Modern intraoperative imaging modalities for the vascular neurosurgeon treating intracerebral hemorrhage

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This paper reviews the current intraoperative imaging tools that are available to assist neurosurgeons in the treatment of intracerebral hemorrhage (ICH). This review shares the authors’ experience with each modality and discusses the advantages, potential limitations, and disadvantages of each.

Surgery for ICH is directed at blood clot removal, reduction of intracranial pressure, and minimization of secondary damage associated with hematoma breakdown products. For effective occlusion and safe obliteration of vascular anomalies associated with ICH, vascular neurosurgeons today require a thorough understanding of the various intraoperative imaging modalities available for obtaining real-time information. Use of one or more of these modalities may improve the surgeon’s confidence during the procedure, the patient’s safety during surgery, and surgical outcome.

The modern techniques discussed include 1) indocyanine green–based video angiography, which provides real-time information based on high-quality images showing the residual filling of vascular pathological entities and the patency of blood vessels of any size in the surgical field; and 2) intraoperative angiography, which remains the gold standard intraoperative diagnostic test in the surgical management of cerebral aneurysms and arteriovenous malformations. Hybrid procedures, providing multimodality image-guided surgeries and combining endovascular with microsurgical strategies within the same surgical session, have become feasible and safe. Microdoppler is a safe, noninvasive, and reliable technique for evaluation of hemodynamics of vessels in the surgical field, with the advantage of ease of use. Intraoperative MRI provides an effective navigation tool for cavernoma surgery, in addition to assessing the extent of resection during the procedure. Intraoperative CT scanning has the advantage of very high sensitivity to acute bleeding, thereby assisting in the confirmation of the extent of hematoma evacuation and the extent of vascular anomaly resection. Intraoperative ultrasound aids navigation and evacuation assessment during intracerebral hematoma evacuation surgeries. It supports the concept of minimally invasive surgery and has undergone extensive development in recent years, with the quality of ultrasound imaging having improved considerably.

Image-guided therapy, combined with modern intraoperative imaging modalities, has changed the fundamentals of conventional vascular neurosurgery by presenting real-time visualization of both normal tissue and pathological entities. These imaging techniques are important adjuncts to the surgeon’s standard surgical armamentarium. Familiarity with these imaging modalities may help the surgeon complete procedures with improved safety, efficiency, and clinical outcome.

Key Words • intracerebral hemorrhage • intraoperative imaging • indocyanine green • angiography • magnetic resonance imaging • ultrasound

Intracerebral hemorrhage occurs in many conditions and has a wide spectrum of causes;7,29,31,39,42,58 most commonly, ICH occurs as a result of degenerative vascular disease, amyloid angiopathy, and hemorrhagic transformation of ischemic strokes. However, up to 10% of ICHs are due to underlying vascular structural anomalies (AVMs, aneurysms, and cavernous angiomas being the most common). Other less common vascular malformations include sinus or cortical vein thrombosis, arteriovenous fistula, and arterial dissection.

Intracerebral hemorrhage is associated with a high early mortality rate and a significant long-term morbidity rate. Among all stroke subtypes, it is considered to be the one with the highest mortality rate. Hematoma volume is an important predictor of 30-day mortality, and hema-
toma growth is a principal cause of early neurological deterioration. One should especially emphasize the high percentage of vascular pathological entities associated with ICH in the pediatric population, in which such entities were confirmed in a recent series in 61% of pediatric patients.

Therapy for ICH is directed at blood clot removal, reduction of intracranial pressure, and of secondary associated damage. In the International Surgical Trial in Intracerebral Haemorrhage (STICH), the effect of medical versus surgical management of ICH was compared, but, except for a small subgroup of patients who experienced a benefit from surgery, no significant advantage was demonstrated for any of the treatments.

The concept of “suction surgeries” (referring to ICH removal through large craniotomies) is now obsolete. Vascular neurosurgeons treating ICH should be prepared to deal not only with clot removal but also with the underlying cause. These tasks are often complex, both from the morphological and the technical point of view; and increase the risk for potential vessel compromise. For effective occlusion and safe obliteration of vascular anomalies, the neurosurgeon today may require intraoperative imaging modalities for obtaining real-time information. The use of intraoperative imaging modalities is of particular relevance when preoperative vascular imaging studies are negative but the intraoperative findings reveal a discrete lesion. In these complex cases the surgeon has to adapt and perform the procedure without a complete picture of the task ahead. Intraoperative imaging assessment in such situations can be particularly informative.

Along with the advances in neurosurgical techniques, significant progress has been made in the field of intraoperative imaging, especially intraoperative neurovascular imaging. From the development of uniplane angiography, the first description of CT contrast infusion to identify vascular lesions, and Doppler techniques to MR angiography and transcranial Doppler, reliable intraoperative imaging technologies have been developed. Several intraoperative modalities have been implemented: ICG-VA, iDSA, iCT, iMRI, iMD, and 3D iUS. These new imaging techniques and the concept of true hybrid rooms providing multimodality image-guided surgeries have improved diagnostics considerably. Such techniques may significantly assist the surgeon in challenging cases.

