Sonography in Neurosurgery: History, Current Applications, and Future Innovations

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Sonography is a noninvasive technique that uses a hand-held transducer placed directly on the body to produce pulses of acoustic energy at frequencies between 2 and 20 MHz that reflect off of tissues with different acoustic resistance to create images.[1] There are 3 different modes of ultrasound, including amplitude or A-mode, brightness or B-mode, and motion or M-mode. B-mode imaging is the most used form of sonography that produces a 2-D image of tissue. Sonography also can be enhanced by employing the Doppler effect, which can distinguish between objects moving toward and away from the transducer and often is used in medicine to visualize blood flow.

Sonography has been incorporated into neurosurgery from the earliest days of ultrasound technology and continues to be an essential technology in the field. Historically, sonography has been used to localize tumors in the brain parenchyma and assess tumor resection, and its use has expanded throughout neurosurgical subspecialities, including spine, peripheral nerve, trauma, and vascular surgery. Although computed tomography (CT) and magnetic resonance (MR) imaging remain the most essential and employed imaging tools in neurosurgery, sonography offers the unique benefit of immediate availability, as well as relatively low cost and real-time imaging in the operating room. As sonography evolves, its current practices in neurosurgery will expand.

Background of Sonography in Neurosurgery

Karl Dussik, a pioneer in sonographic technology, began studying sonography in the 1930s. In 1937, Dussik and his brother used a 1.5-MHz transmitter to detect changes in amplitude of energy when scanning the human brain.[2] Initially, they believed that areas of decreased wave transmission were lateral ventricles; however, the areas were later shown to be variations in bone thickness. Regular use of sonography in medicine began in the 1950s in the field of obstetrics and became routine in the 1960s when the first sonography devices became commercially available.[2]

The first successful use of sonography to localize brain tumors was in 1951, when Lyle A French et al attempted to use ultrasonic pulses to localize brain tumors.[3] Through this trial, the researchers concluded that ultrasonic pulses did not damage cerebral hemispheres and that subcortical cerebral neoplasms could be localized using sonography.[3] In 1978, Michael Reid published a case report outlining the use of sonography in evaluating a cervical spinal cord cystic astrocytoma. By employing the interlaminar spaces, he was able to accurately evaluate the spinal cord with definition adequate enough to detect intraspinal lesions.[4] One year later, Nornes et al published their success with Doppler technique sonography allowing visualization of cerebral artery flow characteristics and its use during procedures for arteriovenous malformations[5] and intracranial aneurysms.[6] Dohrmann and Rubin then published their experience in the 1980s with intraoperative sonography for spinal cord visualization.[7] They reported the ability to visualize a healthy spinal cord, as well as the ability to distinguish between intramedullary, extramedullary, intradural, and extradural lesions.[7] Furthermore, in the 1980s, sonographic technology was introduced into intracranial neurosurgeries to image pathologic structures during surgery. Imaging could be accomplished with equal clarity by placing a transducer on the dura or on the brain surface itself. Because sonography does not emit radiation and is, therefore, considered inherently safe, the researchers concluded sonography could be used throughout the procedure while providing immediate localization and shortening operating times.[8]

Current Applications of Sonography in Neurosurgery

Currently, sonography enjoys broad use in neurosurgery. Sonography as an intraoperative imaging modality is employed in spinal surgeries to localize intradural mass lesions when anatomical shifts might follow bony exposure and lead to inaccurate preoperative imaging. This can allow surgeons to adapt their surgical approaches to provide a more accurate dural opening, in location and size.[9] Improved accuracy not only allows for a less invasive technique, which can preserve the stability of surrounding bony and ligamentous structures, but also can allow for safer maximal resection of pathologic lesions by limiting iatrogenic effects on healthy neurological tissue.

