TECHNOLOGICAL ADVANCES IN SKULL BASE SURGERY

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The options for skull base surgery have expanded dramatically during the last 2 decades. This expansion has been facilitated by the use of technological developments.

Intraoperative navigation systems and intraoperative magnetic resonance imaging are 2 powerful tools that allow more aggressive surgical strategy with increased accuracy and safety. Intraoperative monitoring of the neural functions is another important tool to decrease the surgical risks. This is particularly important for brainstem and cranial nerves because these structures might be at risk during skull base surgery. Biologic glues proved to be very useful in skull base surgery. These substances may be used in skull base reconstruction, for protection or reconstruction of cranial nerves, and for vascular anastomosis.

Several factors have contributed to the enormous strides in surgery of the cranial base that were made during the past few years. Extensive anatomical research, numerous courses, and scientific meetings have all added to the knowledge and improvement of our understanding of the complex anatomy of the neural, vascular, and bony structures of the skull base. This enabled the development of new surgical approaches and the refinement of old ones. Cranial base surgery has also been positively affected by new developments in the field of imaging. The advent of new imaging modalities has significantly increased the accuracy of preoperative diagnosis and the delineation of anatomic structures, pathologic processes, and their relationship. The developments in interventional radiology and its use for embolization as an adjunct in the treatment of vascular lesions or tumors with rich vascularity has enabled the surgeon to be more radical in the approach of treating these defects with increased safety. The multidisciplinary approach and collaboration between surgeons from different specialties—particularly neurosurgeons, otolaryngologists, and plastic surgeons—has probably been one of the most beneficial factors to facilitate such enhanced surgery of the skull base.

The use of advanced technologies in the development of instruments and different auxiliary systems in the operating theaters has markedly influenced almost all disciplines of surgery. This article concentrates on some of the technological advancements as applied to skull base surgery.

INTRAOPERATIVE NAVIGATION SYSTEMS OR FRAMELESS STEREOTAXY

In recent years, we have witnessed a significant leap in the development and surgical applications of computer-assisted technologies. These technologies have had significant impact on almost all fields of surgery, including that of the skull base. Image-guided surgery uses either frame-based stereotaxy or navigation (frameless) systems. A navigation system consists of 3 essential parts: A computerized workstation for preoperative registration of magnetic resonance imaging (MRI) or computed tomography (CT) images acquired before surgery, a device for intraoperative localization, and a computer image display during surgery.

Intraoperative localization devices use one of 4 technologies: Mechanical arms,[1,2] ultrasonography,[3,4] infrared light emission,[5,6] and magnetic scanning. Fiducials made of aluminum markers and plastic socket are glued to the skin of the patient's head, and a CT scan or an MRI is obtained. The images are stored on an optical disc and transferred to the workstation, where 3-dimensional reconstruction can be made in 3 planes (ie, horizontal, sagittal, and coronal). These reconstructed images enable the planning of the best surgical approach and choosing the optimal trajectory.

The patient is positioned for surgery and registration is done with infrared light-emitting diodes and a special pointer provided with reflective markers. The infrared light reflected from the pointer is received by 2 cameras and displayed on a video controller. The navigation system is used to project the lesion on the skin surface, thereby allowing the surgery to be done with a smaller and more precise skin incision and craniotomy. The distance and the direction of the target (lesion) from the surface can be measured. The tip of the pointer tool or any other instrument equipped with reflective markers can be shown in real time during surgery, and its position relative to the lesion and to anatomic structures can be estimated.

The navigation system provides accurate localization, the distance from the surface, and the trajectory of a lesion, as well as a good definition of its borders. By means of this information, the surgeon can choose the optimal approach and trajectory for the case at hand. The navigator is linked to the operating microscope through a serial computer surface. The whole system is easy to use and is operated by the surgeon with no need for additional technical personnel.