This paper reviews the current intraoperative imaging tools and the clinical use of each modality. Our experience with the various modalities and their advantages and potential limitations are discussed.

**Intraoperative Imaging Techniques**

**Indocyanine Green–Based Video Angiography**

Indocyanine green–based video angiography provides real-time information on the residual filling of aneurysms and on the patency of blood vessels of any size in the surgical field, including perforators, based on high-quality images. First introduced into the neurosurgical operating room in 2003, the ICG-VA technique was found to be a simple and safe way to assess blood flow intraoperatively. Sequential studies compared the findings of ICG-VA with iDSA or postoperative DSA and reported them to be comparable in 90% of cases. Subsequently, the use of DSA for intraoperative evaluation of aneurysms has decreased. In the setting of ICH surgery with an underlying vascular pathological entity such as cerebral aneurysm or AVM, ICG is a powerful tool (Fig. 1). The ICG-VA technique is now widely used in multiple settings beyond aneurysms. It is routinely used for intracranial and spinal AVMs and arteriovenous fistulas. Unquestionably, ICG-VA has become an important adjuvant in vascular neurosurgery.

However, ICG is not suited for all applications. Its use is limited to the microscope’s field of view and only to exposed blood vessels, so that not all vasculature can be...
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assessed. In addition, there are various factors that may limit the accuracy of ICG fluorescence signals, such as thick-walled or partially thrombosed aneurysms or cases of deep-seated or giant aneurysms.27 The utility of this imaging modality in the setting of AVM surgery is still unclear because of these visualization issues. Because only the parts of the AVM that are already visible in the surgical field will be visible to ICG-VA, standard intraoperative DSA remains the gold standard imaging modality in the assessment of AVM resection.

We use ICG-VA on a routine basis during vascular surgeries, including ICH evacuations, when the need arises (Fig. 2). It helps us assess residual filling of vascular lesions such as aneurysms and the patency of surrounding vessels after clipping. Sometimes multiple injections are performed after complex clip reconstructions. Use of ICG-VA has reduced our need for intraoperative DSA, which is now reserved for more difficult cases or those in which there is doubt following the ICG-VA.

Intraoperative DSA

This is a powerful diagnostic tool in the surgical management of cerebral aneurysms and AVMs and is still considered the gold standard procedure when assessing precise aneurysm clipping and vessel patency. It allows the neurosurgeon to confirm complete occlusion of the aneurysm and to demonstrate patency of all surrounding vasculature.

Several groups have evaluated iDSA efficiency and have revealed that it is both effective and accurate.9,37,49 In the largest single-center study, of 1093 vascular cases in which patients underwent routine iDSA, a greater than 8% revision of clip placement due to abnormalities found on iDSA was reported.9 In 9 (8.9%) of 101 patients, iDSA demonstrated residual AVM requiring additional resection. Two of these patients (22.2%) required a second surgical revision, and successful excision of the residual AVM was confirmed by repeat iDSA in all 9 patients. With minimal risk of morbidity (0.99%) and neurological complications occurring in only 0.09% of cases, the authors reaffirmed iDSA safety and utility in the surgical treatment of aneurysms and vascular malformations.

As always, the value of iDSA must be weighed against the risk of complications and technical difficulties.14,21 The reported complication rate is as high as 3%. Various technical challenges include the need for skilled neuroradiology staff, high costs, the need for a DSA C-arm, a radiolucent operating table head holder, and angiography equipment. At times the additional equipment can make the operating room particularly cramped (Fig. 3). In the
setting of ICH treatment, iDSA may be too cumbersome to perform during an urgent operation due to availability of staff or equipment.

The drawbacks of iDSA may lead some to conclude that it is not a practical tool for all vascular cases. It is therefore best applied selectively, for complex vascular malformations and lesions in challenging anatomical locations.

**Hybrid Operating Room: Applications in ICH Surgery**

The concept of a hybrid operating room combining endovascular and microsurgical strategies within the same surgical session is applicable, cost-effective, and safe.

Full biplane neuroangiography in a fully equipped neurosurgical operating room provides a seamless transition between the operation and iDSA, which can be performed without repositioning the patient or moving in a portable C-arm. The result is higher-quality angiography in 2 planes, which provides immediate intraoperative assessment of vessel patency and occlusion rate of different vascular pathological entities.

An example for this kind of setup is the addition of an iMRI unit to the hybrid operating room. Examples are the Advanced Multimodality Image-Guided Operating (A.M.I.G.O.) Suite at the Brigham and Women’s Hospital and Harvard Medical School and the implementation of so-called IMRIS suites (IMRIS, Inc.) at various locations internationally. These systems are able to integrate a 1.5- to 3-T iMRI unit into a fully operational neurosurgical operating room and a full biplane angiography suite.