In addition, sonography is used to assess the degree of decompression of the thecal sac during spinal surgeries performed for spinal cord decompression (see **Figure**). Sonography can be used to evaluate residual stenosis from multiple compressive pathologies such as removal of a herniated disc, bony fragment from trauma, decompression of degenerative spinal stenosis, or separation surgery before radiation therapy in patients with spinal tumors. Intraoperatively, it provides the ability to visualize the ventral epidural space, which cannot be visualized directly by the surgeon and might not be adequately decompressed without intraoperative imaging guidance.[10-12] Although intraoperative CT and MR imaging are also options for evaluating such pathologies, intraoperative sonography can be used in a more timely manner and is more readily accessible compared with other intraoperative imaging modalities, which are substantially more costly and might not be available in many medical facilities.

Figure. *Sagittal view of a thoracic spinal arachnoid cyst causing spinal cord compression. Image courtesy of the authors.*

Sonography also is gaining popularity for accurately localizing intracranial mass lesions intraoperatively. Along with assisting in planning surgical trajectory for resection of mass lesions, real-time use of sonography shows promise when adjusting for intraoperative brain shifts that occur as a lesion is resected and can lead to inaccuracy of preoperative imaging and neuronavigation.[13] After craniotomy and dural opening, the brain might shift up to 2 cm, and this makes preoperative imaging inaccurate.[14] Maximal safe resection of an intracranial lesion is a key contributor to overall survival and postprocedural symptomatology in patients with intracranial malignancy, and without accurate intraoperative imaging, there is greater risk of causing damage to healthy neural structures, as well as leaving residual abnormal tissue that might affect overall patient prognosis. Similar to their use of evaluating for residual stenosis during spinal surgeries, intraoperative CT and MR imaging provide an advantage in terms of being able to evaluate for residual lesion before the patient leaves the operating room, but these technologies do not provide real-time, intraprocedural evaluation, and they add logistical difficulty to surgical cases. One downside of intraoperative sonography in intracranial surgeries is the limitation of use depending on patient positioning, as the sonography field must be filled with saline to provide images of the highest quality. If the craniotomy performed is not parallel to the ground, there might be difficulty filling the resection cavity with saline, a limitation unique to sonography compared with CT and MR imaging.[15]

The use of sonography for localization and resection of intracranial lesions is not limited to malignancy but more recently has been described for evacuation of intracranial hematoma. Sonography has assisted in finding the most appropriate corticectomy trajectory for use during evacuation. By defining the shortest transcortical trajectory, surgeons can take a less invasive approach to hematoma evacuation, allowing preservation of as much healthy brain tissue as possible.[16] In addition, sonographic guidance might provide visualization of residual hematoma to improve the degree of evacuation.[17]

Doppler mode, which can distinguish objects moving toward and away from the ultrasound probe and determine their speed and direction by observing shifts in wave frequency,[2] is used frequently in intracranial vascular neurosurgery, particularly in managing intracranial aneurysms. When aneurysms are clipped, sonography can be used to detect incomplete aneurysm obliteration as well as adjacent vessel stenosis, allowing improved aneurysm clipping and the ability to reposition clips without requiring subsequent surgery.[18]

This same duplex technology can be used in other realms of neurovascular surgery. During carotid endarterectomy, duplex sonography is useful in identifying intraluminal defects that could lead to thromboembolic events and worsen patient outcomes. Not only has sonography been shown to visualize residual intraluminal thrombus, it also can identify iatrogenic pseudoaneurysms, intimal flaps, dissection, and stenosis. These pathologies are all in the realm of correctable intracarotid defects that can be managed before full surgical bed closure, preventing perioperative stroke or transient ischemic attack.[19,20]

Future Innovations of Ultrasound Technology in Neurosurgery

Innovations of ultrasound technology include contrast-enhanced sonography, 3-D imaging, and improved training on intraoperative sonography for neurosurgeons.

Contrast-Enhanced Sonography

Contrast-enhanced sonography differs from traditional sonography in that it uses contrast agents containing microbubbles injected intravenously that can be used to visualize vasculature.[21] These microbubbles are similar in size to a red blood cell (ie, 2-20 µm) and remain intravascular, allowing unimpeded transfer throughout the lungs to better image the arterial system. After the microbubbles have entered the vasculature, they enhance echogenicity, causing areas where the contrast has accumulated to appear bright white.

