Open Anterior Skull Base Reconstruction: A Contemporary Review

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Abstract

Skull base extirpative and reconstructive surgery has undergone significant changes due to technological and operative advances. While endoscopic resection and reconstruction will continue to advance skull base surgery for the foreseeable future, traditional open surgical approaches and reconstructive techniques are still contemporarily employed as best practices in certain tumors or patient-specific anatomical cases. Skull base surgeons should strive to maintain a working knowledge and technical skill set to manage these challenging cases where endoscopic techniques have previously failed, are insufficient from anatomical constraints, or tumor biology with margin control supersedes the more minimally invasive approach. This review focuses on the reconstructive techniques available to the open skull base surgeon as an adjunct to the endoscopic reconstructive options. Anatomic considerations, factors relating to the defect or patient, reconstructive options of nonvascular grafts, local and regional flaps, and free tissue transfer are outlined using the literature and author's experience. Future directions in virtual surgical planning and emerging technologies will continue to enhance open and endoscopic skull base surgeon's preparation, performance, and outcomes in this continually developing interdisciplinary field.

Keywords
- ► skull base surgery
- ► cranial base surgery
- ► skull base reconstruction
- ► anterior skull base
- ► open skull base

Surgery of the anterior skull base continues to present significant challenges to ablative and reconstructive surgeons. Historically, when tumors were approached intracranially, these operations would commonly result in high rates of morbidity and mortality.[1,2] Propelled by the technological advances and surgical pioneering in both neurosurgery and otolaryngology and improved collaboration between both disciplines, there have been significant advances in ablative and reconstructive skull base surgery techniques. Now considered an interdisciplinary specialty, the majority of anterior skull base surgery is performed via minimally invasive endoscopic intranasal approach. With advanced imaging, image guidance surgery, and high definition optics, the limits of anterior skull base surgery have expanded while minimizing morbidity.

Although open approaches may still be considered the standard of care for ablative margin control and definitive reconstructive surgery by many, endoscopic skull base surgery has gained tremendous popularity and is rapidly becoming the standard of care. The pendulum has shifted far toward endoscopic techniques in current surgical training and practice such that open skull base surgery is in danger of becoming a "lost art" in some centers. Despite the promising growth of endoscopic surgery, open skull base reconstruction is still often indicated for certain malignant tumors, larger composite defects, major craniofacial trauma, osteoradionecrosis, and failed previous endoscopic reconstruction (►**Fig. 1**).

Skull base reconstructive objectives focus on providing water-tight separation between the intracranial and

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Fig. 1 Surgical defect after salvage resection of sinonasal squamous cell carcinoma.

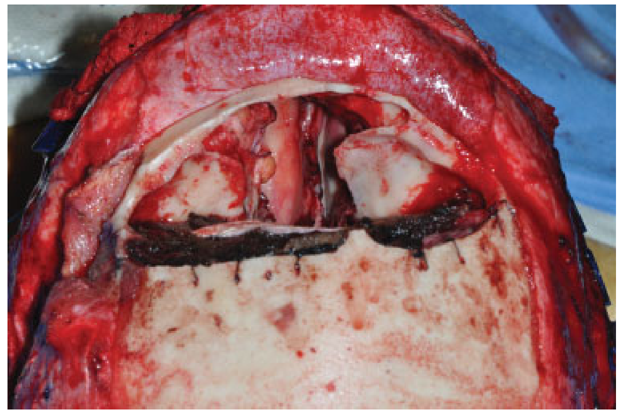

Fig. 2 Top–down view of anterior cranial base and sinonasal relationships.

extracranial contents, closing dead space, and returning reasonable form and function. Minor defects, as typically seen from endoscopic skull base surgery, may be successfully reconstructed with grafting of tissues or manufactured substitutes used in combination with local vascularized nasal septal flaps. As the extent of defects increases, larger pedicled muscle or fascia flaps, such as pericranium or temporalis muscle, may be required. Finally, in the case of large volume defects, composite resection, salvage surgery, or other complex reconstructive problems, free tissue transfer provides a much wider variety of options and should be considered the gold standard. Free tissue transfer is also indicated for the reconstruction of large or complex skull base defects resulting from osteoradionecrosis, due to the improved vascularity, to promote wound healing. Often two or more reconstructive options are used in combination to achieve reconstructive goals. Especially in aggressive open skull base surgery, the increasing extent or complexity of surgical defects must be matched by the sophistication of reconstructive strategies.

