Historical, Current, and Future Intraoperative Imaging Modalities

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KEYWORDS

- Intraoperative imaging • MRI • Computed tomography • Ultrasonography • Fluorescence • X-ray fluoroscopy • Navigation

KEY POINT

- Intraoperative imaging for immediate intraoperative quality control, extended resections with increased patient safety, less neurological deficits, individualized tumor therapy.

INTRODUCTION: INTRAOPERATIVE IMAGING MODALITIES

Soon after Röntgen discovered x-rays in 1895 their use was introduced in medical imaging. Conventional fluoroscopy and angiography were the first imaging methods applied intraoperatively. Ultrasonography and computed tomography (CT) followed later, although their initial image quality was less than satisfactory for neurosurgical procedures. The first attempts in the late 1970s and 1980s applying ultrasonography or CT to determine the extent of a resection were disappointing. At that time, image quality was limited, so neither modality gained wide acceptance for intraoperative application. Since then, MRI has become the primary imaging modality for preoperative diagnosis of brain and spinal diseases, providing critical information about anatomy, metabolism, structure, and function. However, the first magnetic resonance (MR) scanners could not be used in an operating environment because of the closed-bore design and the strong magnetic fields. Then, in the mid-1990s, the concept of intraoperative imaging experienced a distinct renaissance with the development of open MRI systems. For the first time, these systems made it possible to apply MRI for intraoperative imaging.

Methods like intraoperative x-ray fluoroscopy are applied as quick, easy to use, and reliable navigation tools showing where a surgical instrument is located in the patient in relation to bony landmarks, and this approach is still used; for example, in transsphenoidal and spine surgery. Ultrasonography is also a method for direct localization and navigation, because of its real-time imaging capability. Tomographic methods like CT and MRI need additional tools to provide localization and navigation, unless the procedure is performed directly in the scanner. These tools are classic frame-based stereotaxy or frameless stereotaxy, clinically known as navigation. All tomographic modalities allow delineating the placement of an implant or device in three-dimensional (3D) space, as well as evaluating the extent of a resection.

Another technique that has emerged in the last few years as alternative or adjunct to the use of classic imaging possibilities is the application of fluorescence methods; that is, application of a fluorescent dye/fluorophore that visualizes vasculature or tumor extent in the surgical field.

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Because the role of resection in surgery for gliomas has become increasingly accepted in the recent years,[1] intraoperative methods to optimize the extent of resection are getting more attention from the neurosurgical community. The combination of preserving function while optimizing the extent of resection seems to be the optimal intraoperative treatment strategy.

NAVIGATION AND IMAGING

Typical real-time intraoperative imaging modalities like fluoroscopy and ultrasonography are tools for immediate localizing. However, CT and MRI as standard means of diagnostics in radiological units generally provide preoperative image data that historically were just displayed in the operating room. The integration of the stereotactic principle allowed using CT and MRI also in the sense of localization, leading to modern image-guided surgery in which navigation technology allows the visualization of the essentials of preoperative imaging in the surgical field.

In standard navigation the physical space of the surgical field is registered to the 3D image space, which is based on anatomic data from CT, MRI, or even ultrasonography. Microscope-based navigation provides an intuitive data visualization directly in the surgical field. Navigation accuracy is influenced by a variety of factors. Major factors degrading navigation accuracy are related to an unwanted movement of the registration coordinate system (positional shift), as well as intraoperative events like altering the intraoperative geometry by tumor resection or brain deformation (brain shift). Positional shift and brain shift can both be compensated for by updating the navigation with intraoperative image data, increasing navigation accuracy as well as the safety for the patient.

The overall application accuracy of navigation systems is additionally influenced by the quality of imaging, by the technical accuracy of the system, and by the quality of patient registration, which defines the process of registering image space and real/surgical space.[2]

Standard anatomic navigation is based on anatomic image information only. Integration of additional data obtained from other imaging submodalities results in multimodal navigation. An initial step in establishing multimodal navigation was the development of functional navigation in which preoperative data from magnetoencephalography (MEG)[3–5] and functional MRI (fMRI),[6,7] which both define localizations of cortical eloquent brain areas, such as the motor and speech areas, were coregistered with the standard anatomic data and thus could be visualized in the surgical field. This method of functional navigation allowed more thorough resections of tumors in risk zones with low morbidity. Integration of fiber tracking data derived from diffusion tensor imaging (DTI) delineating the course of major white matter tracts extended this concept to subcortical areas,[8,9] whereas the coregistration of PET data and information from MR spectroscopy added metabolic information leading to true multimodal navigation.[10–14]

Placing CT and MRI scanners into an operating room for intraoperative imaging provides immediate intraoperative feedback. The most important aspect is to prevent increased neurologic deficits despite increased resections that might result from the attempt to remove initially overlooked tumor remnants that are detected by intraoperative imaging. Therefore, intraoperative imaging should be accompanied by the integration of navigation.[7,15,16]

INTRAOPERATIVE X-RAY FLUOROSCOPY AND INTRAOPERATIVE ANGIOGRAPHY

Radiographs were the first imaging modality introduced in routine operating procedures. In 1980, Rey[17] concluded that, "Intraoperative control in neurosurgery requires mainly fluoroscopy, with the possibility of a single exposure for checking purposes." Fluoroscopy is still used routinely as a reliable and quick means for intraoperative orientation; for example, in transsphenoidal procedures to identify the trajectory to the sella turcica, in stereotactic surgeries,[18] as well as in spine procedures for level identification and assisting pedicle screw trajectory adjustment.[19] Catheter and electrode placements are easily controlled during surgery; for example, in placement of atrial shunt catheters, road mapping in deep brain stimulation procedures, as well as in other kinds of electrode placements procedures such as spinal stimulation or epilepsy surgery.

Further developments of fluoroscopy imaging led to volumetric imaging by acquiring multiple fluoroscopic images about an isocentric point in space, providing axial plane tomographic images that may be reconstructed into an accurate 3D volume (Iso-C arm technology).[20] The usefulness of the Iso-C lies in its convenience and diversity. It provides quick, seamless, and accurate data acquisition for intraoperative imaging with or without navigation. It can be used during traditional open spinal and cranial base approaches or in conjunction with minimally invasive approaches such as thoracoscopy, vertebroplasty, biopsy, and minimally invasive pedicle screw placement. This technology is readily adaptable to any operating room.[20]

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