Contrast-enhanced sonography is a well-established technique for many organs, including the liver and kidneys, but it has been introduced into neurosurgery relatively recently.[21,22] Although trials began in 2008 and 2009 to test the effectiveness of contrast-enhanced sonography in the resection of brain tumors,[23] by 2013, 3 intraoperative neurosurgical studies had been performed using contrast agents,[21] and no standardized protocol for the use of contrast-enhanced sonography for tumor resection had been established in the United States.[24] Contrast-enhanced sonography has the potential to be a safe and cost-effective method to characterize brain tumors in real time. Not only does contrast-enhanced sonography have the possibility of use as a localization tool, it also might augment the ability to distinguish residual tumor tissue from healthy brain or edematous tissue to visualize the full extent of a lesion. Defining the tumor border and the extent of resection of the tumor are considered 2 key concerns in neurosurgery, and many studies have hypothesized that contrast-enhanced sonography might be an efficient, cost-effective, and nonrestraining tool to maximize outcomes for these components. Traditional preoperative imaging tools are not always reliable when it comes to planning surgical approach and resecting the entire extension of a lesion.[14,25] After craniotomy and durotomy, the brain might shift up to 2 cm.[14] Real-time imaging is particularly important because it provides the ability to adjust for intraoperative movement after preoperative image capture.

3-D Imaging

Three-dimensional sonographic reconstruction technology originally was attempted almost 35 years ago, with most development focused on cardiac and fetal scanning.[26] Near the time that contrast-enhanced sonography use in neurosurgery was investigated, trials evaluating the use of 3-D reconstructed sonography for resection of brain tumors began.[23] Although traditional sonography is limited by 2-D slices, 3-D reconstruction relies on several 2-D slices put together, compiled by tilting the probe over the area of interest.[27] Three-dimensional ultrasound can be used to reconstruct 3-D images of the brain to assist with imaging of surgical anatomy.[27] Many studies have evaluated its use in neurosurgery, including in resection of brain and spinal tumors,[28-30] and have found that 3-D sonographic imaging acquisition is time effective and cost effective when compared with other 3-D imaging modalities such as MR imaging or CT, and imaging quality can be comparable to that of intraoperative MR images.[31-33]

Contrast-Enhanced Sonography and 3-D Imaging

Despite promising reviews of contrast-enhanced sonography in the realm of neurosurgery, particularly for evaluating intracranial malignancies, there are few commercially available contrast-enhanced sonography devices for use in neurosurgery. In addition, none of these available devices combine contrast-enhanced sonography and 3-D imaging.[15] The intraoperative combination of 3-D contrast-enhanced sonography has shown promise in detecting brain tumors preoperatively as well as residual tumor after resection[23] compared with postoperative MR imaging. Incorporating contrast-enhanced sonography with 3-D sonography might improve the ability to navigate the brain and better plan resection throughout the operative process, and future development of commercially available devices combining 3-D and contrast-enhanced sonography will allow further exploration of the use of this technology in areas of neurosurgery other than intracranial malignancy.

Improved Training on Sonography for Neurosurgeons

Currently, neurosurgeons undergo extensive training on how to interpret CT and MR images in the coronal, axial, and sagittal planes. This training allows them to be comfortable with reviewing imaging outside of the operating room and intraoperatively. Because sonographic technique and interpretation are not widely taught during training, some neurosurgeons might find themselves uncomfortable with the use of intraoperative sonography. Sonography use depends on probe positioning, and thus is user dependent. Inability to appropriately position the probe limits the adequacy and timely use of intraoperative sonography. In addition, sonography has a limited field of view, particularly with the use of small incisions or craniotomies, and the entirety of a lesion might not be visible, unlike with MR- or CT-guided neuronavigation. Future use of intraoperative sonographic guidance in neurosurgery depends on improved training for neurosurgeons and better understanding and interpretation of sonography images.

Conclusion

Sonography is a powerful tool that is useful in many realms of neurosurgery. With improved surgeon training on intraoperative sonographic device use, as well as access to up-and-coming sonographic technologies such as 3-D sonography and contrast-enhanced sonography, sonography might prove to be an invaluable tool in the future of neurosurgical intraoperative imaging.

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