Anatomic Considerations

Careful consideration of critical structures, unique geometry, and the anticipated components of the defect is required for appropriate planning of reconstruction. The anterior skull base is a convex structure formed by the frontal, ethmoid, and sphenoid bones. This thin osseous structure separates the intracranial contents from the sinonasal and orbital contents. Specifically, the frontal bone makes up the posterior wall of the frontal sinus and orbit roof, while ethmoid sinus roof and cribriform plate come from the ethmoid. Finally, the planum sphenoidale and anterior clinoid processes of the sphenoid bone form the posterior aspect of the anterior skull base.

The anterior skull base has multiple intracranial and extracranial relationships with several neurovascular structures traversing the bony skeleton (►**Fig. 2**). The foramen cecum lying between the crista galli and frontal bone transmits nasal venous drainage to the superior sagittal sinus. Olfactory neurons traverse foramina of ethmoid roof toward the olfactory bulb, which lies above the cribriform plate and the anterior and posterior ethmoid arteries. Laterally, the orbital contents lead posteriorly into the optic canal and superior and inferior orbital fissures. These transmit cranial nerves II, III, IV, VI, V1 as well as the ophthalmic artery and veins. These structures converge posteriorly and medially toward the carotid arteries, cavernous sinus, and optic chiasm where the anterior cranial fossa transitions into the middle fossa at the anterior clinoid processes. It is important to note that both endoscopic and open anterior skull base surgeries frequently involve structures beyond the boundaries of the anatomic anterior cranial fossa and into the middle cranial fossa. These bony areas accessed through an anterior approach may commonly encompass the sella turcica, tuberculum sellae, clivus, and their associated structures.

Factors in Reconstruction

The primary goal for skull base reconstruction includes creating a durable water-tight separation between the intradural contents and external exposure. This is due to the high risk of complications from persistent cerebrospinal fluid (CSF) fistula, such as meningitis, pneumocephalus, and the associated mortality that increases over time. Secondary goals involve closure of dead space, return of function, and restoring comesis.[3] Multiple anatomic and patient factors need to be taken care of when considering a plan for skull base reconstruction as outlined below.

Factors Related to the Defect

Several staging and classification systems for skull base defects have been described previously to guide the reconstructive surgeon in determining the appropriate plan.[4–6] Due to the rapid advance in the skull base literature, many of these classifications have become historical due to the current trend toward minimally invasive skull base surgery. Nevertheless, principles of these staging systems can guide the modern surgeon and should be recognized. The location and volume of the defect are perhaps the most important factors, as these factors determine the extent of the communication between the intradural and extradural spaces, as well as which tissue options are appropriate for reconstruction. Dural reconstructive integrity and dead space obviation cannot be understated in negating complications in open reconstruction. It has been previously shown that high rates of intraoperative CSF leak, clival defects, and large dural openings are associated with persistent CSF leak and may require more advanced reconstruction.[7–10] While there is no accepted definition on what constitutes a high-flow CSF leak, it is generally accepted that arachnoid defects close to or communicating with a cistern or ventricular systems are high-flow defects and thus more difficult to seal.[11] Anterior defects coupled with smaller dural defects or an intact bony ledge may benefit from the weight of the anterior intracranial contents to help seal underlay grafts or flaps and may do well with only multilayered acellular alloplastic materials and free grafts.[12] Not surprisingly, large posterior defects involving significant bone and dura are often the most difficult to seal and often require robust vascularized tissue and postoperative medical management of CSF pressure and potentially, permanent or temporary diversion of CSF. Dural expansion, via duraplasty, should be considered when dead space persists along the skull base with reconstructive tissues in place. Furthermore, large skull base defects, including an orbital exenteration, may pose additional difficulties for reconstruction. Depending on the amount of bony orbit loss as well as the extent of the middle cranial fossa defect, there are multiple factors, including defect volume, loss of a bony buttresses, and high-flow CSF leaks that must be addressed. Orbitocranial defects are notoriously difficult to reconstruct and often require careful selection of free tissue transfer with composite, possibly chimeric flaps, allowing more anatomically matched tissue reconstructions.

