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Assessment of Factors Associated With Internal Carotid Injury in Expanded Endoscopic Endonasal Skull Base Surgery

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IMPORTANCE Injury to the internal carotid artery (ICA) during endoscopic endonasal skull base surgery does not typically occur as an isolated circumstance but often is the result of multiple factors.

OBJECTIVE To assess the factors associated with ICA injury in an effort to reduce its occurrence.

DESIGN, SETTING, AND PARTICIPANTS This quality improvement study used a multicenter root cause analysis of ICA injuries sustained during endoscopic endonasal skull base surgery performed at 11 tertiary care centers across 4 continents (North America, South America, Europe, and Asia) from January 1, 1993, to December 31, 2018. A fishbone model was built to facilitate the root cause analysis. Patients who underwent an expanded endoscopic endonasal approach that carried a substantial potential risk of an ICA injury were included in the analysis. A questionnaire was completed by surgeons at the centers to assess relevant human, patient, process, technique, instrument, and environmental factors associated with the injury.

MAIN OUTCOMES AND MEASURES Root cause analysis of demographic, human, patient, process, technique, instrument, and environmental factors as well as mortality and morbidity data.

RESULTS Twenty-eight cases of ICA injury occurred during 7160 expanded endoscopic endonasal approach procedures (incidence of 0.4%). The mean age of the patients was 49 years, with a female to male predominance ratio of 1.8:1 (18 women to 10 men). Anatomical (23 [82%]), pathological (15 [54%]), and surgical resection (26 [93%]) factors were most frequently reported. The surgeon's mental or physical well-being was reported as inadequate in 4 cases (14%). Suboptimal imaging was reported in 6 cases (21%). The surgeon's experience level was not associated with ICA injury. The ICA injury was associated with use of powered or sharp instruments in 20 cases (71%), and use of new instruments or technology in 7 cases (25%). Two patients (7%) died in the operating room, and 3 (11%) were alive with neurological deficits. Overall, patient-related factors were the most frequently reported risk factors (in 27 of 28 cases [96%]). Factors associated with ICA injury catalyzed a list of preventive recommendations.

CONCLUSIONS AND RELEVANCE This study found that human factors were associated with intraoperative ICA injuries; however, they were usually accompanied by other deficiencies. These findings suggest that identifying risk factors is crucial for preventing such injuries. Preoperative planning and minimizing the potential for ICA injury also appear to be essential.

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Supplemental content

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The expanded endoscopic endonasal approach (EEA) was introduced to the armamentarium of skull base surgery during the 1990s. This procedure enables alternative ventral trajectories to select median and paramedian lesions of the anterior, middle, and posterior cranial fossae.[1] It has enabled approaching deep-seated lesions while diminishing the risks and complications associated with traditional external approaches.[2,3]

Nonetheless, risks to neurovascular structures remain. Furthermore, control of vascular injuries is more complex because of the EEA's narrow corridor and need for specialized instruments. Injury to the internal carotid artery (ICA) during skull base surgery may lead to catastrophic morbidity and mortality. In traditional open skull base surgery, the incidence of ICA injury hovers between 3% and 8%.[4] During routine endoscopic sinus operations, the event is extremely rare (<1%), appearing in the literature mostly as case reports. In contrast to sinonasal surgery for inflammatory disease, the EEA often implies the need for wide surgical exposure and, although still uncommon, is associated with a higher rate of injury.[5,6]

Single-institution reports of intraoperative endoscopic endonasal ICA injury are sparse owing to their rarity, with the largest series to date including 14 injuries.[7] However, as with other catastrophic events, ICA injury is likely underreported. Therefore, understanding its incidence and etiologic factors is limited by both the infrequency of the event and the limited available data in the literature.

Prevention of ICA injury is the best strategy for avoiding any devastating complication. However, this strategy requires identification of all possible causes by robust, thoughtful, and objective analysis. Root cause analysis can assist in guiding a comprehensive, system-based approach to a particular event.[8] Its goal is to understand what happened, why it occurred, and how to prevent it. Therefore, this study used root cause analysis to survey the many factors associated with an ICA injury during EEA.[9-11]

Methods

We performed a retrospective multi-institutional quality improvement study using root cause analysis of all EEA procedures associated with intraoperative ICA injuries from January 1, 1993, to December 31, 2018, at 11 tertiary care centers across 4 continents (North America, South America, Europe, and Asia). This study was approved by the institutional research ethics committee at each participating center. Consent was waived because of the retrospective nature of the study. All cases were deidentified for patient and institutional data.

