effect). The Hawthorne factory experiments in 1920s were remarkable industrial data collection and analysis exercises that lead to Edwards Deming's quality revolution. The Harvard Medical Practice Study (1991), Leape's "Error in Medicine" (1994), and the Bristol pediatric cardiac report (2001) are among many documents that have revealed the huge gap between best practices and actual medical practice. Alarmed by the poor standards of quality at the most respected institutions, the medical fraternity therefore began visiting facilities in different fields and observing their quality assessment processes. The next leap for neurosurgery is to realize that it is unacceptable to treat patients with no regard for the standard of clinical outcomes. The traditional neurosurgery residency training has long ignored the most important issues of self-assessment, reappraisal, relearning, and measurement of skill and surgical outcomes. However, the experience taken from disparate fields, especially cardiac surgery, may encourage research and progress in measurement and improvement of quality in neurosurgery. Like cardiac surgeons, neurosurgeons must examine and analyze the results of their interventions. The concept of quality measurement is the most important single advance we can make in neurosurgery practice. Meticulous and precise measurement of outcomes will allow future progress of our specialty.

Keywords

Clinical audit · Clinical governance · Complication avoidance and prevention · End-result theory · Hawthorne effect · Neurosurgery · Outcome · Quality measurement · Risk stratification

Introduction

Global health care is grossly deficient in quality. Global neurosurgery is an unmet need [1]. Quality is everything, and perhaps nowhere does it matter more than in surgery of the neuraxis—i.e., repair and modulation of the brain, spinal cord, and peripheral nerves. The simplest of neurosurgical procedures are remarkable for the enormous learning and practice that must precede them. The years of toil that go into education and training of a neurosurgeon are steadily increasing. The consequences of an inappropriate neurosurgical operation or an inadvertent error can mar life and burden society through cumulative morbidity and mortality. Arnold Relman called the current phase of medical care the "era of assessment and accountability" and termed it the third revolution in medical care. The first such revolution was the "era of expansion" between 1940 and 1960, during which many hospitals were built. The second era was between 1970 and 1980, and was called the "era of cost containment" or the "revolt of the payers" [2]. If we, as neurosurgeons, do not "bell the cat" and if we hold back from taking the necessary steps to enable quality of outcomes to guide progress in our most difficult branch, then commercial, political, and other nonsurgical profit-centered forces may mislead the public to disrespect our profession, citing poor patient outcomes. "There are no minor neurosurgical procedures" is a truism that cannot be overstated. Errors in surgery and management of chronic subdural hematomas and basilar tip aneurysms are comparable in terms of outcome and cost. Thus, the adage that

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_25

"Everything that can be done should be done" is the best possible one and a truism. The concept of *primum non nocere* (do no harm) has a long history [3]. Incorporating insights gained from other high-risk professions where so much depends upon so few—such as aviation, the space industry, the nuclear industry, anesthesiology, and cardiac surgery—is imperative and urgent. Learning also from widely disparate nonmedical fields, such as aviation and the automobile industry, is allowing us to leap into the era of quality, and outcomes are improving globally. In 1991, the Harvard Medical Practice Study found some alarming facts—including that 4% of all hospitalizations involved an iatrogenic failure—and this is unfortunately the eighth leading cause of death in the USA [4]. Mandatory and transparent outcome measurement and reporting will help us achieve the Six Sigma goal in neurosurgery.

The special field of neurosurgery has made salutary leaps in terms of outcome improvement and quality, thanks to the life's work of individual pioneers, adaptations of technology (e.g., operating microscopes), and newer medications. Perhaps the next leap is to incorporate the total quality concept to aid its further progress and evolution. The end consumer of our services—the patient—is central, and we should improve neurosurgical outcomes and quality, realizing the truth of the adage that "the patient is God." The quality revolution is here and has already impacted all aspect of our lives. Lee Carter, a long-time board member of Cincinnati Children's Hospital Medical Center, put it very well: "You are not the best at everything and can always improve … we will be the best at getting better … until we are the best and then we will remain the best because we will be the best at getting better."

Quality in neurosurgery includes surgical outcomes, patient wellness, patient satisfaction, as well as cost and timeliness of procedures and care in general. Comparisons of outcomes, using pooled individual and institutional large databases, improve results. The patient's perspective and patient-reported outcomes have to be taken into consideration and are the keystone of a total quality revolution in neurosurgery.

The Hawthorne Effect

The Hawthorne effect, also known as the observer effect, is a unique finding that when individuals know they are being observed, they modify their behavior and actions, resulting in an improvement in the quality of the outcome. In 1920s, George Elton Mayo—a psychologist and industrial researcher at the Hawthorne plant of the Western Electric Company in Cicero (IL, USA; Fig. 1)—conducted a series of experiments to study workplace motivation and worker behavior. He found that just the fact that there was observation occurring improved the work quality. This study of efficiency at the factory found that any variable change led to increased productivity when the observation was continued, but productivity went down when the experiment was stopped. These experiments ceased in 1932. In 1950, Henry A. Landsberger, in a review, noted the remarkable insight that the act of measurement itself actually improved the performance.

Fig. 1 The Hawthorne plant of the Western Electric Company in Cicero, IL, USA (about 1930)

W. Edwards Deming, known as the "prophet" of quality control and improvement [5], worked at the Western Electric Hawthorne plant and studied the methods of Walter A. Shewhart. He developed the remarkable Total Quality Management (TQM) program, applicable to any process. He initially used his unique quality work to help American war production. After World War II, he was sent to Japan, and Japanese industry enthusiastically adopted his Plan–Do–Check–Act (PDCA) cycle and TQM to make Japanese quality a benchmark for the rest of the world [6]. In the past three decades, American medical professionals have returned to Japan to study quality in factories (such as those of Toyota) to improve American medicine and rediscover the principles that were previously learned at Western Electric Hawthorne plant [7–12].

Many, if not most, academics dismiss the Hawthorne effect and its importance, calling it a myth or a fable [13]. But experimental design at workplaces, constant collection of huge volumes of data, and data analysis are central to outcome research. Deming spent time at the Hawthorne factory, and his training in these progressive ideas and methods triggered the modern quality revolution.

Clinical Audits

Clinical auditing is a process that seeks to improve the quality of patient care and outcomes by systemic review, evaluation of care against specific criteria, and implementation of change. Clinical audits began with the seminal work of the exemplary nurse Florence Nightingale (Fig. 2) and the remarkable surgeon Dr. Ernest Amory Codman (Fig. 3).

Fig. 2 Lady with the Lamp - Florence Nightingale (1820–1910)

Fig. 3 Dr. Ernest Amory Codman (1869–1940)

During the Crimean War (which lasted from 1853 to 1856), Nightingale and her team of 38 nurses were distressed by the poor outcomes of the wounded soldiers in the barrack hospital in Scutari (Turkey) and started clinical audits by keeping meticulous records of mortality rates. The results of her statistical study and documentation dropped the mortality rate from 40% to 2%.

Codman, a general surgeon at Massachusetts General Hospital, was a pioneer in monitoring outcomes of surgical care. He was a proponent of end-result theory and advocated use of precise record keeping and descriptive statistics to document the final outcomes of one's surgical cases and compare them with those of other surgeons [14]. The end result of care was analyzed at the end of a year, and these outcomes were studied. The treatment errors that were found were further classified as being due to lack of equipment, lack of technical skill or knowledge, or lack of judgment or incorrect diagnosis [15, 16]. As a very skilled surgeon, he was quick to realize that the study of quality in medicine was a very critical area of academic inquiry and research. Harvey Cushing, his classmate and collaborator in their famous work on anesthesia records, is better known, but Codman may be the man with the last word. Stephen J. Haines and Paul B. Nelson rightly stated that "these issues, more than those of science or technology, will determine the role of neurological surgery in the 21st century." Thus, the quality, cost, and outcomes of our operations and patient care have to be looked at carefully and optimized continually [17]. Codman was ignored by his peers and resigned but helped to found the Joint Commission on Accreditation of Health Care Organizations. Cushing himself reported 30 cases in which he made a surgical error, truthfully documenting his failures [18].