Factors Related to the Patient

Additional host factors that should be assessed include a history of radiotherapy, previous surgery, availability of local reconstructive tissues, and previous reconstruction attempts. Prior radiation therapy has been associated with worse wound healing outcomes as well as central nervous system complications, such as CSF leak and meningitis, in skull base reconstruction.[2,7,13] While there is conflicting evidence in the skull base literature on whether radiation therapy confers a significant risk to skull base reconstruction complications, the untoward effects of previously radiated tissue is widely recognized in the head and neck literature.[14] Previous surgical treatment or trauma may alter the anatomy and present poor tissue quality for healing. Additionally, any previous treatment may disrupt the local vasculature and diminish the reliability of local or regional pedicled flaps. Due to the inherent unpredictability of skull base ablative surgery as well as the lack of clear reconstructive treatment guidelines (relating to antibiotics, lumbar drains, nasal packing, CSF leak precautions), skull base reconstructive planning should include multiple possible strategies and reconstructive options, including free tissue transfer.

Reconstructive Options

Nonvascular Grafts and Materials

A variety of free tissue and noncellular manufactured alloplastic materials have successfully been utilized for skull base reconstruction. While a wide variety of autogenous connective tissue grafts have been described, including nasal mucoperichondrium and mucoperiosteum, tensor fascia lata, temporoparietal fascia, calvarial bone, and abdominal adipose tissue.[15–17] Noncellular materials include DuraGen (Integra LifeSciences), AlloDerm (Allergan), DuraSeal (Integra LifeSciences), and hydroxyapatite cements.[18–20] A variety of other biological or synthetic materials have been described. These nonvascular grafts are typically used in combination with multiple layers, gasket-seal configuration, button, or underlay grafting. These are most successful when defects are relatively small and there is a bony ledge present as described in endoscopic skull base surgery reconstruction.[8,11,21] While commonly used in combination with vascularized flaps, these grafts are rarely used as the sole method of reconstruction in open skull base surgery.

Local and Regional Flaps

Vascularized locoregional flaps are the mainstay of anterior skull base reconstructions. The nasal septal flap (Hadad-Bassagasteguy) based off the posterior septal artery revolutionized endoscopic skull base surgery, proving to be a highly reliable and versatile reconstructive option with minimal morbidity. Now considered first-line in endoscopic reconstruction, it has been associated with decreased CSF leak rates.[7,22] This flap can be used alone or in combination with open skull base repair as well as endoscopic surgery. Unfortunately, many advanced tumors of the anterior skull base require resection of the nasal septum, thereby eliminating this option for reconstruction, especially in cases where open approaches are indicated. Therefore, while the nasoseptal flap has revolutionized minimally invasive skull base reconstruction, it is often less useful for larger, open approaches.

The pericranial flap has long been used as the workhorse reconstruction for open craniofacial and skull base surgery. Pedicled from the supratrochlear and supraorbital blood vessels, this flap offers a wide surface area, significant length, and documented vascularity (►**Fig. 3**).[23] The robust nature of the flap makes it an ideal choice for patients with history of radiation or patients expected to undergo radiation. Traditionally, this flap was harvested through a bifrontal incision commonly used for combined open skull base approaches. However, less invasive endoscopic harvest and tunneled techniques have been described.[24] A unilateral or bilateral pericranial flap may be harvested and fashioned to the defect as necessary, and its significant length makes it possible to cover contralateral defects. The thin pliable nature of pericranium

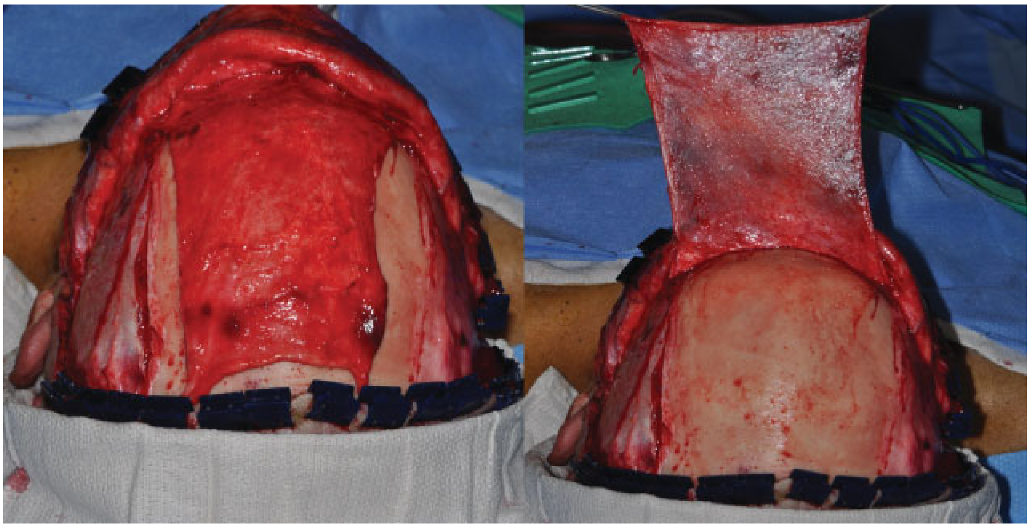

Fig. 3 Pericranial flap harvest from traditional bicoronal incision.