**Intraoperative Microdoppler Techniques**

Microdoppler imaging is a safe, noninvasive, and reliable technique for evaluation of the hemodynamics of vessels in the surgical field and of vascular malformations. It is low cost, and the time to result is 1–5 minutes in most cases. Additionally, it shows good correlation with postoperative angiography and is therefore widely used.

It allows for the measurement of blood flow velocities in the malformation itself and in the surrounding vasculature. It is a valuable tool for providing immediate feedback to the surgeon, thereby improving the chances for an optimal surgical outcome because intraoperative complications such as vessel occlusion can be diagnosed and dealt with immediately. Several groups compared iMD findings to those in iDSA or postoperative DSA. They found a high rate of concordance between the iMD and angiographic findings regarding proper clip placement and complete occlusion of an intracranial aneurysm and associated clip-induced adjacent-vessel stenosis.

There are several iMD techniques available on the market today. Some are simple and cost-efficient, whereas others, such as the ultrasonic perivascular flow probe, are more advanced but are expensive and more cumbersome. The iMD modality carries the advantage of speed and ease of use and is therefore very attractive during surgery for ICH. The primary disadvantage of this technique is its inability to identify residual aneurysm remnants in cases of thrombosed or low-flow aneurysms—which are readily identified by intraoperative angiography and ICG-VA. That is to say, iMD provides qualitative and not quantitative results to the surgeon. Additionally, it is only useful for high-caliber vessels observed under the operating microscope.

**Intraoperative MRI**

Intraoperative MRI has been incorporated into modern neurosurgical operating rooms for more than a decade as a guide for neurosurgical interventions. This technology has proved to be a useful modality in vascular neurosurgery, especially for cavernous aneurysms and AVMs. It provides a highly accurate and precise navigation tool, with excellent resolution, which is a prerequisite for localizing and targeting vascular lesions. It also addresses the problem of the ever-changing organization of intracranial structures during surgery by providing near-real-time, high-quality images.

One of the drawbacks of intraoperative MRI with regard to resection of vascular lesions is delineating the extent of resection. Clearly determining the edge of the lesion can be challenging due to the deposition of hemosiderin from hemorrhage. There are several types of MRI units used today. In our experience the use of iMRI in ICH surgery is limited to cavernoma surgery, and in cases in which MRI may help in delineating the margins of deep lesions surrounded with hematoma, in those cases we consider the low-field portable systems as the most useful. An example of a low-field iMRI unit is the Odin-PoleStar system, which was first introduced in 2001. This compact MR scanner can be installed in a standard operating theater without major modification (Fig. 4). It functions with both an integrated optical system and an MRI tracking system and is operated by the neurosurgeon from an in-room computer workstation.

**Intraoperative CT**

Intraoperative CT imaging is a standard tool in the successful planning and execution of a diverse range of
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Ultrasound-Guided Evacuation of ICH

The iUS technique has undergone extensive development in recent years, and the quality of ultrasound imaging has improved considerably. Still, many neurosurgeons have been reluctant to try advanced versions of iUS due to negative past experiences. The quality of iUS imaging has improved significantly, such that the surgeon can readily assess ICH dimensions and identify structures within the brain in real time. This modality supports the concept of minimally invasive surgery by allowing the surgeon to identify which part of the clot presents closer to the cortical surface, thereby minimizing disruption to the surrounding brain because the shortest transcortical trajectory is taken to enter the clot. Orientation problems of iUS were improved by integrating navigation technologies. As a result, neurosurgeons find it relatively easy to understand and use the iUS navigation systems found in the market today.

The integration of 3D iUS and neuronavigation technology has created a real-time imaging method that can accurately demonstrate ICH. The 3D iUS systems such as the SonoWand have made this technology an efficient tool that can combine the real-time feedback from iUS with the detailed preoperative imaging from CT or MRI studies. During ICH evacuation procedures, iUS facilitates directing an instrument such as a Cavitron ultrasonic surgical aspirator or an endoscope to a target point in real time. During various vascular operations the iUS helps localize lesions and characterize their internal structure, and distance from the surface to the target can be calculated. The relation of various lesions to the surrounding brain can be appreciated before, during, and after excision of vascular pathological entities.

Conclusions

There have been remarkable advances in the intraoperative imaging techniques used in the surgical management of ICH. They have enabled neurosurgeons to visualize and delineate anatomical and pathological structures more accurately, even during the surgery itself. Image-guided therapy has changed the fundamentals of conventional surgery by presenting accurate visualization of both normal tissue and lesion. Particularly within the last decade, advanced imaging modalities have become standard tools of neurosurgical practice, creating image-guided surgery as a subspecialty. In discussing the potential advantages and disadvantages of each modality, it should be pointed out that they are not mutually exclusive. On the contrary, the various intraoperative imaging modalities used in the surgery for ICH may be complementary, and therefore vascular neurosurgeons should be prepared to use any intraoperative imaging modality when the need arises.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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