To determine the denominator to calculate the true ICA injury incidence, we included only those patients who underwent an EEA procedure that involved a substantial potential risk of an ICA injury (ie, lesions along the anatomical course of the ICA). Patients who underwent resections with a low potential for injury (eg, transfrontal, transcribriform, and transodontoid approaches) were excluded. Postoperative ICA lesions, those associated with microscopic or open approaches, and those with incomplete data were also excluded. The study, however, was not constructed to provide a nuanced incidence but to analyze the factors associated with the event.

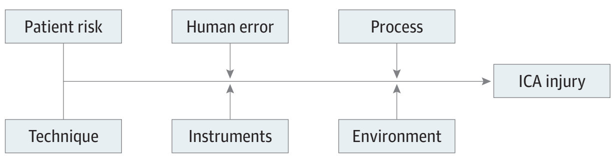
Key Points

Question What are the factors associated with internal carotid artery injury in endoscopic endonasal skull base surgery?

Findings In this multicenter quality improvement study that analyzed 28 cases of internal carotid artery injury sustained during endoscopic endonasal skull base surgery, the incidence of injury was 0.4%. All cases were associated with 1 or more of the identified risk factors; however, patient-related factors were reported most frequently (in 96% of cases).

Meaning Results of this study suggest that internal carotid artery injury during endoscopic endonasal skull base surgery is rare and has multifactorial origins.

Figure. Fishbone Diagram Connecting All Possible Factors to the Outcome of Internal Carotid Artery (ICA) Injury



Root Cause Analysis

To investigate the genesis of the ICA injuries, we conducted a root cause analysis aided by a fishbone diagram (**Figure**). Multiple factors (subcauses) were grouped under major categories to dissect the association of specific factors with the outcome. Factors were categorized as follows, according to their potential association with the injury (**Box 1**): (1) patient risks: anatomical factors, pathological condition characteristics, and previous treatments; (2) human errors: mistakes and oversights by surgeons or operating staff; (3) process deficiencies: preparation of the patient and planning of the surgical procedure with goals and expectations; (4) techniques: surgical technique and intraoperative proficiency; (5) instruments: specific tools, type and setup of instruments, and other surgical devices; and (6) environment and situation: operating room (OR) logistics and setup in relation to the ICA injury.

A questionnaire with pertinent fields in a case report form was distributed to surgeons at the centers to assess these factors. To encourage transparent and candid accounts and to follow privacy and confidentiality protocols, we expurgated any identifiable data from patients, surgeons, and hospitals. Individual case results were not distributed; however, summaries and noncensored data were shared to enable us to reach consensus recommendations.

Results

The survey revealed a total of 28 ICA injuries that occurred in 7160 cases for an incidence (range) of 0.4% (0.001%-2.5%). The

Box 1. Categories and Potential Multiple Factors in Internal Carotid Artery (ICA) Injury

Patient Risks
Age
Sex
Diagnosis
Anatomical risks
Pathological risks
Surgical resection risks

Human Errors
Surgeon's experience
Imaging interpretation
Surgeon's experience
Surgical team
Surgeon's condition
Nurses

Process Deficiencies
ICA injury protocol
ICA injury expectancy
Multidisciplinary team approach

Techniques
Inadequate imaging
Use of surgical navigation devices
Intraoperative imaging
Bloody surgical field
Inadequate exposure

Instruments
Sharp or blunt manual or powered instruments
Type of instrument
Improper device setup
Use of new or unfamiliar instruments or technology

Environment or Situations
Operating room location
Intraoperative distractions
Operating room logistics

Box 2. Characterization of 28 Internal Carotid Artery (ICA) Injuries

Pathological Condition
Pituitary adenoma (14 [50%])
Clival chordoma (4 [14%])
Sinonasal malignant neoplasm (3 [11%])
Juvenile angiofibroma, skull base fibromatosis, craniopharyngioma, meningioma, epidermoid cyst, unclassified malignant neoplasm (1 [4%])