The Japanese Quality Revolution

Sakichi Toyoda was a Japanese engineer and many people believe that the quality revolution was initiated by him in 1902. He started with the power loom industry and then founded the Toyota car company. The TQM concept was built into all of its processes, which continue to evolve and adapt. The concept of *muda* (waste) has been developed into elimination of wastage of time, movement, energy, and money, leading to lean manufacturing incorporating the principle of doing more with less in everything. The practice of *shisa kanko* (pointing and calling) is another

Japanese quality effort, which entails achieving consistency and improved quality through verbal acknowledgment and stating of actions. It is reflected in the time-out procedure now used in operating theaters [19]. This simple method has been shown to reduce errors during performance of tasks by 85%.

The Concept of Clinical Governance

Dr. Paul Lembcke, a surgeon at Johns Hopkins Hospital, promulgated the medical audit—a systemic review and scientific evaluation of medical care [20]. The need for such a process had been demonstrated by problems created by a surplus of poorly qualified doctors in the USA in the early twentieth century. In 1910, this pathetic state of medical education and its remedy were tersely but comprehensibly pointed out by Flexner in a report to the Carnegie Foundation [21]. Dr. Avedis Donabedian, at the University of Michigan, subsequently proposed the model for evaluating the quality of medical care ("Donabedian model"). In 1966, he wrote a pioneering review titled "Evaluating the Quality of Medical Care" [11]. His work has since become the paradigm for quality measurement in health care [12]. Dr. Lucian Leape published a landmark paper titled "Error in Medicine" [22] and proclaimed that safety is the *sine qua non* of quality. He defined terms such as "adverse event" and "negligence." He famously remarked that the greatest impediment to improving the quality of medical care is that we punish doctors for making mistakes. The concepts of negligence and adverse events are just two of many in the new terminology of quality. His research threw up uncomfortable issues, such as the fact that every year in the USA, 120,000 people were dying from preventable medical errors, demonstrating the poor and unmonitored quality of care at even the best medical centers. Because no one measured these outcomes, no one knew of them. He proposed that a system-based approach to reduce errors was better, and he elaborated national policies to reduce errors in medicine [23, 24]. National Academy of Medicine member and executive director of the Kaiser Permanente Center for Effectiveness and Safety Research (CESR) Dr. Elizabeth A. McGlynn famously concluded that there are no guarantees about the quality of care any individual is likely to receive for any medical problem: "There is a gap between best practices and actual practices."

Dr. Donald M. Berwick and his nonprofit organization, the Institute for Healthcare Improvement, have led a worldwide crusade for quality in health care. He studied quality systems at Toyota, NASA, Bell Laboratories, Gillette, Ford, Xerox, and AT&T, among others. He understood that quality is not acquired accidentally; you have to care about it and incorporate it seamlessly into all systems. The main elements in the quality revolution are measurement and comparison of standards and truthful data gathering from both individual doctors and hospitals. All data should be available, on an open access basis, to patients and all caregivers. He proposed continuous improvement as an ideal in health care [8, 9]. The National Demonstration Project on Quality Improvement in Health Care is one of his initiatives. His report titled "Crossing the Quality Chasm" set the agenda for the essential right to access safe, effective, patient-centered, timely, efficient, and equitable care. The report catalyzed better payment incentives, establishment of infrastructure to support evidence-based care, better preparation for the health care workforce, and broader use of information technology.

Dr. Paul Batalden, a pediatric gastroenterologist, rediscovered the work of Deming, whose ideas led to the preeminence of Japanese industry in the quality revolution from 1950s onward. Prior to that time, Japanese goods were cheap and of very poor quality, and this situation was transformed using Deming's approach to quality improvement. Learning from Deming, Batalden realized that quality was a theory of work, which conceptualized continual improvement of quality as intrinsic to the work itself [7]. The Deming chain reaction starts with quality improvement, which leads to decreases in costs and delays, increasing the efficiency and productivity of systems and processes. Drs. Kerr White, John Williamson, Bob Brook, Jack Wennberg, Alan Gittelsohn, Warren Warwick, Vinod K. Sahney, Uma Kotagal, Jim Anderson, and Ronald D. Lee and Lawrence R. Carter (creators of the method for forecasting mortality, currently known as "Lee-Carter model") are among many people who have pursued perfection in health care and have created systems of quality and engines of transformational change.

Critical Incident Analysis

Critical incident analysis was used initially in military aviation in World War II and as a routine tool in the aviation industry from 1950s onward as a way of learning how an adverse event occurred, in order to identify a system or instrumentation failure. In 1978, Jeffrey Cooper applied a modified critical incident analysis technique to anesthesiology, studying 359 errors or critical incidents that occurred in patients given anesthesia [25]. Data on these were collected and evaluated using computer-aided analysis to look for trends and patterns. Human error was the cause in 82% of cases, and instrument failure was seen in 14%. This study and the remedies it suggested transformed anesthesia [25, 26].

Dr. Atul Gawande wrote a seminal article titled "The Bell Curve: What Happens When Patients Find Out How Good Their Doctors Really Are?" in a *New Yorker* issue, published on December 6, 2004. He stated that medical errors are common and that their incidence and the resulting malpractice cases follow a uniform bell-shaped distribution. Serious mistakes will occur everywhere and do not spare "star surgeons" or "ivory tower" institutions. Any complex work requiring a large amount of knowledge and experience is bound to have failures, and the incidence of these has been brought down considerably in aviation, industry, and anesthesia by simple adaptation of the concept of checklists [5, 27]. Dr. Peter Pronovost devised a checklist to decrease bloodstream-related catheter infections in intensive care units, which proved successful, showing that memory and judgment are unreliable and can have serious limitations and bias, causing grave errors [28]. Surgical errors are common and mostly preventable, and individual surgeons must track and analyze their errors to eventually help develop systems that will prevent them [27, 29, 30].

The Near Miss Concept and Lessons from Cardiac Surgery

In the aviation industry, a near miss is an event in which two aircraft come very close to one another but an accident somehow does not occur. These near miss incidents are taken very seriously and are researched to reduce the incidence of actual accidents. In a study of adverse clinical events, also called near misses, the cardiothoracic surgeon Samer Nashef classified near miss events into three types (Table 1) [31]. Identification of the causes of these events may enable reductions in their occurrence. Most near miss events go unreported, and learning and improvement opportunities are lost every day in operating theaters, in neurosurgery critical care units, and even in clinics.

The idea of clinical governance was brought to center stage when the British cardiac surgery community was shocked by the Bristol pediatric cardiac report. The report brought to public notice unacceptably poor outcomes and avoidable pediatric cardiac surgery deaths at an accredited center. The report's 198 recommendations included robust monitoring of outcomes and the need for transparent and true measures of surgical and patient data.

Table 1 Classification of near miss events in clinical medicine (according to Nashef [31])

Type 1	Adverse event occurs. System in place to detect and correct it works as planned. No harm done.
Type 2	Adverse event occurs. One (or more) of the systems fails to detect and correct. No harm done.
Type 3	Adverse event occurs. One (or more) of the systems fails to detect and correct. Harm is sustained but falls short of the worst possible outcome (the marker or indicator outcome).

In 1989, Parsonnet et al. [32] published a method of uniform risk stratification for evaluating the results of surgery in patients with acquired adult heart disease. They introduced the concept of predicted mortality and provided a benchmark and an objective way of predicting and comparing outcomes. In 1995, Roques et al. [33] built on this concept further and published a paper describing the French Score. In 1999, Nashef et al. [34] published a paper describing the EuroSCORE, which went on to be used globally to evaluate risk and the quality of care, and to predict mortality.

In 2009, the published results of Failure to Achieve a Satisfactory Cardiac Outcome (FIASCO) study revealed that in low-risk patients, the cause of death was due to communication errors and use of inadequate methods to protect the heart [35]. It was followed by FIASCO II study, which showed that recognition of such errors had helped to eliminate them [36]. Only in 2013 did the UK National Health Service (NHS) begin publishing outcomes in other surgical specialties, learning from the experience in cardiac surgery. Dr. Samer Nashef deserves credit for highlighting the important role that the Hawthorne effect can play in improving quality and outcomes in surgical specialties.

The Neurosurgeon Who Started It All

Sir Wylie McKissock (Fig. 4), a leading British neurosurgeon, led the quality revolution in neurosurgery by publishing a pioneering randomized controlled comparison of surgical and nonsurgical management of ruptured posterior communicating artery aneurysms [37]. He aptly remarked that "the demonstration of a low mortality rate by a new technique is of no value until an acceptable statistical method of assessment of the natural prognosis and of the proposed treatment is available." Despite being a brilliant and dexterous surgeon in the tradition of Walter Dandy, he believed that performing randomized controlled trials of common neurosurgical conditions and their management was of primary importance [16, 38]. The natural history of the disease and the surgical technique were studied in detail, and large volumes of the data collected were subjected to critical analysis. He is perhaps the person who deserves to be called the "father of the quality revolution" in neurosurgery.