also makes this an excellent choice for rebuilding a dural lining to be used with other soft tissues or bony reconstructions.[25] This flap has also been described as an osteopericranial composite reconstruction using split calvarial bone grafts for defects requiring rigid reconstruction of the skull base.[26]

Other local vascularized flaps that have been described include the temporalis muscle transposition and temporoparietal fascia flaps. These flaps are robust with good blood supply from terminal branches of the external carotid system with the internal maxillary artery supplying the temporalis muscle and superficial temporal artery supplying the temporoparietal fascia. The temporoparietal fascia may be harvested as free graft, random flap, or pedicled axial pattern flap. It is similar to the pericranium, as it is versatile and pliable and may be tunneled through "keyholes" into the skull base.[27] The temporalis muscle supplies more bulk to fill dead space, and muscle tissue has been shown to have improved healing properties.[28] Additionally, the temporalis muscle may be harvested with attached calvarial bone to provide a thin layer of bony reconstruction.[29,30] It is also an excellent option for skull base defects, which include orbital exenteration and can be tunneled via the lateral orbital wall for orbital/skull base reconstruction. However, the temporalis flap has a limited travel distance based on the attachment at coronoid process of the mandible, and its proximal primary blood supply is not ideal for more medially based defects crossing midline.

Fasciocutaneous or myocutaneous regional flaps have been described and while not as commonly used, are worth noting as options in certain cases. As with the temporalis muscle flap, the addition of muscle tissue offers healing benefits, and a skin paddle can aid in water-tight suture lines. Such options include a median or paramedian forehead flap based off the supratrochlear artery as a reliable local option versus regional flaps, such as trapezius, pectoralis, and latissmus.[31] These flaps are often not practical for use for the anterior skull base due to limitations in their reach to regions above the zygoma and inferior orbital rim.

Free Tissue Transfer

Free tissue transfer offers the highest versatility in terms of volume or surface area size, composite or chimeric tissue options, and conformational geometry. Reconstruction of large skull base defects with free tissue flaps is associated with reduced rates of significant postoperative complications, such as CSF leak, meningitis, and pneumocephalus.[32–34] The obliteration of significant areas of dead space is one of the primary advantages of these flaps. Thus, many consider free flaps to be the gold standard reconstructive option for significant anterior skull base dural defects and salvage cases, especially in the setting of previous extensive surgery or radiation.

Soft Tissue Free Flaps

A wide range of soft tissue donor sites have been described for skull base reconstruction.[35,36] The rectus abdominus is classically the most well described and utilized free flap used in skull base reconstruction.[37–39] This musculocutaneous free flap is based off the very reliable deep inferior epigastric pedicle and offers a large area of skin that can be transferred as well as significant muscle bulk for closure of dead space.[31] The qualities that make the rectus abdominus an ideal soft tissue choice for open skull base reconstruction can also be found in latissimus dorsi, which similarly offers significant muscle bulk as well as a large skin area. The anterolateral thigh donor site has become a popular choice for soft tissue skull base reconstruction as well due to its relatively low morbidity and versatility of application, as well as its long and reliable vascular pedicle.[40] The anterolateral thigh donor site based off the lateral circumflex femoral artery can provide a variety of reconstructive options. In addition to being a perforator flap that can supply a large skin paddle, it can supply adipose and fascia tissues as well depending on the patient's morphology. Additionally, the vastus lateralis muscle or vascularized tensor fascia lata can be taken alone or in combination (►**Fig. 4**).[41–43]

Fig. 4 Anterolateral thigh free flap utilized for skull base dural replacement with vascularized fascia and muscle, volume reconstruction, and external coverage in an orbitocranial defect.