Location of ICA Injury
Parasellar ICA (17 [61%])
Paraclival ICA (7 [25%])
Parapharyngeal and paraclinoid segments (2 [7%] each)

Site of ICA Injury
Left side (18 [64%])
Right side (10 [36%])

Timing of ICA Injury
Approach (16 [57%])
Lesion resection (12 [43%])

Type of Instrument
Sharp; manual or powered (20 [71%])
Blunt (8 [29%])

Name of Instrument
Powered instrument (9 [32%])
- Fine diamond burr drill (2 [7%])
- Coarse diamond burr drill (5 [18%])
- Cutting burr drill (1 [4%])
- Microdebrider (1 [4%])

Sharp scissors (4 [14%])
Blakesley forceps (4 [14%])
Thermal injury (3 [11%])
- Bipolar (2 [7%])
- Monopolar (1 [4%])

Rongeur (3 [11%])
Blunt dissector (2 [7%])
Ball probe (2 [7%])
Ultrasonic bone aspirator (1 [4%])

New Instrument or Technology
Drill (3 [11%])
Ultrasonic bone aspirator (1 [4%])
Rongeur (1 [4%])
Microdebrider (1 [4%])
3-Dimensional endoscope (1 [4%])

predominant target lesion was a sinonasal or skull base tumor, representing the main indication for a surgical procedure in all but 1 patient, who presented with invasive fungal sinusitis (**Box 2**). The mean age of the patients was 49 years, with a female to male ratio of 1.8:1 (18 women to 10 men). Characteristics of the site of ICA injury can be found in Box 2.

Anatomical or Disease-Related Factors

Anatomy-related risk factors included morphological variations of the ICA that could predispose a patient to ICA injury. Most patients (23 of 28 [82%]) had 1 or more anatomy-related risks.

Surgical risks included factors associated with the surgical decision and extent of resection. Most patients in this cohort (26 of 28 [93%]) had 1 or more surgical risk factors. A pathological risk factor for bleeding was found in 15 of 28 (54%) injured patients. **Table 1** summarizes the subcauses of the patient-related factors. Overall, 27 of 28 ICA injuries (96%) were associated with 1 or more patient-related risk factor; the exception was 1 case that involved a seemingly straightforward pituitary microadenoma that sustained an ICA injury by a neurosurgical postgraduate year 5 trainee (inexperience was the only identifiable risk).

Table 1. Patient Risk Factors for Internal Carotid Artery Injury

Category	Potential Risk Factors
Anatomical	Dehiscent ICA canal
	Bulging of the vessel
	ICA displaced by the lesion
	Sphenoid septa with attachment to the ICA canal
	Distance between ICAs[a]
	Vessel wall abnormality, such as thinning or fibrosis from previous trauma or treatment, aneurysm, pseudoaneurysm, or fistula[a]
Pathological	Tumor histologic structure[a]
	Previous surgical procedure (scar, graft, flap, fibrosis)
	ICA wall infiltration evident by imaging or intraoperative observation[a]
	Postradiotherapy
	History of bromocriptine therapy
Surgical resection	Radical resection for curative intent[a]
	Tumor encircling ICA>120°[a]
	Need for wide exposure of ICA[a]

Abbreviation: ICA, internal carotid artery.

[a] Indicates high-risk factors.

Human Errors

Inadequate preoperative assessment of imaging studies was reported in 3 cases (11%). In 2 patients (7%), the risk of injury was underestimated by both the surgeon and the radiologist, and an additional patient (4%) lacked a magnetic resonance imaging scan.

Surgeons reported performing EEAs for a mean (range) period of 8 (1-21) years and a median (range) number of 80 (15-1500) cases before experiencing their first ICA injury. Five surgeons (2 faculty and 3 trainees) encountered an ICA injury in their first year of EEA experience.