The issues of quality and cost in neurosurgery attracted the attention of the Congress of Neurological Surgeons (CNS), which released a monograph dedicated to these issues, titled *Quality & Cost in Neurological Surgery* (volume 10 of the Concepts in Neurosurgery series), edited by Mark E. Linskey and Michael J. Rutigliano, in 2001. It is a

Fig. 4 Sir Wylie McKissock (1906–1994); Oil painting by Gerald Festus Kelly; St. George's Hospital (London, United Kingdom)

useful resource for neurosurgeons and neurosurgical organizations aiming to make a TQM leap. The aim is to define methods and orchestrate knowledge and skill to provide the highest quality of neurosurgical care in the most cost-effective way.

The Future of Neurosurgery Worldwide

Being the most difficult and youngest of the surgical specialties, neurosurgery faces an uncertain future and has no other option but to embrace the concepts of total quality, quality control, patient-centered outcomes, and stringent quality measurement and reporting [8, 10, 39–44]. Gawande describes it well as "a commitment to making a science of performance, rather than waiting for new discoveries." Everything matters; small and apparently insignificant details can have major impacts. Checklists matter, teams matter, and communications matter. Memory and judgment are unreliable, and lives depend on us knowing that fact [45]. The final World Health Organization (WHO) Surgical Safety Checklist includes 19 checks. Use of this checklist has made the rates of major complications fall by 36%, deaths by 47%, and infections by 50% [46]. Validation of other checklists such as the Surgical Patient Safety System (SURPASS), which covers the entire surgical pathway, improves their acceptance and reliability [29]. In his 2013 American Association of Neurological Surgeons (AANS) Presidential Address (titled "Changing our Culture to Advance Patient Safety"), Dr. Mitchel Berger asked for consistent system-based strategies, adequate safeguards, improved communication, dismantling of authority gradients, and a well-trained and well-rested workforce [40].

Stone and Bernstein [47] defined a neurosurgical error as an act of omission or commission resulting in deviation from a perfect course for the patient. In prospective reporting of error data in 1108 elective neurosurgical procedures, they found that errors occurred in 87.1% of cases, including technical errors (27.8%), contamination errors (25.3%), and errors related to equipment failure or missing equipment (18.2%). Adverse events should be investigated methodically so we can understand what caused them to occur, and we can thereby work out and implement changes in the workflow to prevent their recurrence [1]. Wrong-side surgery can be mostly prevented by following protocols [45, 48, 49]. Routine use of checklists reduces surgical errors and is already having a huge impact on error reduction [46].

The AANS and CNS have done pioneering work in establishing quality programs such as the Neurosurgical Outcomes Initiative, an online outcome reporting system linked to Neurosurgery On-Call (NOC). The need to create protocols and ensure they are followed also applies to most treatment plans. A national neurosurgical website in the USA collects outcome data on several pathological conditions (such as carotid stenosis, lumbar discectomy, and acute subdural hematoma), and their list will eventually cover the complete spectrum of neurosurgery procedures. The Neurosurgical Report Card is a simple, short, generic, online outcome reporting instrument, which can be used for data collection, data analysis, and outcome research.

Wong et al. [44] recognized six categories of contributory factors in neurosurgical adverse events: (1) issues in surgical technique; (2) perioperative medical management; (3) use of and adherence to protocols; (4) preoperative optimization; (5) technology; and (6) communication. Their five priority recommendations for improving outcomes were (1) development and implementation of a national registry for outcome data and monitoring; (2) full integration of the WHO Surgical Safety Checklist into the operating room workflow to improve fundamental aspects of surgical care, such as adherence to antibiotic protocols and communication within surgical teams; (3) activity by neurosurgical societies to drive increased standardization for the safety of specialized equipment used by neurosurgeons; (4) more widespread regionalization and/or subspecialization; and (5) establishment of data-driven guidelines and protocols [44].

Neurosurgeons know very well the tremendous challenge that even the simplest of cases can throw at them, defeating them and destroying the very patient and his or her family that they have sought to help. Often, sheer mistakes are not recognized and are glossed over as a complication that happens, and we hide in nebulous chaos theory or cite Murphy's law, which states that "if anything can go wrong, it will!" We hide these insecurities and our vulnerability under the guise of surgical arrogance and a highly developed protective instinct of denial. In his book titled *The Naked Surgeon: The Power and Peril of Transparency in Medicine*, Nashef says, "the opposite of evidence-based medicine is sometimes practised by stubborn yet famous high-profile doctors. I call it eminence-based medicine, and it is defined as 'persisting in making the same mistake over and over again, but with ever-increasing conviction'."

The quality revolution is occurring in health care across continents. Since 1990s, there has been a plan to introduce quality measures in German neurosurgery in three phases: the model phase, the study phase, and the actual implementation or practice phase [7]. In the USA, the National Neurosurgery Quality and Outcomes Database (N^2QOD) is being used to help create a specialty-specific qualified clinical data registry (QCDR), which is both physician and patient driven [39, 50]. Outcome research in cranial, spine, and peripheral nerve surgery is of great importance [42]. Development and validation of risk scores in elective neurosurgery require large prospective studies, and these can guide patient management by enabling preoperative outcome estimation [51]. A bedside scoring system to calculate the patient's frailty index has been proposed for classification of adverse outcomes and prediction of mortality and morbidity [52].

High-Volume Centers: Quality and Outcomes

A study of a large nationwide registry of subarachnoid hemorrhage (SAH) found that more experienced centers (treating greater numbers of ruptured aneurysms) had better patient outcomes due to providing more optimized care [53]. Another way of improving quality and outcomes is to have voluntary verification of centers that deal with conditions that require a large collaborative effort, such as trauma centers and pituitary centers of excellence [54].

The National Quality Forum (NQF), a nonprofit organization dedicated to improving the quality of health care in the USA, has listed 28 types of serious reportable events ("never events"), such as wrong-site surgery. The aim of the quality revolution is reduce the incidence of "never events" to zero with corresponding nonpayment for resulting complications [55]. On the other hand, "always events" are defined as positive affirmative behaviors (such as the surgical time-out) that improve patient safety and outcomes [55].

Large-volume national databases and registries can aid comparison of outcomes between institutions and countries. Outcome studies and population-based studies using multinational databases for research on common childhood tumors, such as the UK National Registry of Childhood Tumours (NRCT) or the National Cancer Institute Surveillance, Epidemiology, and End Results (SEER) database, have been found to be useful to avoid bias associated with trial and institutional studies [56]. Patient input is invaluable in assessment and improvement of health systems [57]. McLaughlin et al. [17] have reported the importance of integrating department-specific and physician-specific risk management data into care redesign initiatives in order to minimize litigation and improve the quality of patient care.

Global Neurosurgery and Outcome Research

Kim et al. [30] defined global neurosurgery as an area for study, research, practice, and advocacy that placed a priority on improving health outcomes and achieving health equity for all people worldwide who are affected by neurosurgical conditions or have a need for neurosurgical care. A unified voice of neurosurgery is urgently needed to address the unmet need for basic neurosurgical services [58]. On this way, 2015 was a landmark year and saw the publication of a report in *The Lancet* that heralded the surgical spring [59]. Global neurosurgery quality and outcome research is the only way forward. We need to know what the real state of things is in global neurosurgery. Observation, data collection, and documentation of lacunae will lead to improvement and progress via the Hawthorne effect.

In addition, creation of international neurosurgical databases will allow us to identify best practices and bridge gaps between them and one's actual practice.

Total Quality Management and Neurosurgery Residency

Our residency programs must be assessed for quality and must incorporate teaching of the tools and terminology of the quality revolution into their agenda. The Accreditation Council for Graduate Medical Education in the USA has been evolving goal-based programs, defining and evaluating milestones that have to be reached by neurosurgery

residents. Quality improvement and patient safety issues are made central in the training modules. If they are well structured, even routine mortality and morbidity meetings can have great educational impacts on residents and cause them to reflect on improving surgical quality and outcomes [30]. The importance of this approach cannot be overstated; quality and cost in neurosurgery will shape our future and those of our patients. High quality actually saves money and optimizes resource utilization, and as health care budgets become central to the world economy, it behooves the most resource-intensive and expensive surgical specialty to put its house in order. Resident quality improvement curricula are already being implemented [53]. Reforms have been advocated that are outcome based, encourage lifelong learning, and are patient-centric. These initiatives will also entail creation of a new practice science based in the daily clinical environment and utilizing clinical data registries. Training of experts in outcome science and quality will be required [43].