There are, however, a few limitations. Errors may occur during registration of the fiducials on the patient's head,

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thereby reducing the accuracy of the navigation guidance. However, this difficulty can be overcome with the use of an adequate number of fiducials. Another limitation stems from the fact that the system uses preoperatively obtained information and does not detect changes that might occur later on. The navigation arm and the patient's head must be adequately fixed in place, because errors can also result from movement of either. An additional possible source of errors with navigation is brain shift. This may arise from several factors such as movement of the cortex after opening of the dura mater development of brain edema during surgery or decrease in edema after treatment with drugs and hyperventilation, and drainage of cerebrospinal fluid from the ventricles from cystic lesions or from the subarachnoid cisterns and removal of mass lesions. Skull base and epilepsy surgeries have been associated with less brain shift than surgery for meningiomas or intra-axial brain tumor.[7] Hashizume et al[8] considered that this minimal brain shift renders epilepsy and skull base lesions as being the best targets for navigation-guided surgery. After partial resection, the navigation system no longer detects changes in the position, boundaries, or relationship of the residual lesion. Finally, the system does not detect intraoperative complications such as hemorrhage, brain edema, or insinuation of air into the subdural space.

In spite of these limitations, navigation remains a powerful tool that has proved to be very useful. It is gaining wide acceptance in skull base and intracranial operations.[9,10] Importantly, combining navigation with other advanced surgical technologies can overcome most of these limitations.

INTRAOPERATIVE MRI

Magnetic resonance imaging has proved to be the most accurate modality for imaging skull base tumors. Intraoperative MRI guidance provides real-time, 3-dimensional, and multiplanar imaging information. It also enables the surgeon to differentiate between the pathologic lesion and the normal tissue as well as to define the borders of a lesion. Not infrequently, the differentiation allowed by intraoperative MRI is more accurate than that derived from direct visualization of the surgical field under the operative microscope, because MRI also shows what is beyond the borders of the exposed tissues. This differentiation provides exact and continuous monitoring of tumor removal and detects any residual parts of the tumor while showing its relationship to the surrounding anatomic structures. As a result, surgery can be safer and more radical. It is well known that there is a tendency to overestimate the extent of tumor resection during surgery. Black et al[11] found that intraoperative MRI showed a residual tumor in more than one third of cases when resection was thought to be complete according to the surgeon's judgment.

Intraoperative MRI helps to overcome some of the limitations that are associated with the frameless (navigation) and frame-based stereotactic systems. It requires no skin fiducials or preoperative registration, or transformation of imaging data. The issue of brain shift or distortion is eliminated because these changes are detected by the real-time, intraoperatively acquired images. Another important advantage of intraoperative MRI is its ability to diagnose surgical complications such as hemorrhage, edema, brain herniation, and pneumocephalus. Such complications can be dealt with as they occur. Intraoperative MRI also permits the surgeon to modify the surgical plan to meet dynamic changes during the surgical procedure.

The use of MRI intraoperatively, however, requires complex arrangements. Surgery must be done in a radiofrequency-shielded suite, and all equipment, machines, and tools must be MR compatible. This includes all anesthetic devices and surgical equipment, table, head holder, suction, drills, ultrasonic aspirators, lasers, ultrasound, and other instruments. No ferromagnetic equipment can be allowed because it will cause unacceptable artifacts on the MRI image by interaction with the magnetic field. In addition, electrical machines may cause artifacts in MR images, and adaptation has to be made accordingly.

In the prototype intraoperative MRI,[12] the system was designed in 2 parts in order to allow room for the patient's head as well as access for the surgeon. Many challenges have to be overcome if surgery is to be carried out within an MRI suite. Steinmeier et al[13] used a different system in which the MRI machine is located adjacent to the operating theater, and the patient is moved into the MRI for scanning and back to the operating site as necessary. Sutherland et al[14] introduced a new mobile high-field MRI system in which the MRI machine is separated from the operating room by one door and can be moved in for scanning and moved out in a very short time without mobilizing the patient.

Another mobile intraoperative MRI has recently been developed by Odin Technologies (Yokneam, Israel) in collaboration with our neurosurgical department. This MRI is designed to acquire images of limited volumetric region around the field of interest. The basic premise is that such a field of view is sufficient for the surgeon to visualize the target lesion and surrounding tissue. The new MRI unit is movable, and the region of interest is not entirely enclosed and relatively small so that it can be installed in an ordinary operating room after appropriate radiofrequency shielding. The magnetic probe is mounted on a C arm-type gantry and can be moved to the scan position or returned to its place underneath the operating table in less than one minute. The same operating room is used for conventional surgery when the MRI system is not in use. The system is safe, accurate, compact, user friendly, and relatively inexpensive.

INTRAOPERATIVE PHYSIOLOGIC MONITORING

Surgery of the cranial base carries potential risk to many vital structures such as the brainstem, cranial nerves, and blood vessels. Injury to these structures may lead to severe morbidity and even death.