The ICA was injured by a senior surgeon (faculty level) in all but 3 patients, who were injured by trainees (1 neurosurgery postgraduate year 5 resident and 2 rhinology fellows). Two of the trainees worked in the same institution. Two of the 3 junior surgeons were under the direct supervision of an attending physician at the time of injury. In the remaining case, the attending physician was not in the OR during the incident.

A 2-team approach, comprising an otolaryngologist (head and neck surgeon or rhinologist) and a neurosurgeon, was used in 22 of 28 patients (79%). Conversely, the injury occurred in a single-surgeon scenario in 6 of 28 patients (21%). Agreement between the 2 surgeons to perform the surgical step that led to the injury was found in 21 of 28 cases (75%); conversely, hesitancy and second thoughts were reported in 7 of 28 cases (25%).

The surgeon's fitness during the procedure was addressed by reporting physical and mental status, presence of any sickness, sleep deprivation, emotional stress, hunger, tiredness, just returning from travel or still feeling jet lag, first day after vacation, and rushing during the procedure. Four injuries (14%) were associated with the presence of 1 or more of these factors. These surgeons reported tiredness or hunger associated with prolonged surgical time. Surgeons documented competent scrub nurses in all cases except 1 (4%), in which the injury and its management had some association with the nurse's limited experience.

Process-Related Factors

Seven of 11 institutions or teams (64%) reported not having a protocol for ICA injury in the OR before the first case event. Each team reported the preoperative risk of ICA injury on the basis of the aforementioned risk factors, estimating a low risk in 36%, medium risk in 25%, and high risk in 39% of cases. Most cases were discussed preoperatively in multidisciplinary meetings; however, 5 of the 28 cases with an ICA injury (18%) were not.

Technology-Related Factors

Six surgeons (21%) reported inadequate preoperative imaging either because of the inadequate quality of the images or the inability to obtain critical imaging. Image guidance systems were used in 15 cases (54%). Similarly, an acoustic Doppler was available but was not used routinely, even for high-risk cases (54% of the cases). None of the users of image guidance systems reported that the injury was the result of incorrect information or high margin of error. In 7 cases (25%), the surgeons reported that the use of intraoperative imaging (computed tomography or magnetic resonance imaging) would have helped prevent the ICA injury.

Surgeons related that ICA injuries were associated with a narrow corridor and inadequate exposure in 3 patients (11%). The surgical field was described as bloody just before the injury in 4 cases (14%) and mostly (3 of 4 cases) during the approach and not the resection.

Instrument- or Technology-Related Factors

Most ICA injuries (20 [71%]) were associated with the use of powered or sharp instruments (Box 2), with a high-powered drill reported in 8 of 20 events (40%). In 7 cases (25%), the injury occurred during the use of new or prototype instruments or technology.

Environmental or Situational Factors

Surgical orientation and situational control of the OR environment are critical surgical factors, especially in complex procedures. Surgeons reported that all but 3 ICA injuries (89%) occurred while operating in their usual room. In 3 exceptions (11%), the surgeon was operating in a different country and/or a new OR. However, the ORs were reported as spacious and adequate; in all cases, no distractions were present, such as chatter, music, pagers, or anything different from the usual setting, except in 1 case (4%). In this case, the OR staff was distracted by observers, and the surgeon reported being disturbed by the chatter.

Outcomes

Surgeons used various methods to control the bleeding. Packing was reported in only 10 cases (36%), use of a muscle patch in 15 cases (54%), and use of a transcervical carotid ligation in 3 cases (11%). Use of a muscle patch was reported as early as 2002.

Table 2. Recommendations for Cases at High Risk for Internal Carotid Artery Injury

