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REVIEW

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The expanded endonasal approach in pediatric skull base surgery: A review

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Abstract

Objective: Surgery of the pediatric skull base has multiple unique challenges and has seen recent rapid advances. The objective of this review is to assess key issues in pediatric skull base surgery (SBS), including anatomic limitations, surgical approaches, reconstruction techniques, postoperative care, complications, and outcomes.

Data Sources: PubMed literature review.

Review Methods: A review of the literature was conducted to assess the challenges, recent advances, and reported outcomes in pediatric SBS.

Results: The pediatric skull base presents multiple anatomic challenges, including variable patterns of pneumatization, narrow piriform aperture width, and narrow intercarotid distance at the level of the cavernous sinus but not the superior clivus. These issues may be particularly challenging in patients less than 2 years of age. Endoscopic endonasal approaches in the sagittal and coronal plane have been applied to the pediatric skull base while open approaches may still be necessary in the setting of extensive intracranial or orbital disease, as well as disease lateral to critical neurovascular structures. While the nasoseptal flap was initially called into question for pediatric cases, it has been shown through multiple reports to be a feasible and robust reconstructive option. Complications and outcomes often depend upon the pathology. In children, response to noxious stimuli, ability to avoid Valsalva, and adherence to nasal precautions is variable. The use of lumbar drains is more common in pediatric than adult patients.

Conclusion: While the pediatric skull base presents unique challenges, outcomes data support that endoscopic endonasal approaches are a pertinent surgical technique in appropriately selected patients.

Level of Evidence: 3a

KEYWORDS

endoscopic endonasal approach, pediatric skull base surgery, skull base reconstruction, surgical outcomes

1 | INTRODUCTION

The skull base provides a critical function to separate the sinonasal and intracranial cavities.[1] Pathology of the pediatric skull base is rare, and may include unique congenital lesions, fibro-osseous lesions, and neoplasms such as pituitary adenoma, craniopharyngioma, and chordoma. In the past, surgical treatment of these lesions was primarily through open or external approaches.[2-4] However, with advances in endoscopic technology and advances in expanded endonasal approaches (EEAs) in adults, these techniques have been increasingly applied to the pediatric population.[5] Multiple case series of EEA in pediatric patients have been reported, demonstrating that endoscopic endonasal techniques are an option in appropriate pediatric cases.[6-11] This is not without challenges as the pediatric sinonasal cavity can possess additional challenging anatomic features such as a narrow piriform aperture, poorly pneumatized sphenoid sinus, and narrow intercarotid distance.[12,13] The purpose of this review is to address key issues in pediatric skull base surgery (SBS), including anatomic limitations, surgical approaches, reconstruction techniques, postoperative care, complications, and outcomes. In certain areas of care, the literature regarding the management of pediatric skull base pathology is lacking. In these settings, the authors' current practices have been placed as expert opinion and are delineated as such in the text.

1.1 | Anatomic Considerations

With the transition of endonasal skull base surgical techniques from the adult to the pediatric population, there has been discussion in the literature regarding limitations of the pediatric corridor. Factors from feasibility to ease of surgery to surgical safety have been reviewed and will be addressed in turn.

1.1.1 | Piriform aperture

The access to any endonasal surgery begins at the piriform aperture and in the youngest of patients, the bony entrance to the nasal cavity may limit access.[2] This may impact the ease of maneuverability of instrumentation within the sinonasal cavity and necessitate the use of smaller equipment. The published norms for piriform aperture width at birth, 2 years, and 5 years reveal increasing diameter from 15 to 18 mm to greater than 20 mm, respectively.[12,14-16] Prior radioanatomic studies revealed no statistically significant increase in piriform aperture diameter from that of the neonate until 15 to 18 years,[17] but the *clinical* significance of these small changes is notable. While the authors report clinically meaningful increases in piriform distance at 10 years of age,[17] we would propose that the clinical ease of access undergoes clinically significant increased size between 2 and 6 years. With small changes in diameter from 15 to 20 mm, the cross-sectional area nearly doubles, affording four-handed instrumentation with greater ease and in the experience of the authors, a piriform diameter greater than 2 cm affords unrestricted access for four-handed surgery. In smaller patients, accommodations, including decreasing endoscope size from the standard 4 mm lens to the 2.7 mm lens, transitioning to three-handed approaches, and augmenting standard skull base and sinus instrumentation with otologic microinstruments can be utilized to facilitate endonasal approaches.[18] Below 15 mm, however, even these measures may not be sufficient to afford clear visualization and space for unrestricted instrumentation. In these circumstances, alternate approaches to the cranial base should be considered. These include open approaches for more anterior pathology and transoral-transpalatal approaches for more posterior pathology.[12,19] It should be noted that the age milestones discussed are guidelines and direct assessment of preoperative imaging is recommended in every pediatric patient to gauge challenges with access and the potential impact of pathology on access points[9,12] (Figure 1).