Motor cranial nerves may be monitored by electromyography in which bipolar electrical stimulation is applied on the nerve and the compound muscle action potential (CMAP) is recorded from the muscle supplied by this nerve. The muscular activity may be transformed into audible signals. During surgery, the nerves are at risk of inadvertent damage because they are often displaced from their normal course and may be obscured from the surgeon's vision because of distorted anatomy. Monitoring enables the surgeon to identify the nerves in these pathologic conditions.[15] The nerve will be found in the area with the lowest stimulus intensity required to obtain muscle response. Manipulation of the tumor and dissection from the cranial nerves thus becomes safer and more rapid when done under physiologic monitoring. Cranial nerves may be paralyzed postoperatively even though their anatomical integrity had been preserved during surgery.[16] Intraoperative monitoring helps reduce this risk, because disappearance of the CMAP or a rise in the stimulus intensity to elicit a response denotes that the nerve function is being either directly or indirectly violated (eg, from traction or displacement).

The facial nerve has been the most commonly monitored cranial nerve, especially during surgery of an acoustic neurinoma. The results of facial nerve function after acoustic neurinoma surgery were found to be superior when physiologic monitoring was used and when surgery was done with the retrosigmoid approach.[17] Experience has shown that facial nerve monitoring during skull base surgery is associated with a significant decrease in permanent postoperative facial paralysis.[18]

Surgery for lesions involving the anterior skull base, orbits, and suprasellar region carries risk to the optic nerve and optic chiasm. Several publications have described methods for intraoperative monitoring of the optic nerve and for intraoperative recording of the visual evoked potential.[19,20] For instance, the nerves of extraocular eye movements (oculomotor, trochlear, and abducens nerves) can be injured during surgery of the cavernous sinus and anterior skull base, possibly leading to severe disability and even to a functionally blind eye. Although methods have been developed for monitoring the ocular motor nerves,[21-22] they have not, however, gained wide popularity.

Monitoring of the lower cranial nerves is important during surgical resection of lesions in the cerebellopontine angle, jugular foramen, infratemporal fossa, and neck. Iatrogenic damage to the vagal and glossopharyngeal nerves may be associated with severe complications related to swallowing, aspiration, and respiratory problems. The vagal nerve may be accurately monitored by laryngeal electromyography, in which contractions of the vocalis muscle are recorded in response to electrical stimulation of the nerve. Muscle activity may be recorded by a laryngeal surface electrode or by a hookwire electrode inserted into the muscle either via direct laryngoscopy or percutaneously through the cricothyroid membrane.[23,24] Direct monitoring of the glossopharyngeal nerve is more difficult, because it supplies only one small muscle in the pharynx, which is the stylopharyngeal muscle. The glossopharyngeus, however, is located in very close approximation to the vagus nerve, and monitoring of the vagus can provide adequate information about it as well.

In addition to the motor cranial nerves, intraoperative monitoring can also be applied to sensory nerves and pathways. The brainstem and cochlear nerve can be monitored by brainstem auditory-evoked potentials (ABR). The cochlear nerve can also be directly monitored in patients who are undergoing surgery in the cerebellopontine angle.[25] Somatosensory evoked potentials (SSEP) may be used together with ABR for intraoperative monitoring of the brainstem during surgery of skull base tumors. When ABR and SSEP were significantly altered during surgery, the patients had parallel significant postoperative brainstem dysfunction.[26]

Recording of SSEP is also useful to monitor cerebral function, which may be affected by brain retraction or vascular compromise[15] if the operation involves manipulations, transposition, anastomosis, and especially scarifying of major blood vessels.

There is sufficient evidence that physiologic monitoring during surgery can substantially reduce the risk to the brainstem and cranial nerves. Intraoperative monitoring is easy to perform and does not interfere with the surgical procedure. For these reasons, monitoring has become widely recognized as an important aid in preventing iatrogenic complications in skull base surgery.

BIOLOGIC GLUE

The use of tissue adhesives in medicine has increased significantly over recent years. These adhesives have several actions—hemostatic, sealing, gluing, filling, and the promotion of healing processes. As a result, they may be used to prevent leakage of air, blood, lymphatic fluid, or cerebrospinal fluid. They also can be used to enhance endothelialization of vascular grafts and to facilitate wound healing.