Case	Event Description	Recommendations
1	During the approach for a GH-secreting microadenoma, the left paraclival ICA was injured with a fluted drill tool.	• Avoid using fluted or cutting burrs.
2	During the approach for a GH-secreting pituitary adenoma, the left parasellar ICA was injured with a coarse diamond drill tool.	• Be careful drilling near the ICA by experienced surgeon or trainee. • Be aware that coarse diamond burrs may have fragments or spikes that extend beyond the visualized spinning core.
3	During the approach for a nonfunctional pituitary adenoma, the right parasellar ICA was injured with a sharp instrument.	• Avoid monopolar diathermy of sellar dura, which may injure or weaken the ICA wall. • Be aware that CTA may aid in identification of anatomic ICA variants. • Be aware that image guidance may aid in ICA identification and may be particularly useful for inexperienced surgeons.
4	During the approach for a nonfunctional pituitary adenoma, the right parasellar ICA was injured during the approach with sharp scissors.	• Avoid sharp instruments within operative blind spots. • Be aware that preoperative multidisciplinary team discussion and intraoperative multidisciplinary approach may help in navigating challenging anatomic variants.
5	During a transpterygoid transphenoidal approach and optic nerve decompression for aggressive skull base fibromatosis, the left parasellar ICA was injured with a large Kerrison rongeur.	• Be aware that high-quality CT and use of image guidance may help to identify the ICA and may be particularly useful for cases with distorted anatomy. • Use appropriately sized instruments.
6	During a transphenoidal approach for an undiagnosed skull base mass, the left parasellar ICA was injured by grasping with Blakesley forceps.	• Ensure wide surgical exposure. • Do not grasp or avulse tissues over the ICA. • Be aware that image guidance and intraoperative Doppler may aid in ICA identification in high-risk cases.
7	During the approach for a craniopharyngioma, the left parasellar ICA was injured by grasping with Blakesley forceps.	• Do not grasp or avulse tissues over the ICA. • Avoid distractions during high-risk cases.
8	During a transclival approach for primary chordoma performed emergently owing to the development of a third nerve palsy, the right paraclival ICA was injured with a coarse diamond drill.	• Be aware that coarse diamond burrs may have fragments or spikes that extend beyond the visualized spinning core. • Avoid high-risk cases if possible when returning from extended travel.
9	During a transclival approach for recurrent chordoma, the left parasellar/cavernous ICA was injured with a blunt ball-tip probe.	• Be aware that even blunt instruments may injure an ICA weakened by a previous surgical procedure and proton radiotherapy.
10	During the transsellar approach for recurrent large granular tumor of the pituitary, the right parasellar ICA was injured while removing bone with ultrasonic bone aspirator.	• Avoid using new equipment on a challenging revision case. • Consider an alternative tip without pointed prongs or a diamond high-speed drill. • Be aware that intraoperative Doppler may help in identifying the ICA.
11	During a transsellar approach for apoplectic pituitary adenoma, the left parasellar ICA was injured while stripping the mucosa with grasping forceps.	• Carefully dissect sphenoid mucosa before removal, and confirm the integrity of bone by palpation. • Suction traction to carefully elevate from known bony dehiscence.
12	During a transsellar approach for a pituitary adenoma, the left parasellar ICA was injured with a coarse diamond drill.	• Pay attention to ICA localization based on anatomic landmarks and image guidance. • Be aware that image guidance and intraoperative Doppler may aid in ICA identification.

(continued)

Two patients (7%) died in the OR, and 1 (4%) died of a heart attack within 24 hours of the ICA injury. All surviving patients underwent postoperative angiography. Angiography was followed by embolization in 14 cases (50%), endovascular stenting in 6 cases (21%), and no further intervention in 8 cases (29%).

Twenty-two patients (78%) survived without neurological deficits, 3 (11%) were alive with neurological deficits, and 3 (11%) died. The mean (range) follow-up time for the cohort was 6.5 (2-20) years.

Discussion

A fishbone diagram helps in identifying factors, graphically connecting them to an outcome. Major categories in the diagram are suggested by analysis and brainstorming according to the nature of the event. Therefore, each major category in the diagram represents a source of problems that may contribute to the event. Multiple factors (subcauses) are grouped under major categories to enable the dissection and analysis of the association of each specific factor to the outcome. This method is widely used in the investigation of unexpected or undesirable events in many industries, including aviation, ground transportation, manufacturing, marketing, and health care.

A study of aviation maintenance concluded that 90% of quality lapses are blameless.[12] Appropriate error analysis requires identification of not only human causes but also systems causes. Root cause analysis is a method of comprehensively assessing all possible factors associated with the event. Afterward, an action plan can be implemented to prevent the reoccurrence of the event. The present study identified 1 or more patient-related risk factors in 96% of ICA injuries. Other studies have described the risk factors of ICA injury.[13,14] Identification of such factors can help to improve preparation, maximizing precautions and activating preventive and management measures. When the case is considered high risk, the surgeon must minimize all listed factors.

