Computer-based imaging and interventional MRI: applications for neurosurgery

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Abstract

Advances in computer technology and the development of open MRI systems definitely enhanced intraoperative image-guidance in neurosurgery. Based upon the integration of previously acquired and processed 3D information and the corresponding anatomy of the patient, this requires computerized image-processing methods (segmentation, registration, and display) and fast image integration techniques.

Open MR systems equipped with instrument tracking systems, provide an interactive environment in which biopsies and minimally invasive interventions or open surgeries can be performed. Enhanced by the integration of multimodal imaging these techniques significantly improve the available treatment options and can change the prognosis for patients with surgically treatable diseases. \copyright 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Within the past decade advances in computer technology, in imaging techniques and the development of open MR systems have had a definite impact on radiology and related clinical fields. Imaging has become a central part in diagnosis and therapy and neuroradiology has been boosted by technological advances. No single imaging modality may claim optimal sensitivity or specificity for the assessment of central nervous system (CNS) disorders, although several imaging methods carry independent and complementary information. Magnetic resonance imaging (MRI) in particular has substantial advantages over other modalities to depict the brain. However, the integration and the quantification of image-based information obtained with multiple imaging methods, such as MRI, functional MRI (fMRI), MR angiography (MRA), X-ray computed tomography (CT) and single photon emission tomography (SPECT) is eventually necessary to obtain enough information for neurosurgical guidance.

To achieve the goal of image-guided therapy, in terms of technology two steps need to be taken into consideration, namely image acquisition and image post-processing. The choice of the image acquisition strategy will determine the tissue specificity of the images. Image post-processing techniques for tissue segmentation have been developed to extract quantitative volumetric information for tissue classes in the brain: white matter, gray matter, CSF, white matter abnormalities and other pathologies like brain tumors. While tissue specificity mostly depends on tissue characterization with a given physical system (i.e. CT or MRI) anatomic specificity is primarily determined by post-processing techniques [1].

Neurosurgery and radiology complement each other in the development and implementation of intraoperative imaging. For example, conventional craniotomy is markedly constrained by the relatively small area of exposed brain surface, which lacks spatial clues that surgeons would need to comprehend all of the relevant anatomy. Such limitations of direct surgical visualization have several consequences. First, cortical localization is not accurate, and it is even more compromised within the brain parenchyma. Second, the definition of exact trajectories for targeting is impossible without stereotactic guidance.
Third, if the anatomical and pathological boundaries are not clear (and thus accurate tumor localization is not possible), normal tissue has to be removed to ensure complete resection.

In general image guidance can reduce the inherent invasiveness of surgery and improve localization and targeting by intraoperative imaging via ultrasound, or more recently, MRI. Alternatively, intraoperative image guidance can be based on previously acquired images using reference frames attached to the patient (frame-based stereotaxy), or images that have been registered to the patient (frameless stereotaxy). In the latter case, computers can navigate the operator through 3D coordinates and thus fulfill the need for enhanced visibility during interventional radiological and minimally invasive surgical procedures.

Image-guidance, based on pretreatment modeling requires computerized image-processing methods (segmentation, registration, and display) and image integration techniques, replacing the mental process of generating 3D representations of the patient’s anatomy. Full integration of advanced imaging techniques in neurosurgery will result in fundamental changes in therapeutic strategies and approaches. Advances in technology have already resulted in sweeping changes in diagnostic radiology, and more widespread use of modern therapeutic devices, computers, and advanced imaging technologies will have a far-reaching effect on neurosurgery as well.

2. Surgical planning

The role of surgical planning in tumor surgery is the optimal execution of preoperative plans [2–8] and to define the safest possible approach with the least possible damage to normal tissue. In this trajectory optimization process, alternative navigational paths and movements through the physical space are tested and analyzed using a preoperative model.

Therefore, a detailed model of the patient’s anatomy retrieved from CT, MRI has to be created first. By analyzing this imaging data each voxel in the image will have to be classified into a set of different tissue types: in the case of neurosurgery for example, skin, fat, bone, gray matter, white matter, cerebro-spinal fluid, tumor, blood vessel. Although perfect automatic systems are not yet available, considerable prior effort [9] has resulted in reliable semiautomatic methods. Establishing a simulated procedural environment is also a critical step for creating an image-based virtual reality environment that allows the user to actively enter the 3D environment and perform simulated procedures within it.