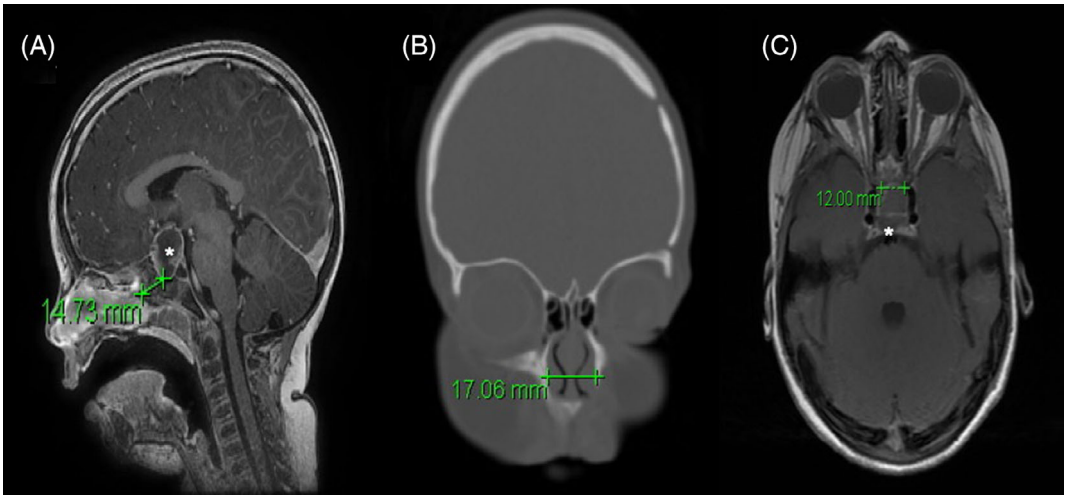

FIGURE 1 Preoperative planning in a 4 year old with craniopharyngioma. A, Extent of nonpneumatized sphenoid is measured on this sagittal T1 weighted magnetic resonance imaging (MRI) to estimate the extent of drilling required to access the sellar and suprasellar craniopharyngioma (asterisk). B, The piriform aperture is measured on this coronal computed tomography (CT) scan demonstrating an acceptably wide nasal access point. C, Intercarotid distance at the sella is measured on this axial T1 MRI revealing adequate intercarotid space for access to the craniopharyngioma (asterisk)

1.1.2 | Endonasal anatomy

Beyond the piriform aperture, endonasal anatomy varies minimally in the neonatal and pediatric patient with an average interturbinate distance of approximately 6 to 10 mm anticipated in toddlers and teenage patients.[9,15] With either lateralization or removal of the turbinates, this provides an adequate corridor for endonasal cranial base surgery.

1.1.3 | Sinus pneumatization

The next hurdle in access encountered more frequently in pediatric patients is incomplete sphenoid pneumatization. As access to transplanum, transsellar, and transclival approaches is through the sphenoid sinus, a nonpneumatized or incompletely pneumatized sphenoid necessitates further consideration. Typically the sphenoid sinus is not pneumatized at birth, begins to undergo pneumatization at 2 to 3 years of age, and is not fully pneumatized until adolescence.[12,20] A poorly pneumatized sphenoid can obscure visualization of critical neurovascular structures such as the internal carotid artery and the optic nerve. Furthermore, removal of the poorly pneumatized bone requires significant drilling and care to avoid injuring one of these structures. Incomplete pneumatization is not a contraindication to endonasal surgery and recent publications have concluded that the degree of pneumatization does not impact operative outcomes.[21] This study included 27 pediatric patients with a median age of 8 years. There was no significant association found between sphenoid pneumatization pattern and extent of resection or postoperative cerebrospinal fluid (CSF) leak rate[21] However, incomplete pneumatization will impact the extent of bony work involved during the surgical approach and consequently the time required during the approach so should be considered in surgical planning (Figure 1).

Multiple authors have characterized the patterns of sphenoid pneumatization with perhaps the most pertinent to the cranial base surgeon being Tatreau et al[12] and Banu et al.[9] In these large retrospective radioanatomic analyses, the pattern and timing of sphenoid pneumatization are described, beginning from the inferior medial sphenoid os and expanding superiorly and posteriorly to pneumatize the sphenoid face by 6 years of age with expansion to the planum and sella face in nearly 80% of patients by this age.[12,15] Of note, prior to 4 years of age, essentially no pneumatization of the sphenoid is identified.[12,15] Following planum and sella face pneumatization, subsequent aeration proceeds in a more inferior and posterior direction toward the clival recess, with no patients demonstrating pneumatization in this region under the age of 10 though there was at least some degree of pneumatization by 15 years in 90%.[12]

1.1.4 | Intercarotid distance

An additional potential challenge when approaching midline pediatric skull base pathology is a narrow intercarotid distance.[2] As the approach to much of the skull base involves a corridor between the carotid arteries, a narrow, constricted corridor can lead to increased degree of difficulty and risk of injury. This is less of a consideration in approaches to the anterior fossa or planum sphenoidale, but should be evaluated prior to any trans-sellar, trans-tubercular, or trans-clival approach. An intercarotid distance of 8 mm or less was noted to be disadvantageous to sellar approaches in 1975 by Rhoton and Renn when referencing transfrontal open approaches.[22] Generally, 1 cm intercarotid distance at the sella and 1.5 cm at the clivus are considered the lower limits of endonasal access by convention (Figure 1).

More specific to endonasal approaches, recent radioanatomic studies have evaluated the role of intercarotid distance and found increases in intercarotid distance associated with lower complication rates.[9] Interestingly, this finding was associated with the intercarotid distance at the superior clivus rather than the cavernous carotid, raising the possibility of this finding being a surrogate for overall increasing size rather than a true anatomic limitation. In their population, the pediatric population observed was older, with all patients under 10 years of age combined into one subgroup. As such, decreases in intercarotid distance at the lower extremes of the pediatric age group were likely under-represented. In another radioanatomic assessment of pediatric patients without skull base pathology, Banu et al identified an average intercarotid distance of 11.3 mm in their cohort of 2- to 4-year-old patients, suggesting sufficient clearance in this age group.[15] In their 2010 work, Tatreau et al found an intercarotid distance less than 10 mm at the sella only in the cohort less than 2 years of age and an intercarotid distance of greater than 15 mm at the clivus in all patients.[12] Taken together, these findings would suggest that the intercarotid distance is most likely to pose a significant limitation in endonasal access to the sella in patients less than 2 years of age but should be assessed in all pediatric patients, as congenital malformations or pathology may alter the natural expansion of the midline.[15]

2 | SURGICAL APPROACHES

The surgical approach chosen depends on a variety of factors including the pathology, lesion location, and expertise of the surgeon and varies from open, endoscopic, and combined surgical approaches. In general, open or external approaches are indicated if the disease demonstrates extensive intracranial or orbital extension, encases or is lateral to critical neurovascular structures, or involves areas that are not readily accessible to a purely endonasal approach such as the lateral frontal sinus.[23] These approaches include subfrontal, subcranial, and transfacial approaches.[23] In some cases, the improved visualization afforded by the endoscope can be added to these approaches in a combined or staged surgical approach (Figure 2).