Finally, the radial forearm free flap is a highly reliable choice when tissue bulk is not desirable, but dural or watertight integrity is paramount. It is pliable, relatively easy to harvest, and has a very reliable blood supply with the longest vascular pedicle available to allow for easy remote vessel anastomosis to neck vessels or in cases of vessel depletion.[44] Additionally, the reliably thin pedicle allows for great flexibility in flap configuration and pedicle tunneling.

Bony Free Flaps

In most cases of anterior cranial base surgery, bony free flap reconstruction is not necessary.[5,31,35] Most often, soft tissue alone with transmitted volume support or combined usage of titanium reconstruction mesh can be used for structural support. However, when the defect or trauma extends to involve the orbit, nasal bone, or midface symmetric supports, or other aspects of the craniofacial functional buttresses, osseous free flaps reconstruction should be considered. As previously mentioned, orbitocranial defects pose unique problems, and choosing a donor site that can rebuild a boney buttress while providing enough volume and closure of CSF is crucial. Past experience has shown that reconstructing buttresses with bone, to support significant soft tissue bulk, is beneficial to long-term outcomes.[35] Vascularized bony reconstruction is generally regarded as preferable to bone grafting or plating alone, especially when postoperative radiation is expected, as free bone grafts have a tendency for resorption and plates have a higher risk for extrusion.[45,46] Fibular osteocutaneous free flaps have been described for skull base reconstruction and are a popular choice for extensive craniofacial reconstructions.[5] The fibula has significant bone stock as well as the option to integrate a large skin paddle. Importantly, soft tissue bulk is usually minimal; however, it can be variable depending on body habitus and can include a muscle cuff harvest. The ability to create multiple bone segments makes it ideal for the contouring requirements of the craniofacial skeleton.[47,48]

Another popular donor choice for bony reconstruction is the scapula. Utilizing the subscapular artery system, there are a wide variety of chimeric tissue types and geometries that can be designed off a single vascular pedicle. A variety of skin paddles can be designed either with random or perforator type vascularity. The latissmus dorsi and serratus muscle can both be harvested for a wide range of muscle reconstructive options. Specifically, these muscles can be used separately for two-layer reconstructions, in which one layer is applied for dural and skull base reconstruction, and then the additional layer can be used for volume or external reconstructive applications. This double layer of vascularized tissue can also provide for dead space control and aid in staged or integrated cranioplasty reconstruction. For bony options, the scapula tip, lateral scapula edge, and rib can all be harvested and chimerically applied. A combination of these tissue types, with impressive variable applications, has been referred to as a "mega flap."[49,50]

Future Directions

Virtual Surgical Planning

The utilization of multiplanar and three-dimensional (3D) reconstruction has been one of the most significant advances in head and neck surgery.[51,52] Since the technology for 3D imaging was developed approximately three decades ago, its continued refinement and novel application of this technology has trickled throughout medicine, including skull base surgery. The most recent fine cut computed tomography (CT) and 3T magnetic resonance imaging (MRI) machines provide high-resolution images at lower costs and less radiation exposure to patients. Surgical navigation based off multiplanar imaging is widespread and considered standard of care (►**Fig. 5**). Further volumetric manipulation of these two-dimensional multiplanar images has refined surgical planning and navigation by producing 3D images able to delineate tumor from normal tissue and highlight vital structures through color coding.[53] These advances in preoperative imaging have been able to increase the utilization of customized hardware and reconstructive planning. This is especially true in the case of bony craniofacial surgery where computer-aided manufacturing has made it possible to precisely plan osteotomies with cutting guides and easily place prebent or custom-milled plates.[54,55] Prefabricated implants and prostheses have been well described in craniofacial surgery to aid in reconstruction.[56] In cases of significant distorted anatomy due to tumor, trauma, or previous surgery, 3D modeling can create appropriate reconstructive plans based on symmetry of the normal craniofacial skeleton.[57] The increasing adaptation of image guidance and virtual 3D surgical planning has become a valuable aide to skull base surgery by reducing surgical time, improving teaching techniques, and reducing the intraoperative workload of surgeons.[58–60]