Progressive learning (ie, the learning curve) has a pronounced association with major complications and outcomes.[15] In certain events, such as cerebrospinal fluid leaks, the learning curve has been quantified. Smith et al[16] and Snyderman and Gardner [17] described the learning curve and a break point in the number of cases. However, this type of analysis for ICA injury is difficult because of its paucity. The present study did not confirm an association between the surgeon's years of experience or number of performed cases and ICA injury. How-

Table 2. Recommendations for Cases at High Risk for Internal Carotid Artery Injury (continued)

Case	Event Description	Recommendations
13	During a skull base approach for invasive fungal, the second genu of the left ICA was injured at the foramen lacerum while drilling the clivus and basisphenoid with a coarse diamond drill.	• Be aware that image guidance may not be accurate, providing an erroneous impression of the anatomy.
14	The inferior hypophyseal artery was coagulated with bipolar electrocautery; however, the artery stuck to the forceps and was avulsed, resulting in injury of the right parasellar ICA at the origin of the inferior hypophyseal artery.	• Be aware that irrigation while performing bipolar electrocauterization may prevent tissue adherence to the forceps.
15	During the tumor resection a nonfunctional pituitary adenoma, via transpterygoid, transsellar approach, the left parasellar ICA was injured with a blunt dissector.	• Be aware that tumors in patients with a history of surgical procedure and radiation therapy and who are strictly adherent to the ICA adventitia carry an increased risk of ICA injury. • Be aware that even blunt instruments may injure a weakened or infiltrated ICA.
16	At the end of the tumor resection for low-grade adenocarcinoma of the parapharyngeal space, via transpterygoid approach, the right parapharyngeal ICA was injured with a high-speed drill (diamond burr).	• Be aware that Doppler acoustic ultrasound is operator dependent and thus may provide an erroneous impression of the anatomy (no instrument is foolproof). • Be aware that intraoperative imaging may be beneficial after extensive tumor resection to identify remaining tumor or changes in location of critical neurovascular structures. • Consider staging lengthy cases to avoid fatigue.
17	During tumor resection for a nonfunctional pituitary adenoma, the right parasellar ICA was injured with a diamond burr drill.	• Reduce distractions. • Use extra precautions when using new equipment.
18	During a transclival, transpterygoid approach for a recurrent chordoma, the left paraclival ICA was injured while using monopolar electrocautery for dura retraction.	• Be aware that monopolar diathermy may injure or weaken ICA wall.
19	During a transpterygoid approach for a pituitary adenoma, the left paraclival ICA was injured during removal of the sphenoid mucosa with grasping forceps.	• Carefully dissect sphenoid mucosa before its removal. • Carefully perform mucosal dissection and suction traction in the settings of bony dehiscence. • If the ICA is not visualized clearly, use image guidance or intraoperative Doppler to confirm location.
20	During tumor removal after a transclival approach for primary chordoma, the left paraclival ICA was injured with blunt instrumentation during the dissection of a tumor from the ICA.	• Be aware that ICAs that are encircled or infiltrated by tumor may be prone to injury even during blunt dissection.
21	During tumor removal after a transsellar approach for GH-secreting pituitary adenoma, the right cavernous ICA was injured with microscissors.	• Thoroughly perform imaging review before any skull base case. • Consider using blunt instrumentation if insecure or hesitant with sharp dissection (which decreases but does not eliminate risk). • Be aware that Doppler acoustic ultrasound is operator dependent and thus may provide an erroneous impression of the anatomy or fail to reveal aberrant anatomy.
22	During the approach for a nonfunctional pituitary adenoma, the left parasellar ICA was injured with a coarse diamond drill.	• Heed concerns voiced by any team member. • Avoid unfamiliar drills on bone overlying the ICA. • When drilling over the ICA, use wide feathering rather than focal drilling.
23	During a transplanum approach for a meningioma of the optic nerve, the left paraclinoid ICA was injured with a Kerrison rongeur.	• Avoid high-risk cases in instances of multiple new variables (ie, new country, new team member, or new OR/equipment). • Avoid rongeur of an intact ICA or optic canal (thin walls with drill to facilitate fracturing and removal). • Be aware that image guidance and intraoperative Doppler may aid in ICA identification in high-risk cases.
24	During the tumor resection after a transpterygoid approach for adenocarcinoma, the right paraclival ICA was injured with a microdebrider.	• Avoid use of microdebriders near the ICA. • Be aware that intraoperative imaging may be beneficial after extensive tumor resection to identify remaining tumors or changes in location of critical neurovascular structures.
25	During the transpterygoid approach for JNA, the left cavernous ICA was injured with sharp scissors.	• Be aware that a multidisciplinary team approach may help in navigating challenging and high-risk cases. • Maintain hemostasis for maximal visualization.
26	During resection after a transtuberculum transsellar approach, a right intradural ICA feeder was injured with a ball probe.	• Avoid high-risk cases in different OR environments or circumstances if possible. • Be aware that even blunt instruments may injure the ICA when dissecting adherent or difficult-to-dissect tumors.
27	During a transsellar, transclival approach for pituitary macroadenoma, the left cavernous ICA was injured with a Kerrison rongeur.	• Maintain hemostasis for maximal visualization. • Avoid complex cases in different OR environments or circumstances. • Confirm anatomic localization, particularly if inexperienced.
28	During endoscopic tumor resection for nasopharyngeal carcinoma, the left parapharyngeal ICA was injured with scissors.	• Use straight line of sight and instruments to minimize disorientation. • Be aware that a multidisciplinary team approach may help in navigating challenging and complex cases.