Deming said that teaching of beginners should be done by a master, not by a hack. Mandatory courses in quality and outcome improvement must be an integral part of our neurosurgery training programs. "Mentoring, not commanding" is the new mantra [60]. A system-level approach, a blame-free environment, open and honest discussion, and root cause analysis have been cited as factors that improve delivery of quality medical care [17]. Improving the quality and consistency of our medical and surgical care decisions could be enhanced by study of and learning from the disparate fields of chaos theory, the science of heuristics and bias, aviation [27], and even management. In his landmark book titled *Thinking Fast and Slow*, Daniel Kahneman talks about the two types of thinking that we do: fast, automatic thinking; and slow, deliberate, type 2 thinking. Both are important, but both types can be error prone. Systemic errors are known as biases. As he says, we can be blind to the obvious, and we are also blind to our blindness. The science of heuristics is a branch of knowledge that studies links between experience, learning, and behavior [61]. Most surgeons make wrong assumptions and think they have a much lower mortality rate than they actually do. Assumption-based medicine must give way to evidence-based medicine [61]. By using both incentives and nudges, and designing user friendly environments, choice architects can make major improvements, as elaborated by Richard H. Thaler and Cass R. Sunstein in their book titled *Nudge: Improving Decisions about Health, Wealth and Happiness*. A behavioral insight team or a nudge unit in neurosurgery could influence a large number of neurosurgeons by applying the principles of behavioral science to improvement of neurosurgical quality.

Conclusion

"Bridging the great gap between actual practice and best practice" is the most important contribution we can make as neurosurgeons. Measuring outcomes and having outcome standards for the entire spectrum of cranial, spinal, and peripheral nerve neurosurgical procedures can lead to a TQM revolution in our specialty. The concepts of "ivory tower" medical institutions and "star surgeons" need to be relegated to the past. Uniformly good outcomes of major and minor procedures—regardless of which institution or surgeon the patient chooses—need to be achieved at all costs. Quality lessons from the aviation, space, and automobile industries, leading to a lean and consistent work theory and getting it 100% right all of the time, need to be ingrained in neurosurgical practice. Quality processes need to be built into the system that are continuously evolving and intrinsic to the work itself. The Hawthorne effect (the observer effect) can be used to achieve a quantum leap in quality and outcomes in neurosurgery through observation, measurement, reporting, and comparison of our surgical outcomes. The patient should be central to our service, and "the patient is God" is not an overstatement. Patient-reported outcomes could help improve quality further. All neurosurgical procedures are likely to improve in quality and outcomes if there is constant observation and analysis of the actual outcomes of every procedure that is performed. The Hawthorne effect is likely to influence the future of neurosurgery remarkably and favorably.

Acknowledgments We would like to acknowledge Ms. Sapline Prabha and Ms. Rathi Priya Annan for their help in the preparation of this manuscript.

Conflict of Interest Statement The authors have no conflict of interest concerning the reported materials or methods.

Appendix: Source Books and Further Reading

The literature on quality in medicine and neurosurgery in particular is sparse but is rapidly increasing.The impact these new and old ideas about preventing error are making is immense indeed.

- Gawande A. Better: a surgeon's notes on performance. New York: Metropolitan; 2007.
- Gawande A. Complications: a surgeon's notes on an imperfect science. New York: Metropolitan; 2002.
- Gawande A. The checklist manifesto: how to get things right. New York: Metropolitan; 2009.

- Institute of Medicine. Crossing the quality chasm. Washington, DC: National Academy of Sciences Press; 2001.
- Kahneman D. Thinking fast and slow. New York: Farrar, Straus and Giroux; 2011.
- Kenney C. The best practice: how the new quality movement is transforming medicine. New York: Public Affairs; 2008.
- Landsberger HA. Hawthorne revisited. Ithaca: Cornell University Press; 1958.
- Linskey ME, Rutigliano MJ (eds) Quality & cost in neurological surgery. Concepts in neurosurgery, volume 10. Hagerstown: Lippincott Williams & Wilkins; 2001.
- Nashef S. The naked surgeon: the power and peril of transparency in medicine. London: Scribe; 2015.
- Thaler RH, Sunstein CR. Nudge: improving decisions about health, wealth and happiness. New Haven: Yale University Press; 2008.
- The report of the public inquiry into children's heart surgery at the Bristol Royal Infirmary 1984–1995: learning from Bristol. London: Department of Health; 2001.

References

1. Vincent C. Understanding and responding to adverse events. N Engl J Med. 2003;348:1051–6.
2. Relman AS. Assessment and accountability: the third revolution in medical care. N Engl J Med. 1988;319:1220–2.
3. Smith CM. Origin and uses of primum non nocere—above all, do no harm. J Clin Pharmacol. 2005;45:371–7.
4. Brennan TA, Leape LL, Laird NM, Hebert L, Localio AR, Lawthers AG, Newhouse JP, Weiler PC, Hiatt HH. Incidence of adverse events and negligence in hospitalized patients. Results of the Harvard Medical Practice Study I. N Engl J Med. 1991;324:370–6.
5. Gabor A. The man who discovered quality. New York: Times Books; 1990.
6. Aguayo R. Dr. Deming: the American who taught the Japanese about quality. New York: Lyle Stuart; 1990.
7. Batalden PB, Mohr JJ, Nelson EC, Plume SK. Improving health care, part 4: concepts for improving any clinical process. Jt Comm J Qual Improv. 1996;22:651–9.
8. Berwick DM. Continuous quality improvement as an ideal in health care. N Engl J Med. 1989;320:53–6.
9. Berwick DM, Nolan TW. Physicians as leaders in improving health care: a new series in *Annals of Internal Medicine*. Ann Intern Med. 1998;128:289–92.
10. Bock WJ. Quality assurance—an important factor in the structure of medical management of the future [in German]. Zentralbl Neurochir. 1992;53:189–93.
11. Donabedian A. Evaluating the quality of medical care. Milbank Mem Fund Q. 1966;44(3 Pt 2):166–206.
12. Donabedian A. Explorations in quality assessment and monitoring, vol. 1. The definition of quality and approaches to its assessment. Ann Arbor: Health Administration Press; 1980.
13. Campbell JP, Maxey VA, Watson WA. Hawthorne effect: implications for prehospital research. Ann Emerg Med. 1995;26:590–4.
14. Kaska SC, Weinstein JN. Historical perspective. Ernest Amory Codman, 1869–1940. A pioneer of evidence-based medicine: the end result idea. Spine (Phila Pa 1976). 1998;23:629–33.
15. Codman EA. A study in hospital efficiency: as demonstrated by the case report of the first five years of a private hospital. Boston: Thomas Todd; 1918.
16. Harbaugh RE. History of outcomes measures in neurosurgery. Neurosurg Clin N Am. 2001;12:217–21, xi.
17. McLaughlin N, Garrett MC, Emami L, Foss SK, Klohn JL, Martin NA. Integrating risk management data in quality improvement initiatives within an academic neurosurgery department. J Neurosurg. 2016;124:199–206.
18. Latimer K, Pendleton C, Olivi A, Cohen-Gadol AA, Brem H, Quiñones-Hinojosa A. Harvey Cushing's open and thorough documentation of surgical mishaps at the dawn of neurologic surgery. Arch Surg. 2011;146:226–32.
19. McLaughlin N, Winograd D, Chung HR, Van de Wiele B, Martin NA. University of California, Los Angeles, surgical time-out process: evolution, challenges, and future perspective. Neurosurg Focus. 2012;33(5):E5.
20. Lembcke PA. Evolution of the medical audit. JAMA. 1967;199(8):543–50.
21. Flexner A. Medical education in the United States and Canada: a report to the Carnegie Foundation for advancement of teaching. Boston: Merrymount Press; 1910.
22. Leape LL. Error in medicine. JAMA. 1994;272:1851–7.
23. Leape LL, Brennan TA, Laird N, Lawthers AG, Localio AR, Barnes BA, Hebert L, Newhouse JP, Weiler PC, Hiatt H. The nature of adverse events in hospitalised patients. Results of the Harvard Medical Practice Study II. N Engl J Med. 1991;324:377–84.
24. Leape LL, Berwick DM, Bates DW. What practices will most improve safety? JAMA. 2002;288:501–7.
25. Cooper JB, Newbower RS, Long CD, McPeek B. Preventable anesthesia mishaps: a study of human factors. Anesthesiology. 1978;49:399–406.
26. Pierce EC Jr. The 34th Rovenstine Lecture: 40 years behind the mask—safety revisited. Anesthesiology. 1996;84:965–75.
27. Sax HC, Browne P, Mayewski RJ, Panzer RJ, Hittner KC, Burke RL, Coletta S. Can aviation-based team training elicit sustainable behavioral change? Arch Surg. 2009;144:1133–7.
28. Pronovost P, Needham D, Berenholtz S, Sinopoli D, Chu H, Cosgrove S, Sexton B, Hyzy R, Welsh R, Roth G, Bander J, Kepros J, Goeschel C. An intervention to decrease catheter-related bloodstream infections in the ICU. N Engl J Med. 2006;355:2725–32.
29. de Vires EN, Hollman MW, Smorenburg SM, Gouma DJ, Boermeester MA. Development and validation of the SURgical PAtient Safety System (SURPASS) checklist. Qual Saf Health Care. 2009;18:121–6.
30. Kim MJ, Fleming FJ, Peters JH, Salloum RM, Monson JR, Eghbali ME. Improvement in educational effectiveness of morbidity and mortality conferences with structured presentation and analysis of complications. J Surg Educ. 2010;67:400–5.
31. Nashef SAM. What is a near miss? Lancet. 2003;361:180–1.
32. Parsonnet V, Dean D, Bernstein AD. A method of uniform stratification of risk for evaluating the results of surgery in acquired adult heart disease. Circulation. 1989;79(6 Pt 2):I.3–12.
33. Roques F, Gabrielle F, Michel P, De Vincentiis C, David M, Baudet E. Quality of care in adult heart surgery: proposal for a self-assessment approach based on a French multicenter study. Eur J Cardiothorac Surg. 1995;9:433–40.
34. Nashef SA, Roques F, Michel P, Gauducheau E, Lemeshow S, Salamon R. European system for cardiac operative risk evaluation (EuroSCORE). Eur J Cardiothorac Surg. 1999;16:9–13.
35. Freed DH, Drain AJ, Kitcat J, Jones MT, Nashef SAM. Death in low-risk cardiac surgery: the failure to achieve a satisfactory cardiac outcome (FIASCO) study. Interact Cardiovasc Thorac Surg. 2009;9:623–5.
36. Farid S, Page A, Jenkins D, Jones MT, Freed D, Nashef SAM. FIASCO II failure to achieve a satisfactory cardiac outcome