2.1. Intraoperative image guidance based on pre-treatment imaging

Intraoperative image guidance is based upon the integration of the previously acquired and processed 3D information and the corresponding anatomy of the patient within the same frame of reference. During the actual neurosurgery, an interactive real-time display can demonstrate the otherwise hidden anatomic information that has been generated by a single modality or composed from multimodal volumetric images.

2.1.1. Intraoperative registration

To achieve the intraoperative registration of a 3D-model to the patient, we need to specify: the characteristics of the model data set to be used in matching, e.g. skin surface, natural landmarks or artificial fiducials; the characteristics of the second data set, taken from the patient on the operating table, e.g. preattached artificial fiducials, features from dense surface scans, sparse surface scans, or video images; and the class of transformations over which a registration solution is sought, e.g. rigid 3D, affine 3D, or flexible/elastica deformations [10–13].

In the original, frame-based stereotactic method, 3D points (of the physical frame) are matched with 2D points (seen on the images). Alternatively, surface points are matched with selected anatomic landmarks or external fiducial markers visible on both the images and on the patient. In these methods the registration process requires pointers attached to position-sensing devices which establish the relationship between the reference frame of the patient and the images.

Other registration techniques match visible anatomic objects, features or shapes represented on both the patient and the reconstructed images. Video camera-based methods detect visible features on the patient (ear, nose, eyes) appearing on both the reconstructed surfaces and on the video images [13]. Skin surface-based registrations can be refined by readjusting them to inner surfaces of the organs as they become exposed during surgery. For example video-registration can be improved by matching cortical vessels, visible on the surface of the exposed brain and on 3D reconstructions based on MR angiograms [14]. Currently, we use laser scanning to obtain digitized surfaces and subsequently match 3D curves with 3D curves obtained with automated methods [15,16].

By merging the view of the surgical field with surface representation of 3D images and in some cases with the correlated maps of functional cortical physiology (obtained from preoperative transcalvarial stimulation or from intraoperative electrode recordings and from functional MRI), one can provide sufficient control of neurosurgical procedures even in high risk areas.

Further, multimodality data from MR images, MR angiography, SPECT or PET scans and spatially recorded functional physiological and preoperative surgical plans can be registered to the patient in order to integrate all the available information intraoperatively [17,18]. Image fusion requires matching all image-based geometric data in a single, unique coordinate system. Therefore, for image-guidance we must bring these segmented models into direct relationship with
the patient, so that the surgeon can easily relate what he sees
in the model to what he sees in the patient.

This includes both supporting visualization (in which the
surgeon can see fused views of the actual patient and
internal model structures exactly aligned (see Fig. 1)) and
navigation (in which the surgeon can specify points within
the patient, e.g. by touching a point, and can see the full
context of the corresponding point within the MRI scan (see
Fig. 2)).

2.1.2. Tracking

In our current system, we use 3D data from the patient’s
position on the OR table obtained by scanning the skin
surface of the patient with a laser ranging device which
we designed and constructed. This scanner operates by
passing a low power laser beam through a cylindrical lens
to create a plane of light. This plane is directed onto the
patient and is observed in a video camera oriented at a fixed
offset angle to the laser plane. As a result, points at different
depths relative to the baseline separating the camera and
laser will appear at different positions or offsets in the
camera. By carefully calibrating the camera’s position rela-
tive to the laser, we can relate the position of the observed
laser points in the image to the 3D position of the reflecting
point in the world. By mounting the laser on a stepper
motor, we can sweep the laser plane across a range of posi-
tions, thus scanning depth positions over a volume of space.
Typically, we scan only 15–20 lines of data, which allows a
rapid acquisition of data.

As a consequence, there is no guarantee that the lines
intersect distinctive features (e.g. tip of the nose, corner of
the eye). Instead, we have a set of 3D points, measured
relative to a coordinate frame attached to the laser ranger,
that all lie on a small set of planes, due to the nature of the
laser data acquisition process. Hence, we need registration
methods that do not rely on a small set of distinctive features
or fiducial landmarks, but rather can align sets of data
features based on goodness of surface fit. Thus, our problem
is to align two data sets, one a dense surface representation
(the skin surface from the MRI reconstruction), the other a
set of points (the sampled laser points).