Endoscopic endonasal approaches have been classified in the sagittal and coronal plane.[2] Sagittal endonasal approaches are used to access midline structures such as lesions of the cribriform, planum, sella, and clivus. To perform a typical endonasal approach to the sella, after the bilateral nasal cavities are decongested, we lateralize the

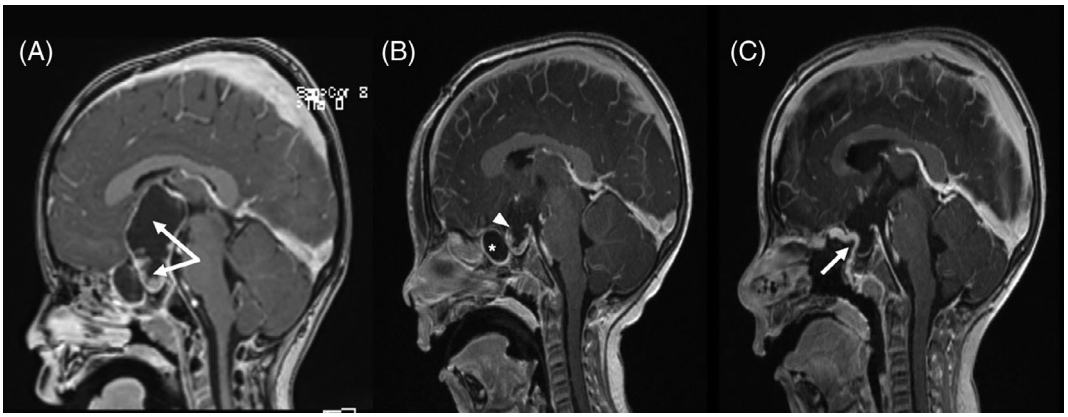

FIGURE 2 Large cystic craniopharyngioma requiring open and endonasal approaches for resection. A, Preoperative magnetic resonance imaging (MRI) demonstrating extensive sellar, suprasellar, and intraventricular extension (arrow). Staged combined modality resection was selected. B, MRI following pterional craniotomy and resection of intraventricular and suprasellar component with remnant sphenoid (asterisk) and intrasellar (arrowhead) component. C, Postoperative MRI demonstrating gross total resection and good position of nasoseptal flap (arrow)

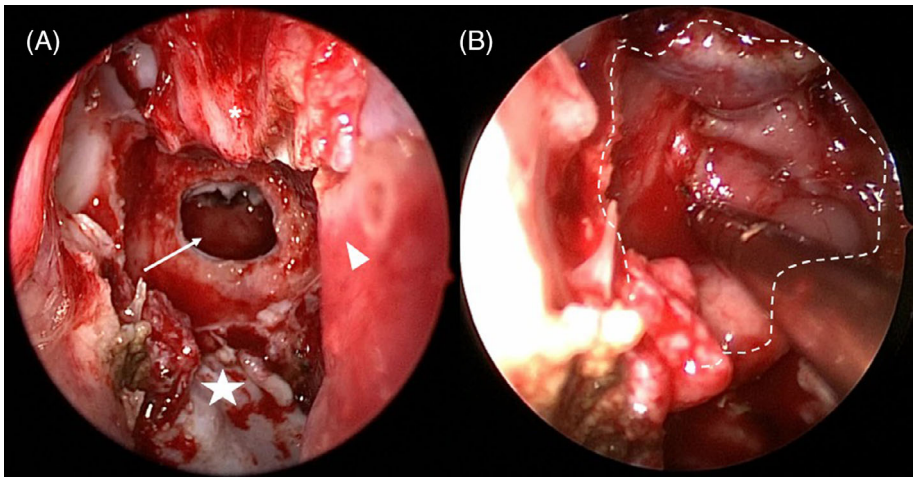

FIGURE 3 The endonasal corridor in a 3 year old. A, Intraoperative view following resection of craniopharyngioma. In the foreground is the septal remnant, resurfaced with the septal mucoperiosteum from the left posterior septum (arrowhead). Superiorly, the stump of the middle turbinate is visualized (asterisk). Inferiorly, the nasoseptal flap is positioned in the nasopharynx awaiting placement (star). More superiorly, the sphenoid is widely opened and the sella defect is seen after resection of the tumor (arrow). B, The nasoseptal flap (dashed line) is positioned over the sellar defect

inferior turbinates and resect the right middle turbinate. In older pediatric patients with strictly sellar disease, the middle turbinate may be lateralized, but in our experience, resection of the turbinate affords improved access in younger patients and when more lateral dissection is needed and supplies a mucosal graft that can be utilized either in cranial base repair or to hasten mucosalization of the nasoseptal flap (NSF) harvest site if NSF is utilized.[24] Additionally, unilateral turbinate resection is accomplished with minimal morbidity and anecdotally increases tolerance of postoperative surveillance. After addressing the turbinate, a right total sphenoethmoidectomy is then performed. An incision is made in the right septal mucosa with care to preserve the vascular pedicle for a potential NSF and no higher than level of the sphenoid os when posterior to the anterior head of the middle turbinate to preserve olfaction. Wide binaural access is then obtained through removal of the sphenoid rostrum and posterior septum (Figure 3). Management of the contralateral nasoseptal mucosa can be tailored to the case, with either (a) preservation of the pedicle and inferior displacement of the pedicle to afford unencumbered access from both nostrils and preservation of the flap for potential later use or (b) division of the pedicle and utilization of the left posterior NSF as a "reverse flap" to reconstruct the defect remaining after the harvest of the right NSF.[25,26] Dependent upon the degree of sphenoid pneumatization, the bone is then drilled and removed or the septations and sellar face are drilled away to identify the sella dura.

3 | RECONSTRUCTION

Reconstruction of the skull base in children follows the same principles as in adults; namely to: (a) support the brain and/or orbit, (b) separate the intracranial and extracranial compartments by a watertight dural seal, (c) provide mucosalized lining for the nasal cavity when possible, (d) reconstruct nasal vault and aerodigestive tract, (e) provide volume to decrease dead space, and (f) preserve optimal function and the aesthetic appearance of the face. Aside from the location of the defect, other factors should be considered before planning the appropriate reconstructive technique. These factors include size of the defect, planned adjuvant or previous

radiation therapy, high vs low-flow CSF leak, previous cranial base surgeries or traumas, presence of infection, intracranial pressure, disposition of grafts, and radiologic and intraoperative measurements of the flap/defect ratio.