study: the elimination of system errors. Interact Cardiovasc Thorac Surg. 2013;17:116–9.
37. McKissock W, Richardson A, Walsh L. "Posterior-communicating" aneurysms: a controlled trial of the conservative and surgical treatment of ruptured aneurysms of the internal carotid artery at or near the point of origin of the posterior communicating artery. Lancet. 1960;275:1203–6.
38. Haines SJ. History of randomised clinical trials in neurosurgery. Neurosurg Clin N Am. 2001;12:211–6, x.
39. Bekelis K, McGirt MJ, Parker SL, Holland CM, Davies J, Devin CJ, Atkins T, Knightly J, Groman R, Zyung I, Asher AL. The present and future of quality measures and public reporting in neurosurgery. Neurosurg Focus. 2015;39(6):E3.
40. Berger MS, Wachter RM, Greysen SR, Lau CY. Changing our culture to advance patient safety: the 2013 AANS Presidential Address. J Neurosurg. 2013;119:1359–69.
41. Bernstein M, Hebert PC, Etchells E. Patient safety in neurosurgery: detection of errors, prevention of errors, and disclosure of errors. Neurosurg Q. 2003;13:125–37.
42. Gerszten PC. Outcome research: a review. Neurosurgery. 1998;43:1146–55.
43. Selden NR, Ghogawala Z, Harbaugh RE, Litvack ZN, McGirt MJ, Asher AL. The future of practice science: challenges and opportunities for neurosurgery. Neurosurg Focus. 2013;34(1):E8.
44. Wong JM, Bader AM, Laws ER, Popp AJ, Gawande AA. Patterns in neurosurgical adverse events and proposed strategies for reduction. Neurosurg Focus. 2012;33(5):E1.
45. Makary MA, Mukherjee A, Sexton JB, Syin D, Goodrich E, Hartmann E, Rowen L, Behrens DC, Marohn M, Pronovost PJ. Operating room briefings and wrong-site surgery. J Am Coll Surg. 2007;204:236–43.
46. Wilson I, Walker I. The WHO Surgical Safety Checklist: the evidence. J Perioper Pract. 2009;19:362–4.
47. Stone S, Bernstein M. Prospective error recording in surgery: an analysis of 1108 elective neurosurgical cases. Neurosurgery. 2007;60:1075–82.
48. Cohen FL, Mendelsohn D, Bernstein M. Wrong-site craniotomy: analysis of 35 cases and systems for prevention. J Neurosurg. 2010;113:461–73.
49. Jhavar BS, Mitsis D, Duggal N. Wrong-sided and wrong-level neurosurgery: a national survey. J Neurosurg Spine. 2007;7:467–72.
50. Parker SL, McGirt MJ, Bekelis K, Holland CM, Davies J, Devin CJ, Atkins T, Knightly J, Groman R, Zyung I, Asher AL. The National Neurosurgery Quality and Outcomes Database Qualified Clinical Data Registry: 2015 measure specifications and rationale. Neurosurg Focus. 2015;39(6):E4.
51. Vorster SJ, Barnett GH. A proposed preoperative grading scheme to assess risk for surgical resection of primary and secondary intra-axial supratentorial brain tumors. Neurosurg Focus. 1998;4(6):E4.
52. Tomlinson SB, Piper K, Kimmell KT, Vates GE. Preoperative frailty score for 30-day morbidity and mortality after cranial neurosurgery. World Neurosurg. 2017;107:959–65.
53. Prabhakaran S, Fonarow GC, Smith EE, Liang L, Xian Y, Neely M, Peterson ED, Schwamm LH. Hospital case volume is associated with mortality in patients hospitalized with subarachnoid haemorrhage. Neurosurgery. 2014;75:500–8.
54. McLaughlin N, Laws ER, Oyesiku NM, Katznelson L, Kelly DF. Pituitary centres of excellence. Neurosurgery. 2012;71:916–26.
55. Lembitz A, Clarke TJ. Clarifying "never events" and introducing "always events". Patient Saf Surg. 2009;3:26.
56. Mathew RK, O'Kane R, Parslow R, Stiller C, Kenny T, Picton S, Chumas PD. Comparison of survival between the UK and US after surgery for most common pediatric CNS tumors. Neuro Oncol. 2014;16:1137–45.
57. Holliman D, Bernstein M. Patients' perception of error during craniotomy for brain tumour and their attitudes towards preoperative discussion of error: a qualitative study. Br J Neurosurg. 2012;26:326–30.
58. Park KB, Johnson WD, Demsey RJ. Global neurosurgery: the unmet need. World Neurosurg. 2016;88:32–5.
59. Meara JG, Leather AJM, Hagander L, Alkire BC, Alonso N, Ameh EA, Bickler SW, Conteh L, Dare AJ, Davies J, Dérivois Mérisier E, El-Halabi S, Farmer PE, Gawande A, Gillies R, Greenberg SLM, Grimes CE, Gruen RL, Ismail EA, Kamara TB, Lavy C, Lundeg G, Mkandawire NC, Raykar NP, Riesel JN, Rodas E, Rose J, Roy N, Shrime MG, Sullivan R, Verguet S, Waters D, Weiser TG, Wilson IH, Yamey G, Yip W. Global Surgery 2030: evidence and solutions for achieving health, welfare, and economic development. Lancet. 2015;386:569–624.
60. Cote DJ, Karhade AVG, Larsen AMG, Burke WT, Castlen JP, Smith TR. United States neurosurgery annual case type and complication trends between 2006 and 2013: an American College of Surgeons National Surgical Quality Improvement Program analysis. J Clin Neurosci. 2016;31:106–11.
61. Detmer DE, Fryback DG, Gassner K. Heuristics and biases in medical decision-making. J Med Educ. 1978;53(8):682–3.