Most of the commercially available biologic glues are based on 2 main components, which are fibrin and thrombin. The fibrin is supplemented by tranexamic acid, which is a synthetic antifibrinolytic substance currently used with coagulation factors to prevent hemorrhage. Thrombin is found in this sealant as alpha thrombin in a concentration of 550 to 1,000 u/ml and is responsible for rapid coagulation. Thrombin also has other biologic actions such as activation of blood platelets and epithelial cells. Both fibrin and thrombin play an important role in the coagulation process as well as in the formation of scar tissue.

The main factors to be considered in the preparation and use of biologic glue are:

(1) Safety of the agent, its components and its metabolites or degradation products; (2) Speed of polymerization; (3) Mechanical properties such as elasticity, intrinsic tensile force, and strength of tissue adhesion; (4) The volume required; and (5) The method of application (eg, spraying or spreading). Because fibrin and thrombin are used in their natural form and undergo biodegradation in the human body, it is very unlikely that they will have any hazardous effects such as immune response or carcinogenesis. The safety of biologic glues has been further augmented by their being manufactured by modern antiviral technologies that inhibit transmission of viral diseases. Currently, we use fibrin-based glues that contain a concentrated cryoprecipitate of clottable proteins that include fibrinogen and human thrombin. These products are free from any animal material and their preparation process involves double viral elimination. The glues are available in a frozen or a liquid form and can be applied to tissues as either a drip or a spray.

Skull base surgeons frequently use biologic glues for a variety of purposes. Among the important ones in cranial base surgery is the reconstruction and repair of dural and bony defects. Such defects may be attributable to congenital malformations, invasive tumors, trauma, and surgical interventions, and may lead to cerebrospinal fluid fistulae, pneumocephalus, and intracranial infections. Biologic glues have proved to be very effective when used for direct repair of tears of the dura mater, and to enforce flaps (mucosa, fascia, muscle, or periosteum) during cranial base reconstruction.[27-30] These adhesive substances may also be used to repair transacted cranial nerves,[31] to coat cranial nerves in order to protect them from inadvertent surgical injury,[32] and to protect brain tissue from CO2 laser beam during it use in surgery.[33] Fibrin glue was also found to be useful in stabilizing vessels and in transposition or fixation of vessels in microvascular surgery.

SUMMARY

Modern technological advances in imaging modalities and surgical systems have significantly contributed to rapid development in skull base surgery. New imaging technologies provide better understanding of the nature and anatomical relationships of different skull base defects. Advanced surgical systems help decrease the operative risks to neural and vascular structures, and shorten the time of surgery. Additional refinements of these technologies and innovation of additional systems are expected in the future and, hopefully, they will help to make the challenging field of skull base surgery a safer and less complicated one.