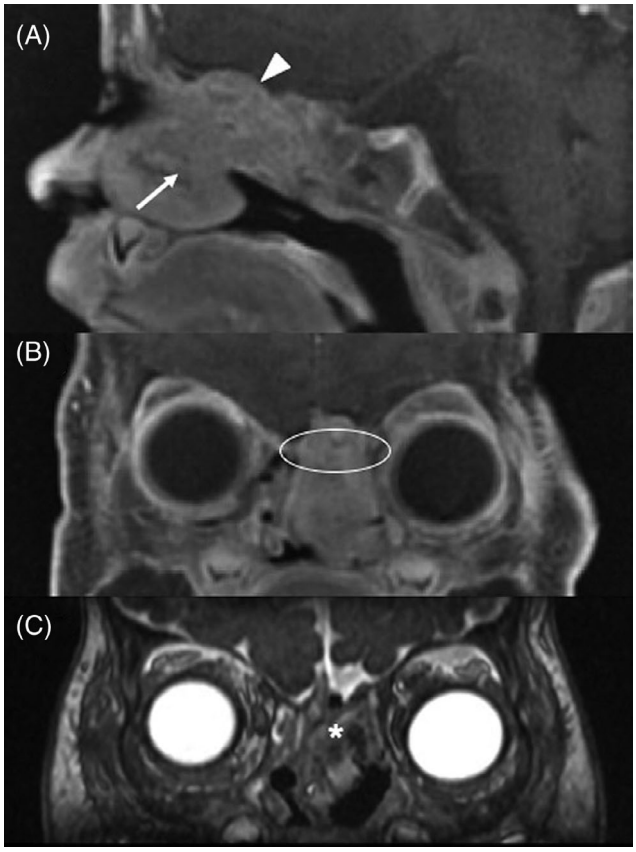

FIGURE 4 Nasoseptal flap reconstruction of anterior fossa defect in a 2 month old. A, Sagittal T1 magnetic resonance imaging (MRI) demonstrating intranasal (arrow) and intracranial (arrowhead) extent of the heterogeneously intense nasal chondromesenchymal hamartoma. B, Coronal T1 weighted MRI illustrating lateral and superior extension of the hamartoma with presence of an ethmoid roof defect (circle). C, T2 weighted coronal MRI after resection revealing reconstruction of the anterior fossa with nasoseptal flap (asterisk)

The use of the NSF endonasally is akin to the use of the standard pericranial flap reconstruction for open approaches.[27] First described in 2006, the NSF revolutionized skull base reconstruction in the endonasal approach and has become the workhorse of reconstruction in the adult population.[28] However, adequacy of the NSF was initially called into question in children, arguing that the cranial growth exceeds the rate of facial growth before 9 to 10 years, and a mismatched flap/defect ratio can cause a failure to cover the anterior skull base (under 9-10 years), sellar defects (under 6-7 years), and clival defects (for all pediatric patients).[29] Recent literature and the experience of high caseload centers have shown the feasibility of NSF reconstruction for sellar and suprasellar lesions.[30-34] More recent reports have demonstrated the use of the NSF in management of congenital skull base defect repair in the first year of life, illustrating the fact that the NSF can safely be utilized for reconstruction even into infancy and can be advanced to address select anterior fossa defects (Figure 4).[35] One reason for this greater than anticipated utility of the NSF is the reduced volume of the sphenoid sinus producing a smaller bony distance to be covered. Examples of the immediate appearance of the NSF and its appearance 1 year after surgery are seen in Figure 5.

The NSF is used in a similar method as in adults with some slight differences. Though the utility of the NSF in pediatric skull base reconstruction has proven much greater than initially anticipated, preoperative measurements are recommended to confirm the size of the flap and to prepare additional grafts if necessary.[31] Use of the "rescue" flap is a reliable option in children.[36] Despite variations in sphenoid pneumatization, the sphenoid os—the landmark for the superior NSF incision—is reliably located approximately 1 cm superior to the choana and medial to the superior turbinate. In the pediatric population, there are some considerations and potential limitations. The nasal vault diameter is smaller making instrumentation and elevation more challenging. In addition, the denuded cartilage begets crusting and the need for debridement and nasal irrigation, both of which can be challenging in pediatric patients, especially less than 6 years of age.[13] Even though complications rates are rare in children with reported rates of synechiae (7%), anosmia (7%), and crusts (14%) in the literature,[34] children are theoretically more susceptible due to restricted anatomy and potential difficulty with adequate debridement and surveillance in-office.

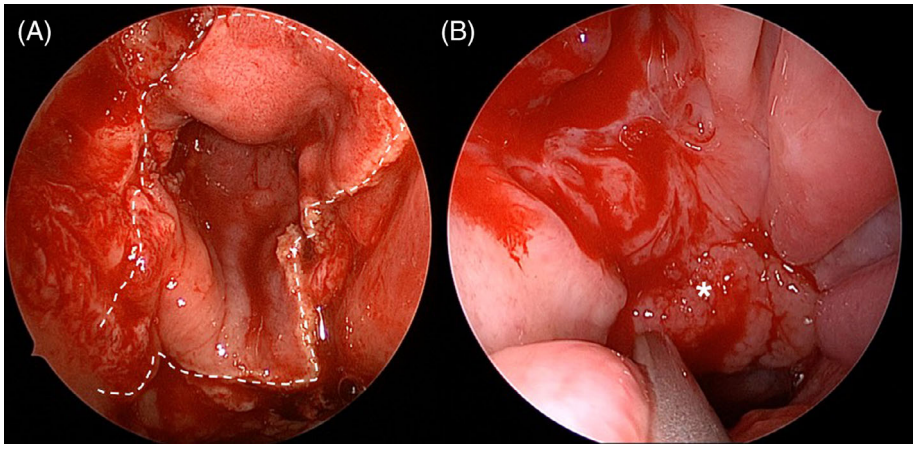

FIGURE 5 Pediatric nasoseptal flap. A, Nasoseptal flap inset to cover the sphenoid cavity and sella defect (dashed line) in a 4 year old. B, The appearance of the sphenoid cavity 1 year after surgery. The cavity is completely mucosalized and slightly contracted with mild adenoid bulk visualized inferior to the flap (asterisk)