Complications in Neurosurgery: General Ethical Principles for Minimizing Them and Subsequent Legal Action

Sunil K. Pandya

Abstract

Medicine and surgery carry inherent risks of inadvertent and unintended harm to the patient. Training, experience, and skill help ensure smooth recovery in most cases. However, there are circumstances beyond the control of the neurosurgeon that may predispose to complications. This review discusses steps that may help to diminish risks to the patient and can be taken before their admission to hospital, in the operating theater, and after surgery. When a complication does occur despite all care, it is essential to maintain total transparency with the patient and his or her family. It is important that they are active witnesses to the care and treatment being lavished on the individual to minimize the harm from the mishap. Should legal action follow despite such efforts, the neurosurgeon must be prepared to defend with the help of a wise, experienced lawyer and to provide evidence of his or her professional competence and the appropriateness of care offered to the patient. In any case, it is counterproductive to view every patient as a potential legal threat or indulge in defensive medical practice.

Keywords

Ethical principles · Legal defense · Medical malpractice · Medical negligence · Neurosurgical complications

Introduction

Despite our best efforts, from time to time, surgical procedures and other forms of treatment result in unexpected and unwelcome consequences. Analyzing the causes of such events, Dr. Atul Gawande [1] duly noted, "We look for medicine to be an orderly field of knowledge and procedure. But it is not. It is an imperfect science, an enterprise of constantly changing knowledge, uncertain information, fallible individuals, and at the same time lives on the line. There is science in what we do, yes, but also habit, intuition, and sometimes plain old guessing. The gap between what we know and what we aim for persists. And this gap complicates everything we do."

When the effect on the patient is mild and short lived, such as after the development of mild thrombophlebitis at the site of a venipuncture, the event is soon forgotten. Long-lasting and serious handicaps following surgical misadventure trouble both the surgeon and the patient. Death of the patient—unexpected, sudden, or during or immediately after an operation—is the ultimate disaster. The family suffers greatly, but so do the surgeon and the entire operating team. The surgeon will replay the entire operation again and again in his or her mind, pondering whether something could have been done differently to avoid the mishap, consult colleagues and seniors, and learn articles published in journals and textbooks. The surgeon self-confidence will be battered. Eventually, strength will return along with a resolve to do better the next time. Such recovery is facilitated by long years of the surgeons training; earlier experiences during complex interventions done by their seniors, peers, and themselves; and the help rendered by everyone around them. So, the surgeon will start the next operation with a heightened awareness of possible pitfalls and a renewed urge to do the best for the new patient.

What of the patient and his or her family? Much will depend on their own philosophical development and their estimation of the surgeon's capabilities. Where strong faith

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K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_26

brought them to this particular surgeon, they will attempt to view their tragedy for what it is: an accident in the best hands.

What can we, as medical professionals, do to help mitigate the shock and dismay that must, inevitably, engulf those who must live with the outcome?

Steps Before the Patient Enters the Hospital and the Operating Theater

The first encounter between the patient and the physician sets the stage for all subsequent interactions. Tense and anxious from the symptoms that trouble him or her, and worried about the gravity of the illness, the sick person faces the physician with trepidation. The physician greeting with a gentle smile and showing evidence of genuine concern about the illness puts the patient at ease. Unhurried consultation, devoting all attention to the individual during the interview, receiving a detailed account of the medical history and the evolution of symptoms, and a careful and thorough clinical examination convey volumes to the patient about the doctor's intent to help. A discussion of the probable diagnosis and the need for tests, and cautious and thoughtful answers to all questions posed by the patient and his or her family sow the seeds of trust and faith.

Good cheer, continued concern, and serene dialogue during each subsequent encounter help deepen the patient–doctor relationship. An unhurried explanation of the need for surgery, a general outline of the nature of the operation, the expected intraoperative findings, and the possible hazards, coupled with some indication of the likely prognosis, are greatly appreciated by all patients. At times, especially if the operation is hazardous, such explanations and replies to queries may be necessary more than once.

Tests to confirm fitness for surgery under general anesthesia and consultations with appropriate experts and the anesthesiologist will ensure that risks during the intervention have been kept to a bare minimum. Concomitant illnesses (e.g., diabetes mellitus, high blood pressure, or renal impairment) are best managed by appropriate specialists before, during, and after surgery.

When the patient says, "Doctor, I have no fear. I am confident I am in good hands," you know that you have met your preoperative goal.

Steps During Surgery

There are several important steps directed at avoidance of complications and their consequences, which each surgeon should take during the procedure.

"Be Prepared"

In 1907, Robert Baden-Powell, then an English soldier, devised a motto for the Boy Scouts movement he was organizing: "Be prepared." He was asked, "Be prepared for what?" His reply applies to us in our operating theaters: "Why, for any old thing!" Amplifying this statement, he said he wanted young people equipped to react quickly to an emergency. The 13th edition of the *Boy Scout Handbook* states, "He wanted every Scout to be ready in mind and body to meet with a strong heart whatever challenges await him." Another piece of advice from him can also stand us in good stead: "Smile and whistle under all circumstances." It emphasizes the need to avoid panic and base all decisions on cool calculations [2].

Humility

The Bible (Proverbs 16:19) pronounces a universal truth: "Pride goes before destruction and a haughty spirit before stumbling." We need to consider each operation afresh while using our training and experience in performing it. We are fortunate in having around us, in the operating theater, experienced professionals from other disciplines: anesthetists, nurses, and technicians. It behooves us to use their expertise for the benefit of our patient. The anesthetist monitoring the progress of the patient during surgery can provide invaluable guidance, as can the nurse who has helped in countless operations with numerous surgeons. Words of caution sounded by them must ring alarm bells and make you pause and consider the next step carefully.

Avoiding Negligence

Negligence is the basis of many legal actions against medical practitioners. Medical negligence is defined as an act (commission) or failure to act (omission) by a medical professional that deviates from the accepted standard of care and results in harm to the patient.

An act of omission may take the form of failure to obtain informed consent for surgery. Included in this is failure to explain the pros and cons of intervention and the potential hazards inherent in the operation being performed. Lapses in ensuring the safety—such as when there is insufficient insulation of electrocautery used during surgery, resulting in burns to the patient—are other examples of acts of omission.

Innovation—based on reason, experience, and experiment—is not frowned upon, but reckless and potentially hazardous adventurism has no place in the operating theater. This is an act of commission.

The phrase "accepted standard of care" carries great importance in a court of law. Such a standard is derived by the judge from recent editions of relevant medical textbooks, professional journals, and testimony given by eminent local practitioners of the relevant medical specialty. The law expects that you have performed your operation with the same skill and care that a reasonably competent neurosurgeon would have shown in your place. An error of judgment in which a competent surgeon with similar skills would not have taken a particular step is included under negligence. Operating on the wrong side of the patient, operating on the wrong patient, and removing the wrong organ are examples.

It must be emphasized that harm to the patient from an unexpected accident is not negligence. It is important, however, to ensure that everything possible is done to rectify matters after the accident.

Likewise, a complication inherent in the operation, explained to the patient and family before the operation, cannot be termed an act of negligence. Rupture of an intracranial aneurysm while the neck is being dissected falls into this category.

Performing an operation without having obtained informed consent, operating on the basis of a faulty diagnosis, performing procedures not validated by peers, unnecessary surgery, and experimentation on the patient are grounds for a charge of medical malpractice being made against the surgeon.

Importance of Checklists and Operation Notes

Dr. Gawande [3] popularized the use of checklists in the operating theater as an aid to minimizing mishaps. With his help, the World Health Organization (WHO) issued patient safety alerts along with its surgical safety checklists. It is highly recommended that each surgeon makes the use of such a checklist a standard procedure in the operating theater.

Ensure that your operation notes are detailed, listing all of the facts and providing an account of events as they occurred. If you have been able to uncover the reason for the complication, place it on record. Provide a detailed account of each step taken after the event to reduce the consequences of the complication. Record subsequent improvements (if any) in the patient's pulse, respiration, and blood pressure. At the end of surgery, make a detailed examination of the central nervous system and record your findings. They can be used for comparison with observations made during later periodic assessments. End your note with details of drugs given during surgery, fluids infused, and urine drawn out through the indwelling urinary catheter. Attach your note, with a copy of the postoperative instructions and prescription, to the patient's case file.