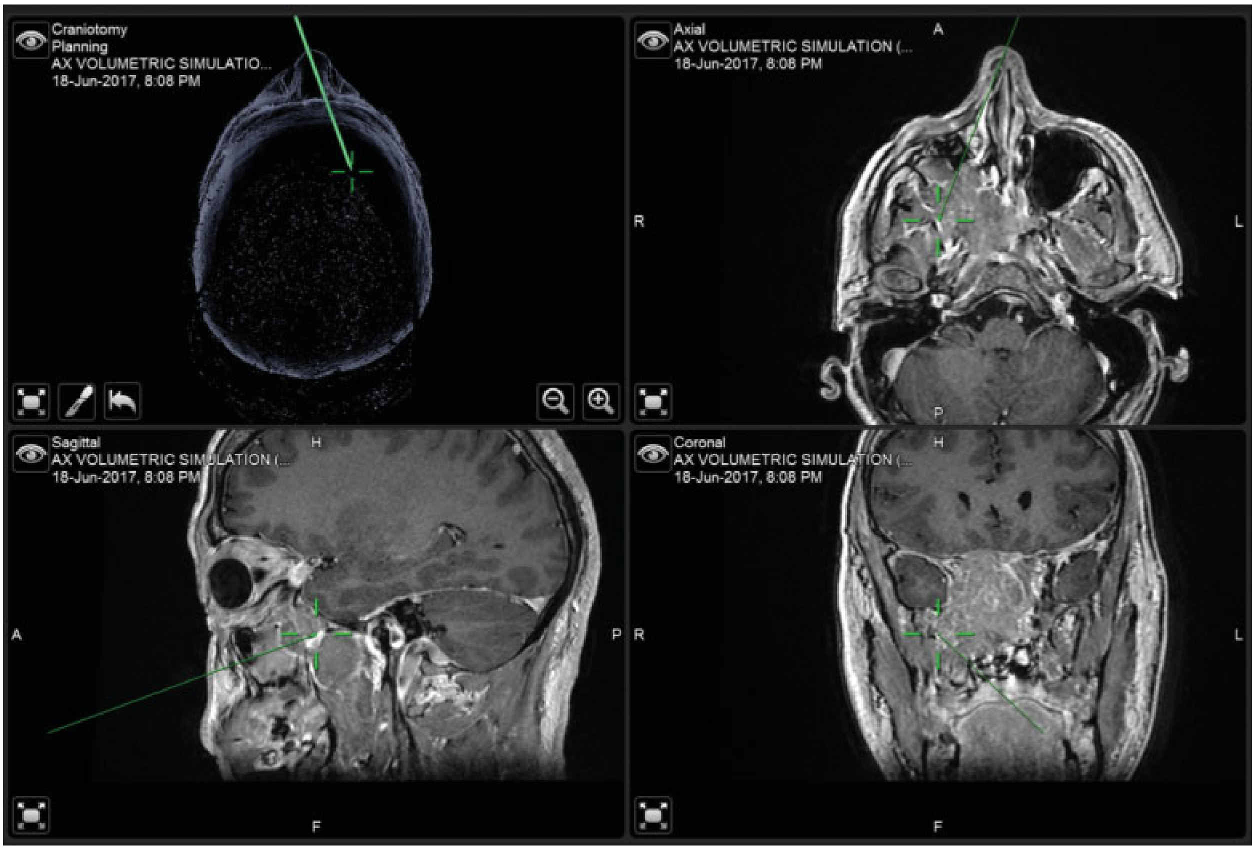

Fig. 5 Intraoperative image guidance with multiplanar MRI and 3D images. 3D, three-dimensional; MRI, magnetic resonance imaging.

Emerging Technologies

Other advances in skull base surgery include virtual reality or augmented reality skull base surgery. Color coded stereotactic virtual reality models can be made for individual cases creating a virtual operating field. This has been used for surgical education of trainees as well as creating opportunities for simulations prior to surgery.[61–64] Additionally, real-time integration of virtual reality technology into the operative field can be done by overlying 3D images onto microscope or endoscope views enhancing spatial navigation.[53] Finally, taking advantage of the fixed bony skeleton, surgical robots combined with stereotactic navigation systems are being developed to improve ergonomics and protect vital structures by creating "no fly zones."[65] The final role of these technologies remains to be seen, but these have numerous potential applications in both ablative and reconstructive skull base surgery.

Conclusion

Skull base surgery and reconstruction has undergone significant changes over the past several decades. While minimally invasive endoscopic resection and reconstruction will continue to advance skull base surgery for the foreseeable future, traditional open surgical approaches and reconstructive techniques are still contemporarily employed as best practices in certain tumors or patient-specific anatomical cases. Skull base surgeons should strive to maintain a working knowledge base and skill set to manage these challenging cases when endoscopic techniques have previously failed or are insufficient from anatomical or tumor constraints.

Conflict of Interest
None.

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