Smaller defects involving the fovea ethmoidalis, planum sphenoidale, or sella could be repaired with dura substitute (Duragen) and mucosal grafts. Middle turbinate flaps or grafts are another option for small suprasellar and sellar defects. For greater defects that are not entirely covered by the NSF, one option is to underlay fascia lata at the edges of the reconstruction.[34] Another consideration is decreasing the effective depth of the defect with an abdominal fat graft placement deep to the NSF and/or use of tunneled extranasal vascular flaps like the pericranial flap or temporalis fascia flap.[37]

4 | POSTOPERATIVE CARE

Management of the pediatric patient following endonasal cranial base surgery is—in principle—no different than management in the adult population. The goals of maintaining integrity of any cranial base repair, controlling pain, aiding in the clearance of secretions and crusting, and assessing postoperative nerve function and monitoring for surgical site complications remain the focus of postoperative care. However, accomplishing these goals in the pediatric patient can be more challenging given the range of neurocognitive maturity and developmental progress present in children. Unfortunately, there is very little in the existing literature beyond opinion evaluating these parameters and recommendations herein are subsequently based upon the available published data, expert opinion from prior publications, and the authors' experience.

4.1 | Location and duration

Following EEA, pediatric patients are typically observed in the pediatric intensive care unit (ICU) for several reasons.[38,39] The ICU provides a setting capable of frequent neuromonitoring, close monitoring for endocrine dysfunction, tight control of fluid balance, and ability to incorporate interventions to correct perturbations in endocrine function or fluid homeostasis.[38,40] Exceptions to planned ICU observation would include extradural cases with low concern for neurological insult or focal CSF leak repair cases. Transfer out of the ICU is contingent on neurological and endocrinological stability but typically occurs in the first 48 hours after surgery.[13] Stapleton et al reported average lengths of stay at 1.8 and 4.5 days for ICU duration and overall hospitalization in a pediatric sample of 55 patients, respectively.[13] Overall hospital stay is determined by endocrinological stability, return to ambulatory activity, and stable skull base repair. In younger patients who may require a return to the operating room for first debridement, this could prolong postoperative hospitalization.

4.2 | Diet

Diet is typically not restricted after endonasal surgery in pediatric patients. The primary consideration in this aspect of care is for posterior fossa approaches in which the surgeon is working in close proximity to the lower cranial nerves. In these situations, close attention to oral intake is paid after surgery with low threshold for clinical or instrumental swallowing assessment if there is evidence of cough, choking, or other concern for aspiration. Unrelated to aspiration risk but relevant to patient diet in those at-risk for challenges with sodium homeostasis, a patient may also benefit from fluid restriction in the setting of postoperative diabetes insipidus (DI), but this limitation is not extended globally to all post-EEA patients.

4.3 | Pain control

The goal for analgesia following endonasal SBS is for adequate pain control balanced with ability to reliably examine the patient to identify evolving neurologic changes. In the pediatric patient, both pharmacologic and nonpharmacologic strategies are employed for this purpose. Acetaminophen is the primary medication for postoperativce pain control with adjunctive opioid medications utilized as needed for breakthrough pain. Ibuprofen is avoided due to concern for potential postoperative intracranial hemorrhage. While adequate pain control is the goal, one must actively manage the discomfort while also remaining wary of progressive headache which may prompt evaluation for intracranial complication.[41] In addition to pharmacologic pain control, alternative methods to manage patient perception of pain are employed in the pediatric population. The use of distraction has been demonstrated to decrease subjective experience of pain and can applied in various ways including therapeutic recreation, music therapy, and child life services to assist with tolerance of what can be a challenging hospital stay.[42]

4.4 | Imaging

While there are no evidence-based guidelines, the principles of assessment for complications, evaluation for completeness of surgical endeavors, and surveillance for recurrence drive recommendations for acute perioperative and postoperative surveillance imaging in pediatric patients following cranial base surgery.

4.4.1 | Acute

Generally, computed tomography (CT) is completed within 12 hours of surgery to assess for acute complications.[39,43,44] When the potential for reoperation exists, early magnetic resonance imaging (MRI) to assess for focal residual disease is also obtained.[39,44] This is typically performed within 72 hours of surgery. Beyond these imaging guidelines, additional CT imaging is obtained with any acute change in mental status or vision to assess for postoperative complications such as hematoma, infarct, or pneumocephalus in the perioperative period (Figure 6). In fact, some advocate for no use of routine imaging following cranial base surgery in the adult population citing no complications identified by imaging that were not already suspected based on

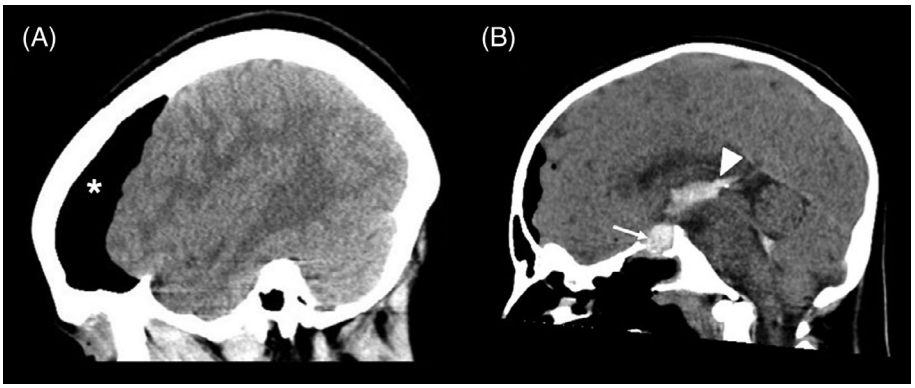

FIGURE 6 Complications identified on postoperative imaging. A, computed tomography (CT) obtained immediately after sudden onset of headache on a patient 1 day following EEA and resection of a suprasellar teratoma. The patient had a coughing event immediately prior to the onset of headache. Extensive pneumocephalus (asterisk) is noted that was addressed with revision of the skull base repair. B, CT obtained 12 hours after EEA and resection of a sellar and suprasellar craniopharyngioma demonstrates opacification within the sellar cavity (arrow) extending into the ventricular system (arrowhead) indicative of hemorrhage. This patient returned urgently to the operating room for endonasal management of a dura-based bleeding vessel. EEA, expanded endonasal approach

clinical symptoms.[45,46] This is not recommended by the authors in the pediatric population due to potential limitations in the ability of the pediatric patient to effectively communicate many of the clinical changes that would prompt imaging.