It is important for us to remember that in a court of law, oral accounts are not given much importance by the judges. The focus is on the patient's case notes and what was recorded therein before, during, and after surgery.

What Should One Do After a Complication Occurs During Surgery?

In the event of an intraoperative complication, the first step must be in keeping with your behavior with the patient before the admission and surgery. As soon as the operation has been completed, offer a detailed explanation to the patient and his or her family of the series of events, with a rational commentary of why there was a complication. Remain honest and truthful. Do not be evasive, shifty, or vague.

Do not shift the blame onto others, especially the junior members of the team. As was emphasized by US President Harry Truman in 1945, as you are the leader of the team, the buck stops with you.

Provide the patient and his or her family with detailed responses to queries, emphasizing that everything possible is being done to help the individual overcome the effects of the complication. Show your concern and willingness to help by your actions, such as:

1. Frequent visits to the patient.
2. Careful examination on each occasion and discussions with your colleagues, resident doctors, and nurses.
3. Bringing in other consultants who can help the patient.
4. Briefing the patient and his or her relatives after each visit, on the condition progress or lack of it.
5. Encouraging the patient's relatives to visit him or her and interact with resident doctors and nurses.
6. Willingly accepting a request from the patient or his or her family for a second opinion from another neurosurgeon, and facilitating such a consultation.

Evidence of genuine concern and sincere attempts to improve the patient's status go a long way in consoling the patient and family.

If You Are Sued …

If you are sued, do not embitter your relationship with the patient and his or her family. Treat them with the same courtesy you have displayed thus far, and freely provide all of the information they request, as you have nothing to hide.

At the same time, prepare your defense carefully, consulting an experienced and wise lawyer. Provide a testimony of your qualifications and expertise. Should you have

publications on the subject, provide reprints or photocopies. Provide a complete copy of the patient's case notes, including the consent form, the clinical findings (from the day the patient was admitted to hospital onward), your operation notes, the anesthetic chart, nurses' observations, and prescriptions. Emphasize all steps taken to provide "reasonable care."

Obtain opinions on your case from respected senior colleagues. Judges pay special attention to opinions from experts in reputed teaching hospitals. Provide photocopies from respected references on the subject (from textbooks and journals) that support your contention that the complication is well known to occur in such operations, and validation that the measures used by you to prevent and treat the complication are those in common practice.

Instead of a Conclusion: A Cautionary Note

Do not assume that every patient is a potential legal threat. Most patients and their families, who have developed trust in your abilities and faith in you as a professional, will stand by you.

The individual or family suing you may be doing so on incorrect advice or because emotion has overruled reason. Should you have the misfortune of being sued, do not fall into the error of "defensive practice" [4]. Insisting on expensive medical tests or using blunderbuss therapy penalizes all of your patients for no fault of theirs. Such behavior goes against the principle that every step taken by you when treating a patient shall be aimed at doing them good and not doing them any harm. Continue to do your best for all patients seeking your guidance and treatment. To refuse to treat a critically ill person merely because the outcome may not be favorable is to deny the chances of a cure—howsoever slim they may be—and to discard the Hippocratic injunction to "cure sometimes, treat often, care always." Such behavior also goes against Hippocrates's definition of the art of medicine: "Wherever the art of medicine is loved, there is also a love of humanity" [5].

In about 1895, Nobel Prize laureate Rudyard Kipling wrote his famous poem "If" in the form of paternal advice to his son John, which holds wisdom invaluable to all of us as well:

> If you can keep your head when all about you
> Are losing theirs and blaming it on you;
> If you can trust yourself when all men doubt you,
> But make allowance for their doubting too …
> … Or being lied about, don't deal in lies,
> Or being hated, don't give way to hating,
> And yet don't look too good, nor talk too wise …
> … Yours is the Earth and everything that's in it,
> And—which is more—you'll be a Man, my son!

Conflict of Interest Statement The author has no conflict of interest concerning the reported materials or methods.

References

1. Gawande A. Complications: a surgeon's notes on an imperfect science. New York: Metropolitan; 2002.
2. Wendell B. Be prepared: the origin story behind the scout motto. Bryan on Scouting: A Blog for the BSA's Adult Leaders. 8 May 2017. https://blog.scoutingmagazine.org/2017/05/08/be-prepared-scout-motto-origin/. Accessed 14 Jan 2018.
3. Gawande A. The checklist manifesto: how to get things right. New York: Henry Holt; 2009.
4. Ortashi O, Virdee J, Hassan R, Mutrynowski T, Abu-Zidan F. The practice of defensive medicine among hospital doctors in the United Kingdom. BMC Med Ethics. 2013;14:42.
5. Hippocrates. The genuine works of Hippocrates. Translated from the Greek with a preliminary discourse and annotations by F. Adams; in two volumes. London: Sydenham Society; 1849.

Preventing Medicolegal Problems in Neurosurgical Practice: Do's and Don'ts

Lalit Kapoor

Abstract

There is a sea change in the scenario of medical practice, manifested in a serious trust deficit between patients and doctors and an exponential rise in malpractice litigation. This has given boost to the practice of defensive medicine by doctors. Neurosurgery is considered to be a high-risk branch of surgery in terms of potential for medicolegal issues. It is inevitable that as a response to these changes, we should identify the potential problem areas and adopt measures to deal with them. Practicing ethical, rational, and evidence-based medicine can minimize medicolegal problems. It is suggested to avoid treating patients beyond one's competence. In this review, the concept of negligence is defined, and the common allegations and causes of litigation in neurosurgical practice are identified. The importance of keeping meticulous patient records in preventing medicolegal problems is emphasized. The value of obtaining informed consent and operation-specific consent is highlighted. It is advised not to overpromise the results of treatment. The roles of effective communication and display of empathy toward treated individuals are important factors in averting litigation by them. Communication failure results in breakdown of the doctor–patient relationship. The protective value of professional liability insurance to deal with potential problems is stressed. Finally, the practice of "jousting," or badmouthing a colleague, is strongly condemned, as it can provoke malpractice litigation.

Keywords

Complication · Medicolegal problems · Neurosurgery

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Introduction

Medicolegal liability is now an increasingly challenging reality for all doctors and health care establishments [1]. Never before in the history of the medical profession have we witnessed the kind of hostility and aggression against doctors and/or hospitals as are evident today. A quick review of the current scenario of medical practice would reveal the tremendous metamorphosis and sea change that have taken place over the years in the way we practice medicine now. The aura of infallibility of doctors and their demigod status is a thing of the distant past. The public's expectations of doctors and medical science have risen sharply, even unrealistically at times, in the era of high-tech medicine. The new buzz words are "quality assurance," "accountability," "medical audit," "accreditation," and so on—words that doctors thought were not applicable to them. There is also a widespread emergence of consumerism all over the world, resulting in fallout on the medical profession. In 1985, the medical profession in India was brought under the jurisdiction of the Consumer Protection Act (CPA), whereby a patient was equated to a consumer, no different from a consumer of goods, with the same consumer laws being applicable. This has been the single most important cause of the exponential rise in medical litigations in India. Huge compensation awards by the courts have now become the order of the day.

There is an increased frequency of doctors facing criminal charges and even being sentenced to jail terms for medical negligence. Incredibly, more often than not, doctors are treated as common criminals even in cases of alleged "medical negligence," which may simply have been some sort of complication or, at worst, an error of judgment. Any unfavorable outcome of treatment could be labeled "medical negligence" and become the subject of litigation under the heading "deficiency of service" in the parlance of the consumer laws.

Physical violence against doctors and hospitals following mortality or even morbidity in a patient is not uncommon now. There is unprecedented doctor bashing by the print and

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6_27

electronic media, which invariably conduct media trials of alleged offenses of medical negligence. In effect, the media acts as a plaintiff, prosecutor, jury, judge, and executioner all rolled into one!

Consequently, there has been a steady erosion of the doctor–patient relationship. The mutual trust between patients and doctors is being replaced with mutual suspicion. This serious trust deficit has led to the practice of what is known as "defensive medicine," where every patient is viewed as a potential plaintiff, and investigations and procedures are ordered by the doctor not so much because they are needed to treat the patient, but to protect the doctor in the event of allegations of malpractice!

The Need to Adopt Preventive Measures

As Charles Darwin said, "It is not the strongest of the species that survives nor the most intelligent but the one most responsive to change."