REFERENCES

1. Guthrie BL, Adler JR Jr: Frameless stereotaxy: Computer interactive neurosurgery. Perspect Neurol Neurosurg 2:1-22, 1991
2. Mosges R, Schlondorff G: A new imaging method for intraoperative therapy control in skull base surgery. Neurosurg Rev 11:245-247, 1988
3. Reinhardt HF, Zweifel HJ: Interactive sonar-operated device for stereotactic and open surgery, in Gildenberg PL (ed): Stereotactic and Functional Neurosurgery. Blacklick, OH, McGraw-Hill, 1990, pp 393-397
4. Barnett GH, Kormos DW, Steiner PC, et al: Use of a frameless, armless stereotactic wand for brain tumor localization with 2-dimensional and 3-dimensional neuroimaging. Neurosurgery 33:674-678, 1993
5. Germano IM: The neurostation system for image-guided frameless sterotaxy. Neurosurgery 37:348-351, 1995
6. Smith KR, Frank KL, Bucholz RD: The neurostation: A highly accurate, minimally invasive solution to frameless stereotactic neurosurgery. Comput Med Imaging Graph 18:247-256, 1994
7. Dorward NL, Alberti O, Velani B, et al: Postimaging brain distortion: Magnitude, correlates, and impact on neuronavigation. J Neurosurg 88:656-662, 1998
8. Hashizume K, Tanaka T, Kunimoto M, et al: Image-guided surgery for epilepsy. No Shinkei Jeka 25:329-335, 1997
9. Sargent EW, Bucholz RD: Middle cranial fossa surgery with image-guided instrumentation. Otolaryngol Head Neck Surg 117:131-134, 1997
10. Carrau RL, Snyderman CH, Curtin HD, et al: Computer-assisted intraoperative navigation during skull base surgery. Am J Otolaryngol 17:95-101, 1996
11. Black P McL, Alexander E, Marten C, et al: Craniotomy for tumor treatment in an intraoperative magnetic resonance imaging unit. Neurosurgery 45:423-433, 1999
12. Black PM, Moriaty T, Alexander E, et al: Development and implementation of intraoperative magnetic resonance imaging and its neurosurgical applications. Neurosurgery 41:831-842, 1997
13. Steinmeier R, Falbusch R, Ganslandt O, et al: Intraoperative magnetic resonance imaging with the magnetom open scanner: Concepts, neurosurgical indications and procedures: A preliminary report. Neurosurgery 43:739-748, 1998
14. Sutherland GR, Kaibara T, Louw D, et al: A mobile high-field magnetic resonance system for neurosurgery. J Neurosurg 91:804-813, 1999
15. Stechison MT: Neurophysiologic monitoring during cranial base surgery. J Neurooncol 20:313-325, 1994
16. Sekiya T, Hatayama T, Iwabuchi T, et al: Intraoperative recordings of evoked extraocular muscle activities to monitor ocular motor nerve function. Neurosurgery 32:227-235, 1993
17. Grey PL, Moffat DA, Palmer CR, et al: Factors which influence the facial nerve outcome in vestibular schwannoma surgery. Clin Otolaryngol 21:409-413, 1996
18. Magliulo G, Pethi R, Vingolo GM, et al: Facial nerve monitoring in skull base surgery. J Laryngol Otol 108:557-559, 1994
19. Feinsod M, Selchorst JB, Hoyt WF, et al: Monitoring optic nerve function during craniotomy. J Neurosurg 44:29-31, 1976
20. Russ W, Luben V, Hempelmann G: Effect of neuroleptanalgesia on the visual evoked potential (VEP) in man. Anaesthesist 31:575-581, 1982
21. Sekhar LN, Moller AR: Operative management of tumors involving the cavernous sinus. J Neurosurg 64:879-889, 1986
22. Sekiya T, Hatayama T, Iwabuchi T, et al: Intraoperative recordings of evoked extraocular muscle activities to monitor ocular motor nerve function. Neurosurgery 32:227-235, 1993
23. Leonetti JP, Jellish WS, Warf P, et al: Intraoperative vagal nerve monitoring. Ear Nose Throat J 75:489-491, 1996
24. Severtson MA, Leonetti JP, Jarocki D: Vagal nerve monitoring: A comparison of techniques in a canine model. Am J Otol 18:398-400, 1997
25. Gueva RA, Morris GF, Preoleau GR: Direct cochlear nerve monitoring: First report on a new, atraumatic, self-retaining electrode. Am J Otol 19:202-207, 1998
26. Gentili F, Lougheed WM, Yamashiro K, et al: Monitoring of sensory evoked potentials during surgery of skull base tumors. Can J Neurol Sci 12:336-340, 1985
27. Wiegand DA, Hartel MI, Quander T, et al: Assessment of cryoprecipitate thrombin solution for dural repair. Head Neck 16:569-573, 1994
28. Tokoro K, Chiba Y, Murai M, et al: Cosmetic reconstruction after mastoidectomy for transpetrosal presigmoid approach. Technical note. Neurosurgery 39:186-188, 1996
29. Van-Den-Abbeele T, Elmaleh M, Herman P, et al: Transnasal endoscopic repair of congenital defects of the skull base in children. Arch Otolaryngol Head Neck Surg 125:580-584, 1999
30. Sawamora Y, Asaoka K, Tarasaka S, et al: Evaluation of application techniques of fibrin sealant to prevent cerebrospinal fluid leakage: A new device for the application of aerosolized fibrin glue. Neurosurgery 4:332-337, 1999
31. Van Overbeeke JJ, Cruysberg JR, Menovsky T: Intracranial repair of divided trochlear nerve. Case report. J Neurosurg 88:336-339, 1998
32. De-Vries J, Menosky T, Grotenhuis JA, et al: Protective coating of cranial nerves with fibrin glue (Tissucol) during cranial base surgery. Neurosurgery 43:1242-1246, 1998
33. Menovsky T, de Vries J: Use of fibrin glue protect tissue during CO2 laser surgery. Laryngoscope 108:1390-1393, 1998