4.4.2 | Surveillance

Beyond the perioperative period, surveillance imaging is obtained with frequency and modality based on pathology, with more frequent imaging reserved for malignancy or aggressive benign disease and follow-up imaging intervals typically ranging between 6 and 12 months.[39,44] While MRI is typically the favored imaging modality in the pediatric population given its superior soft tissue definition and lack of radiation exposure, bony skull base lesions such as fibrous dysplasia (FD) or ossifying fibroma are often better delineated on CT.[47]

4.5 | Activity

Activity limitations following pediatric cranial base surgery mirror the management of this adult population and general principles are well described in the literature.[44] Typically, patients are positioned with head of bed elevated 15 to 30° to optimize CSF outflow and encouraged to mobilize on a time frame based on the presence and extent of CSF leak encountered during surgery.[38,44] Nuances in the pediatric population revolve around limitations of very young (<6 years) or developmentally delayed patients to comply with activity restrictions and whether special precautions are necessary to mitigate this issue. In situations where the patient's ability to comply with activity restrictions is limited, further limitations on activity may be enacted including prolonged bed rest, exercise restrictions, and potentially chemical sedation in the highest risk patients.[48] Additional measures to optimize compliance include use of mittens or pediatric elbow immobilizers (Snuggle Wraps) to avoid removal of the nasal packing and nasal manipulation.

4.6 | Nasal hygiene

Routine of nasal saline spray while nonabsorbable packing and/or doyle splints are in place with transition to nasal saline irrigations following removal of nonabsorbable packing and splints is utilized in the postoperative period following pediatric EEA. If no packing is in place, nasal saline irrigations are initiated on the day following surgery.[44] Tolerance of nasal saline in the pediatric population is frequently discussed. Previous reports demonstrate tolerance of nasal saline irrigation of 60% to 90% in pediatric patients with appropriate coaching and provider involvement.[49-51] In these studies, the average patient age was approximately 8 years,[49-51] raising the question of tolerance in even younger patients. As such, nasal saline irrigation is utilized when tolerated with a general guideline of nasal saline irrigations in patient older than 6 years and continued use of nasal saline spray in younger patients and those intolerant of a trial of nasal saline irrigation.[36,39,40,52]

4.7 | Nasal precautions

In general, nasal precautions are geared toward avoidance of increases in intracranial pressure and disruption of the cranial base repair site. These include prohibition of nose blowing, leaning forward, or lifting more than 10% of body weight as well as reminders to sneeze with mouth open and avoidance of straining.[36,38,44] To minimize constipation and attendant increases in straining with bowel movements, stool softeners are included in the postoperative regimen.[36,44] Adherence to nasal precautions increases with age and maturity in the pediatric population, with greatest challenges in the very young (<6) and/or developmentally delayed. This has implications for nasal debridement (discussed below) as well as the maintenance of nasal precautions. In the rare patient judged to be high risk for postoperative CSF leak (large dural defect, communication with cistern/ventricle, previous CSF leak) *and* high risk for noncompliance with nasal precautions due

to age, behavioral disorder, or developmental delay, a brief period of sedation and intubation in the postoperative period is utilized to allow for healing of the cranial base repair to optimize outcomes.[48]

4.8 | Debridement

Debridement to clear excess secretions, crusts, and excess bulk of packing occurs approximately 1 to 2 weeks after surgery and subsequently at intervals determined by the extent of crusting and efficacy of nasal saline at clearing the nasal cavity. With the use of prolonged nasal splints and mucosal grafting on the septal donor site, the interval to initial debridement can be delayed to allow for maturation of the flap and mucosal grafts. In the pediatric population, tolerance of in-office or bedside instrumentation is variable. While many adults and older teen patients will tolerate this instrumentation, this is less likely in younger (<6 years) or more anxious patients[13,36,38,44] and a planned return to the operating room for nasal endoscopy and debridement is elected to debride and assess the operative cavity in a controlled setting. In their 2015 analysis, Stapleton et al report a 24% rate of return to the operating room for this purpose in their series of 55 patients (age 1 month-19 years).[13]

4.9 | CSF diversion

The role of lumbar drainage in the prevention of CSF rhinorrhea following cranial base surgery has been examined extensively in the literature with an excellent recent review.[53] The most robust evidence supporting use of lumbar drainage in a high risk (>1 cm^2 dural defect, extensive arachnoid dissection, and/or operative cavity in communication with a ventricle or cistern) population comes from a recently published randomized controlled trial demonstrating significantly lower risk of postoperative CSF leak with 3 days of lumbar drainage in a high risk adult cohort.[54] Within the literature, there is no pediatric-specific analysis of lumbar drainage and series with adults and pediatric patients have identified the pediatric age group as higher risk for postoperative CSF leak.[55] Expert opinion in pediatric series recommend CSF diversion in high risk cases as defined above and in the management of intradural chordoma as this pathology has been found to be highest risk for postoperative CSF leak in a pediatric series.[39,56] Lumbar drainage is also an option in the management of postoperative low flow CSF leak if operative management is not initially pursued.[53,57]

4.10 | Endocrine management

With any surgical intervention around the sella, there is potential for pituitary and/or hypothalamic dysfunction following surgery. As such, a high suspicion is maintained in these patients and endocrinology is consulted to assist in the assessment and management of endocrine function.[38,52]

5 | COMPLICATIONS

SBS in the pediatric population carries unique considerations including the concern for impact on facial growth and the possibility of limited debridement opportunities in addition to the same neurovascular complication risks as in the adult population. The cranio-orbito-zygomatic skeleton reaches 85% of adult size by 5 years of age.[58] The nasofacial second growth peak occurs at age 13.1 years for females and at 14.7 years for males.[59] Among the essential growth zones, the sphenodorsal center plays a critical role in the development of the bony and cartilaginous skeleton of the midface. Even though there is fear of damaging and affecting the growth centers of the underdeveloped skull during SBS, recent publications in patients undergoing functional endoscopic sinus surgery or EEA demonstrate no impact on midface growth.[60,61] Parasher et al utilized established landmarks and linear measurements selected by neuroradiologists to assess midfacial growth in patients who had undergone EEA[62] vs open resections for craniopharyngioma and found no difference when considering anterior midfacial height, posterior midfacial height, palatal height, and sella-nasion distance. Chen et al found similar results favoring no impact in skull growth in another assessment with 5 year follow-up.[63] Although prospective studies with greater follow-up are needed, recent literature supports no significant operative impact on craniofacial growth. With these reassuring findings in mind, the pediatric endonsasal skull base surgeon's approach should aim to safely expose critical structures to facilitate management of disease without unnecessary resection of normal anatomic structures.