Medical malpractice litigation is one of the most stressful events in the life of any physician [1, 2]. Neurosurgery is one of the most difficult branches of surgery, and neurosurgeons are considered a high-risk group in terms of medicolegal liability. This is reflected in their higher malpractice insurance premiums. In view of the prevailing scenario of medical practice, as outlined above, it is inevitable that we adopt measures to cope with changing societal and legal norms. We need to identify the potential problem areas and learn how to deal with them, just as we need to familiarize ourselves with the laws relevant to medical practice in our geographical area.

The Concept of Negligence

The simplest definition of medical negligence is "deviation from accepted standards of medical practice, as a result of which harm results to the patient."

To prove a charge of negligence against a doctor, the plaintiff (the patient or their relative) must prove the following four elements:

1. The doctor owed the patient a duty of care.
2. There was a breach of that duty.
3. The breach resulted in injury.
4. Damage was caused as a result of the injury.

The burden of proof lies on the complainant, and all of the above four elements must be established.

The Bolam Test

A doctor is not guilty of negligence if they have acted in accordance with a practice accepted as proper by a responsible body of medical professionals skilled in that particular branch of medicine, even if there may be a body of opinion that would take a contrary view. The doctor would not be at fault if he or she had done what other doctors would have done in the same or similar circumstances.

Common Causes of Malpractice

The most common causes of malpractice litigation in neurosurgical practice include the following:

- Missed diagnosis
- Delayed diagnosis
- Failure or delay in referring a patient
- Anesthesia errors and mishaps
- Surgical injuries
- Wrong-site surgery
- Postoperative complications
- Medication errors
- Lack of informed consent
- Failure to communicate with the patient

The Importance of Keeping Patient Records

The importance of good patient records in preventing medicolegal problems cannot be overemphasized. Good records are critical to the delivery of safe, competent, and quality medical care. Good records are the best defense against medical negligence. Records that are correct, clear, comprehensive, chronological, and contemporaneous inspire confidence in the treatment given to the patient and denote diligence. On the other hand, shoddy and inaccurate records denote shoddy treatment! That's how judges look at it; therefore, that's how important records are.

Poor records also invite adverse inference from the courts. In law, there is a dictum: Justice should not only be done but also be seen to be done. To draw a parallel in medicine, it can be said that diligent and competent treatment should not only be given to the patient but also be seen to be given. What better way can there be to do this than to maintain good patient records? And, in any case, we ought to remember that, legally, "What is not documented never happened!"

Informed Consent

Ever since the paternalistic model of the doctor–patient relationship was discarded and the model of patient autonomy was adopted, it has become mandatory for doctors to obtain informed consent from the patient before carrying out any procedure or operation [1, 3]. In fact, it is mandated by law. Failure to obtain informed consent is considered negligence *per se*. Good informed consent encourages a relationship of collabora-

tion between the physician and the patient, and it highlights their mutual responsibility for medical decision-making.

Obtaining Informed Concept: Five Do's

When obtaining informed concept, it is necessary to be sure that the patient understands:

- The nature of his or her condition
- The alternative procedures or treatment
- The nature of the proposed treatment
- The risks of the proposed or alternative procedures
- The chances of success or failure of the treatment

Obtaining Informed Concept: Five Don'ts

When obtaining informed concept, do not inform the patient of the following:

- That you are going to do a routine procedure (because none are routine)
- That the procedure is simple
- That no complications will occur (because complications can and do occur)

In addition, do not omit to record denial of consent or refusal to consent, and do not fail to inform the patient of the approximate cost of the treatment.

The Importance of Operation-Specific Consent

Gone are the days when blanket consent used to be taken without referral to the specific operation that was going to be performed. Obtaining operation-specific consent is now necessary. Excellent consent forms for almost all operations have been designed and are available. For example, consent forms for burr holes, ventriculoperitoneal shunts, anterior skull base lesion surgery, craniotomy, minimally invasive microdiscectomy, open lumbar discectomy, brain biopsy, and so on can easily be downloaded from medical resources.

Typically, an operation consent form will include the following sections:

- A brief description of the procedure
- The risks of the procedure, including (1) common risks and complications; (2) uncommon risks and complications; and (3) rare risks and complications
- Significant risks and procedure options (with a blank space in which to write special risks and benefits specific to the patient)
- The risks of not getting operated on
- The type of anesthesia and its risks

The Importance of Communication

It is important to remember that simply obtaining the patient's signature on the dotted line on a standard preprinted informed consent form does not constitute informed consent and does not provide you with complete legal protection. Proper communication should have actually transpired between the surgeon and the patient, and this should have been documented. The patient should have understood what the physician said.

The Role of Good Communication Skills in Preventing Medicolegal Problems

It is well-known that a good many malpractice suits have their origin in poor communication or apathy on the part of the surgeon. Communication failure results in breakdown of the doctor–patient relationship. An unanswered question of a patient or relative often leads to anxiety, aggravation and anger which eventually lead them to an advocate, a social worker or a media person.

Many studies have indicated that there is a need for improvement of the communication skills of neurosurgeons [1, 4]. This can help patients effectively participate in their recovery process and accept less than optimal outcomes of treatment.

A common complaint from patients is that doctors do not listen. In fact, listening is the key to good communication. And, by the way, the mere fact that we can hear does not mean we know how to listen! Listening is a skill that we must learn and practice in order to become good communicators. Also, most patients do not only expect their neurosurgeon to be capable and confident; they also expect compassion from the surgeon, as reflected in their communication style, both verbal and nonverbal. Patients would like their neurosurgeon to come across as humane. This is one important aspect that would most certainly lower the incidence of malpractice claims.

Provocation by Colleagues

A fair proportion of malpractice litigation is prompted by adverse comments from fellow colleagues, who may happen to be consulted after some posttreatment complications in your patient. This is known as "jousting" and is said to occur when one health care professional makes critical comments about another care provider, directly or indirectly, either to the patient or in the medical record. Simply put, it is nothing but bad-mouthing or speaking ill about your colleague. It can have the effect of provoking a malpractice suit against the concerned doctor.

Jousting is something that should never be done, even though it may please the patient. On hearing the patient's

version, it may be easy to jump to conclusions without knowing his or her treatment history in full. If doctors were to resist the temptation of jousting, the incidence of malpractice litigations could drop considerably.

Professional Liability/Indemnity Insurance

Despite taking all precautions, one may still face a malpractice claim by a patient. It is therefore imperative that the doctor has adequate professional indemnity cover through a reputed insurance carrier after carefully studying the terms and conditions. This would mitigate a lot of the related problems and help to address the malpractice crisis a lot better.

Conclusion

In the author's experience, there are 11 mantras to avoid malpractice litigation [1]:

1. Practice ethical, rational, and evidence-based medicine.
2. Do not undertake to treat patients beyond your competence or the medical infrastructure available to you.
3. Ensure meticulous keeping of patient records as a routine.
4. Adhere to guidelines for taking informed consent from patients, and make operation-specific consent a norm.
5. Do not overpromise the results of treatment.
6. Work on developing good communication skills.
7. Avoid vicarious liability by judicious selection of staff.
8. Update your knowledge and upgrade infrastructural facilities.
9. Make sure you have adequate professional liability insurance.
10. In indefensible cases, consider a prelitigation settlement, i.e., alternative dispute resolution (ADR).
11. Resist the temptation of jousting; you may be on the receiving end sooner than you think!

Remember: The best way to deal with medicolegal problems is to prevent them! It's better to be safe than sorry!

Conflict of Interest Statement The author has no conflict of interest concerning the reported materials or methods.

References

1. Kapoor L. Better safe than sorry: medico-legal do's & don'ts. Mumbai: Association of Medical Consultants; 2005.
2. Nahed BV, Babu MA, Smith TR, Heary RF. Malpractice liability and defensive medicine: a national survey of neurosurgeons. PLoS One. 2012;7(6):e39237.
3. Singh D, Tanshi D. Consent taking in neurosurgery: education and tips for safe practice. Neurol India. 2016;64:742–50.
4. Rozmovits L, Khu KJ, Osman S, Gentili F, Guha A, Bernstein M. Information gaps for patients requiring craniotomy for benign brain lesion: a qualitative study. J Neurooncol. 2010;96:241–7.

Author Index

K. E. Turel et al. (eds.), *Complications in Neurosurgery*, Acta Neurochirurgica Supplement 130,
https://doi.org/10.1007/978-3-030-12887-6