Abbreviations: CTA, computed tomographic angiography; CT, computed tomography; GH, growth hormone; ICA, internal carotid artery; JNA, juvenile nasopharyngeal angiofibroma; OR, operating room.

ever, an association may be possible, as 5 ICA injuries occurred during the surgeon's first year of EEA experience. Three surgeons were residents or fellows in training, highlighting the importance of structured training with supervision, progressively matching the trainee skills with appropriate challenges and thus enabling learning without compromising safety.[18-20] High-risk surgical procedures and critical steps should be performed by the most experienced surgeon.

In many centers, EEA procedures are performed by a multispecialty team (generally an otolaryngologist or head and neck surgeon and a neurosurgeon). Intraoperative communication, especially regarding surgical steps, is essential. In this study, the importance of clear and effective communication was illustrated by the finding that in 21% of the cases, hesitancy or disagreement occurred between surgeons specifically regarding the surgical step that caused the injury.

The EEA may be a long and exhausting procedure that requires all involved, especially the surgeons, to be physically and mentally fit. In 14% of events, surgeons reported physical distress from fatigue, hunger, operating after long travel or with jet lag, or having scheduled multiple cases. Fatigue, sleep deprivation, and hunger affect psychomotor performance and thus have implications for patient safety and operational alertness.[21,22] Overall proficiency is reduced in fatigued surgeons, potentially leading to inadvertent complications.[23-25] Whenever possible, surgeons should avoid high-risk cases when experiencing fatigue and/or physical or mental malady, on the first day after a long vacation or with jet lag, or when feeling rushed.

In this study, 64% of the centers had no ICA injury protocol in place before the first incidence. Implementing an institution-specific protocol for ICA injury enhances prevention and management of the event.[13,14] Although seemingly unnecessary for straightforward cases, a standardized multidisciplinary team-based approach allows the accumulation of joint experience, which augments the precision of the surgical approach and extent.

Intraoperative use of a surgical navigational device was reported in 54% of cases. Theoretically, an image guidance system can aid in identifying intraoperative anatomical risks and reducing adverse outcomes.[26] However, a meta-analysis of the literature did not demonstrate a statistically significant effect, only showing a nonsignificant reduction in revision operations.[27] Nevertheless, a carefully calibrated image guidance system is advantageous for confirming landmarks and the position of ICA bony canals. During the resection, the vessels may be displaced from their preoperative position. Debulking of tumor and collapse of adjacent soft tissues change the anatomy, nullifying the accuracy of the navigation system. The present study revealed that, in many instances, an acoustic Doppler was available but was not used routinely even for high-risk cases (54% of the cases). Using this device may have prevented an ICA injury.[28] Surgeons should question and confirm the accuracy of a surgical navigation device or acoustic Doppler sonography, anticipate errors, and recall anatomical knowledge and pattern recognition. Although these tools may have advantages, they can also be misleading or inaccurate and become a source of blunder.