As in adults, other complications in the pediatric population are distributed temporally. In the immediate postoperative period, crusting, epistaxis, anosmia, cranial nerve injury, or cerebrovascular accident may be identified while nasal obstruction or chronic sinusitis would be anticipated in a more delayed fashion. In contrast, infection, endocrine dysfunction, or CSF leak can present at any time in the postoperative period. Minor events such as crusting and epistaxis are most common with nasal crusts managed with saline irrigations and serial debridement as mentioned above. To minimize crusting, efforts referenced above should be made intraoperatively to cover exposed bone and cartilage with mucosa as able.

Hemostatic control is of 2-fold importance. First, the smaller blood volume of pediatric patients compared to adults leads to a greater relative loss of blood with prolonged mucosal oozing or venous or arterial bleeding that can be encountered during EEA. As endonasal procedures can be lengthy, consideration for interval assessment of hemoglobin levels should be made with low threshold to replace if levels are decreasing and/or if significant blood loss is projected in management of the pathology. Second, improved hemostasis at the conclusion of the procedure will decrease the extent of bloody crusts that need to be debrided or irrigated. Bleeding should be carefully managed during surgery and cautery of the base of the middle turbinate (if resected) and ensuring hemostasis at the harvest site and edges of the NSF (if utilized) can aid in this effort.

Regarding CSF leak as a SBS complication, it is key to consider situations that can put the reconstruction at risk in the pediatric

population. In children, response to noxious stimuli, ability to avoid Valsalva, and adherence to nasal precautions is variable. Regarding the rate of success for each reconstruction option, Soudry et al reported recently that in an adult population vascularized flaps appear to be superior for reconstruction of high-flow intraoperative CSF leaks (defined as a cistern or a ventricle leak).[64] In the pediatric literature, however, Stapleton et al identified no difference between nonvascularized vs vascularized reconstruction, though their findings are likely skewed by the tertiary population treated.[56] More recently, Nation et al reported the use of NSF in high-flow intraoperative CSF leaks while utilizing autograft or allograft for management of low-flow or no-leak cases as an effective management strategy in the pediatric population.[65]

Incidence of CSF leak varies widely (0%-23%).[34,56,66-68] While the strongest risk factor for postoperative CSF leak is intraoperative CSF leak,[56] the rate of leak is variable and also dependent on the pathology being managed[56] as well as the volume, complexity, and experience of the surgeon.[69] Should a CSF leak be suspected, prompt attention and management is imperative as a delay in diagnosis of more than 7 days carries a significant risk of meningitis.[64]

6 | OUTCOMES

6.1 | Juvenile nasopharyngeal angiofibroma

Intraoperative bleeding is one of the main concerns and embolization is used in 53.5% of reported cases to minimize intraoperative blood loss.[70] Reported average blood loss approaches 800 mL.[70] Andrew's stage IIIa and IIIb are the most common stage at presentation and gross total resection (GTR) was obtained in 76.2% to 79.0%, subtotal resection (STR) in 11.9%, and partial resection in 1.8%.[66,70] Surgery remains as the primary treatment and embolization decreases the volume of blood loss in 70%[71] with commensurate improvement in recurrence rates.[72] Although rare, central retinal artery occlusion and stroke are possible complications of embolization and should be considered when weighing the value of embolization. Considering complications following surgery, a review of 239 cases demonstrated that cranial nerve palsy (3.3%) and xerophthalmia (1.7%) occur rarely and trismus, CSF leak and chronic nasal crusting were each reported in 1.3% of all patients.[70] Recurrence was reported between 0% and 7% for stages I and II, and 8% to 36% overall with follow-up of 6 to 36 months, supportive of the minimum follow-up of 3 years.[70,71]

6.2 | Chordoma and chondrosarcoma

These pathologies together account for ~7% of pediatric SBS cases.[70] Treatment is characterized by EEA and open far lateral approaches, but adjuvant therapy with chemotherapy and/or radiotherapy also play a role. Given that tumor resection is usually associated with positive margins, GTR is possible in 34.6% of the surgeries with STR achieved in 53.8%. Chordomas hold the highest rate of CSF leak in reported series (10%-36%).[56,70] Histological subtypes can play different roles in terms of outcomes. A dedifferentiated subtype that is more common in the young population has a more aggressive course and worse prognosis. Mortality rates reported were 100% for dedifferentiated, 37.5% for chondroid, and 23.1% for classical tumors.[73]

6.3 | Pituitary adenoma

Pituitary adenoma comprises 3% of all pediatric skull base surgeries.[4] GTR is achieved in 40% to 89% and STR in 7.7%.[70] Chang et al identified an 11% recurrence rate for GTR vs 45% for STR in a series with up to 10 year follow-up.[74] Recurrence-free survival ranges from 48% to 97%. Disease control is dependent on the adenoma's histology with Cushing disease, prolactinoma, growth hormone (GH)-secreting adenoma, and nonfunctional adenomas having decreasing rates of chemical remission.[75] Remission rates for Cushing disease vary from 60% to 98%.[76] Revision surgeries usually have a 14% rate of surgical cure, while radiation demonstrates control rates of 64% to 100%.[52] Regarding complications, diabetes insipidus was the most common endocrinopathy reported. Visual changes (6.4%), CSF leak (2.3%), and intracranial bleeding (2.1%) are also uncommonly seen complications in pediatric adenoma management.[4] Hanba et al revealed higher complication rates in patients under 10 years of age, with increased incidence of DI, hydrocephalus, and panhypopituitarism in younger patients.[77] The most typical surgical indication for adenomas in children is symptoms related to hormonal secretion as opposed to macroadenomas with optic nerve compression as seen in adults.[78,79] Considering that less favorable outcomes are identified in cases with prior neurological deficits caused by tumor compression, this differential presentation may play a role in outcomes.

6.4 | Craniopharyngioma

Craniopharyngioma is the second most prevalent brain tumor in the pediatric population (5%-10%) and 30% to 50% of all craniopharyngioma cases are childhood craniopharyngioma.[80] GTR is achieved in 71.9% to 91% while STR occurs in up to 27.6%[70] in series in which GTR is advocated with higher rates of STR when planned STR and radiotherapy are the treatment goal.[81] The treatment choice should be tailored individually given the high survival rate and potential lifetime complications related to injury to the optic apparatus or hypothalamus.[81] Madsen et al demonstrated that GTR is possible in 85.7% of endonasal cases vs 53.3% in open approaches and the recurrence rate (40% vs 14.2%) and need for adjuvant therapy (20.0% vs 10.7%) are higher in open approaches.[82] This trend toward improved resection and decreased recurrence with judicious application of endonasal approaches to pediatric craniopharyngioma are seen in multiple additional series.[83-86] Zacharia also described fewer visual complications in endoscopic vs open approaches (56.2% vs 33.1%).[33] In general, postoperative diabetes insipidus is the rule rather than the

exception, with nearly all patients experiencing at least transient diabetes insipidus after surgery and 64% to 80% continuing to permanent DI.[38] Additional complications include persistent visual disturbances (48%-75%) and endocrinopathy (15%-98%).[38,70] As compared to adults, the incidence of pituitary dysfunction is greater after craniopharyngioma treatment in the pediatric patient.[6,38,83-86] The rate of recovery of visual and endocrine deficits differs, with 75% to 100% improving or returning to normal visual perception, but only 12.5% of hypopituitarism improving or normalizing after surgery.[38,87] CSF leak and meningitis are seen less frequently with the use of the NSF, with rates under 11% for CSF leak and 6% to 12% for meningitis.[6,38,85] Recurrence is noted in up to 23.6% of patients.[70]

6.5 | Fibro-osseous lesions

FD is the most common fibro-osseous lesion of the skull with the sphenoid and ethmoid bones being the most frequently impacted.[47] The need for surgical intervention should be carefully considered as cessation of growth is expected around 18 years for monostotic FD and 22 years for polyostotic.[88] FD is associated with a 0.4% risk of malignant degeneration.[89] With these factors in mind, surgical options are reserved for symptomatic cases such as neuropathy, diplopia, and proptosis.[90] The role of surgery for pain management or prophylaxis is not well established.[91]

When resecting an ossifying fibroma, it requires complete resection; otherwise recurrence rates are higher than 30%.[91] The endoscopic endonasal approach may be suitable to minimize morbidity and maximize the potential for gross resection.[90] In children, unerupted dentition and minimizing disruption of craniofacial growth centers are important.[47] More aggressive lesions such as ossifying fibroma, aneurysmal bone cyst, and osteosarcoma have a greater propensity than FD and ossifying fibroma to present with cranial neuropathies earlier in their course.[89]

6.6 | Malignancies

6.6.1 | Esthesioneuroblastoma

Esthesioneuroblastoma, also known as olfactory neuroblastoma, is the most common malignancy originating from the nasal cavity in children with an incidence of 0.1/100,000.[92] Esthesioneuroblastoma presents in a bimodal pattern with the first peak around the second decade,[93] although the youngest age description was 2 year old.[94] The most commonly utilized systems, Kadish stage and Hyams' grade, have not been well validated in children.[92,95] Treatment may include a combination of neoadjuvant/adjuvant chemotherapy, open/endoscopic surgery, and radiation therapy. Despite the more advanced presentation stage than adults, the 5-year overall survival (OS) in children varies from 72.5% to 91%.[93,96] Recurrences can be seen more than 8 years later.[97] Endoscopic surgery has become the main option showing results similar to the craniofacial approaches in adults,[98] including a report of unilateral resection with olfactory preservation in children.[92]

6.6.2 | Rhabdomyosarcoma

Rhabdomyosarcoma (RMS) represents 5% to 7% of all pediatric malignancies and is the third most common pediatric solid tumor.[99] RMS occurs in the head and neck region in 30% to 40% of cases, and may also present as parameningeal tumors, which can expand throughout the skull base.[100] The former subtype is associated with advanced disease in 50% of cases, characterized by intracranial extension, skull base erosion, and cranial nerve involvement.[101] Surgery should be highly considered in nonmetastatic disease with minimal response to induction chemotherapy in whom complete resection with clear margins is anticipated since delayed primary resection waiting for radiation therapy could impact the local control rate.[102] However, resections are challenging owing to the risk of intracranial complications, positive margins (<0.5 cm), and postoperative morbidities.[103]

7 | CONCLUSION

The pediatric skull base presents multiple anatomic challenges including variable patterns of pneumatization, narrow piriform aperture width, and narrow intercarotid distance at the level of the cavernous sinus but not the superior clivus. These issues may be particularly challenging in patients less than 2 years of age. Endoscopic endonasal approaches in the sagittal and coronal plane have been applied to the pediatric skull base while open approaches may still be necessary in the setting of extensive intracranial or orbital disease, as well as disease lateral to critical neurovascular structures. While the NSF was initially called into question for pediatric cases, it has been shown through multiple reports to be a feasible and robust reconstructive option. Although the pediatric skull base presents unique challenges, limited outcomes data support that endoscopic endonasal approaches are a pertinent surgical technique in appropriately selected patients. Little data exist in the literature regarding evidence-based postoperative care of pediatric skull base patients and is an area available for further investigation.

CONFLICT OF INTEREST

N.R.L. was a consultant for Cooltech, Inc. and holds a small amount of stock in Navigen Pharmaceuticals, both of which are not relevant to this article. All other authors have no relevant conflicts of interest to disclose.

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