In this study, 71% of ICA injuries occurred with the use of sharp instruments. A high-powered drill was in use during 40% of the events. Surgeons should be aware that large-diameter coarse diamond burrs (4.5 mm) may have large diamond fragments (spikes) that can reach far from the core of the burr. As the burr spins, its round core is highly visible, but the spikes become transparent or ghostlike; thus, a surgeon may misjudge the depth of penetration, increasing the potential to injure the ICA wall when drilling its bony canal.[13]

In 25% of cases, the ICA was injured during the use of new instruments or technology. Disorientation, inadequate setup, or unfamiliarity may potentially lead to errors. Trying new surgical devices in the OR is a common practice; however, extra caution is necessary when using unfamiliar instruments.

The OR is a complex environment that presents many potential risk factors that can interfere with surgical procedures and predispose to errors. In this study, 11% of ICA injuries occurred when the surgeon was operating in a different theater and/or country. This finding raises the issue of operating in a new environment and its association with the surgeon's performance.[29] Operating in new environments for educational or business purposes involves a unique set of circumstances with additional challenges and pressure. Significant factors include lack of appropriate equipment, having an audience, jet lag, language barriers, and having a different operating team.[30,31] Khan et al[32] conducted an anonymous survey of 106 surgeons who performed live surgical broadcasts. The results showed that 19% of the surgeons reported a significant increase in stress levels or anxiety when they performed procedures away from home, and 24% reported the surgical quality as slightly worse and 3% as significantly worse compared with the performance in their home institution. Therefore, from our findings, we suggest that when a surgeon operates in a different environment, maximum precautions should be directed toward optimizing the operating environment.

Recommendations

Injury to the ICA is the most catastrophic surgical complication of EEA and may lead to permanent disabilities or death. This study attempted to identify the root factors associated with this injury for a better understanding of the event. Each clinical scenario should be appraised individually during the preoperative period to stratify cases according to the degree of risk. Once a case is labeled as high risk, a cascade of preventive measures should be applied to avoid or minimize the risk of ICA injury. **Table 2** summarizes our recommendations on the basis of the root cause analysis; the expanded recommendations can be found in the eTable in the Supplement.

Limitations

This study has some limitations. Although the fishbone diagram helped with identifying and analyzing the causes and subcauses of ICA injuries during EEA, it relied on brainstorming and, therefore, was based on the authors' subjective assumptions of the potential factors. Although this process allows for broad thinking, it is often based on opinions rather than facts. Another limitation was the inability to measure the magnitude of each factor and its association with the ICA injury. Given the study design, cause-effect analysis was not possible. To yield meaningful statistical significance, we should have analyzed all EEA procedures (n = 7160) in relation to ICA injury, which was beyond the scope of this study. In addition, many factors presented limitations owing to selection and recall biases. The cases occurred from 1993 to 2018; thus, memories of the event and the surrounding circumstances may be inaccurate, and although all identifiers were removed, reluctance to fully reveal all of the details of the event may persist. Furthermore, there was selection bias, as surveys were limited to skull base surgical teams at tertiary care centers across the world and could not account for factors outside of large centers. Therefore, the results may not be generalizable to all skull base teams. Outcomes may depend on resources and other unique factors pertaining to individual teams, and there may be additional factors not assessed by the questionnaire we distributed. Nevertheless, we believe the study identified general themes and concepts, identifying areas for improvement to prevent ICA injuries.

Conclusions

This study found that rare ICA injuries in EEA skull base surgery, which can have catastrophic complications, are predominantly associated with more than 1 risk factor. We believe that understanding the potential risk factors in patients who require EEA is an utmost priority. We also believe preoperative planning and minimizing the potential for ICA injury are essential in preventing a catastrophic scenario.

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