This allows us to bring our model information into the
coordinate frame of the laser. Thus, by solving the position
and orientation of a video camera relative to the laser, we
can then render images of the internal structures of the
model through the associated camera model. This gives us
a synthetic view of what internal structures look like with no
intervening material. By mixing this with life shots from the
camera, we can create enhanced reality visualizations
(see Fig. 3) allowing planning and guidance of surgical
procedures.

This registration allows the surgeon to visualize the
patient’s internal anatomy. Ideally, however, the surgeon
would like to be able to query the system about points within
the patient. For example, he should be able to take a probe,
touch a point on or in the patient, and see exactly where that
point is in the full original or segmented MRI scans. In our
current system, we accomplish this by using an IGT Flash-
point system, which tracks a set of infrared LEDs and uses
triangulation by a set of high-resolution CCD-cameras to
determine the LEDs positions relative to a coordinate
frame attached to the camera system. By attaching a set of
LEDs to the probe, we can determine the position and ori-
tentation of the probe in the Flashpoint’s coordinate frame.
By calibrating the position of the Flashpoint with respect to the
laser system, we can connect all of these coordinate frames
together. This allows us to relate probe points to the laser
coordinate frame and hence to the MRI scans (Fig. 3).

However, all this methods assume that the patient has not
been moved since the original registration. To account for such possible movement, we also attach LEDs directly to the patient, then track changes in position of such markers to account for changes in patient position.

The Flashpoint itself can be used then as an acquisition device. By tracing the probe along the skin surface of the patient, and recording the position of the probe tip, we can collect additional data points to include with the laser data as part of our registration process. The standard application of our existing system in neurosurgical cases proceeds as described in Table 1.

2.2. MR-guided intraoperative neurosurgery

Imaging during interventional and surgical procedures provide near real-time updates about the patient anatomy or the changing position of movable organs, depicts the position of instruments and without registration establish the necessary relationship between the patient and the images. Recent advances in imaging technology, particularly in 3D ultrasound, high speed CT and MRI with high performance computing now permits the combination and integration of near-real time, high contrast and spatial resolution volumetric images with frameless stereotactic, interactive localization methods while performing image-guided therapy.

Because of its high tissue contrast and spatial resolution as well as multiplanar and functional imaging capabilities, MRI has the most appeal for monitoring and controlling therapy. Nevertheless, several obstacles hindered the evolution of MRI-guided interventions. Its value for guiding biopsies of tumors best detectable by MRI was apparent, but the closed magnets conventional at the time made it a cumbersome procedure to perform. The incompatibility of the electromagnetic environment, the inaccessibility of patients within the magnets, and the expense of MRI impeded the widespread acceptance of MRI for percutaneous procedures. Advances in low-field open-configuration magnet design and recognition of MRI’s potential for monitoring and controlling thermal ablations and other percutaneous therapies really initiated this new direction in interventional radiology.

The research and development in the field of interventional MRI was initiated by the vision of interventional MRI imaging [19]. As a result, a 0.5 T interventional MRI system (SIGNA SP) was developed by General Electric Medical Systems in collaboration with the Brigham and Women’s Hospital [20]. This system has a unique open configuration, which allows the surgeon to perform procedures on patients placed within it. Images are acquired using optical tracking of surgical instruments in order to establish accurate intraoperative correlations between instrument position and anatomic structures [21]. The images can be viewed on monitors located conveniently within the vertical gap of the magnet. The neurosurgeon is thereby equipped with a near real-time, interactive navigational device [22–24].

Such Image Guided Surgical systems should enable the surgeon to perform more accurate surgeries, with less invasion of neighboring tissue, to perform these surgeries in less time, and to be able to plan and execute safer paths to

<table>
<thead>
<tr>
<th>Surgical procedures</th>
<th>Image-guidance procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient is prepared for surgery up to head sterilization process as usual; the patient’s head is still visible</td>
<td>System registers MRI segmentation to patient: laser triangulation device scans patient’s head to acquire 3D information about the position of the patient’s skin. Additional data points (position of the head clamp or marked skin points on the patient) can be acquired using the Flashpoint tracking system and a non-sterile probe.</td>
</tr>
<tr>
<td>Patient is then sterilized and draped</td>
<td>Alignment of MRI reconstruction with patients position: all data points acquired so far are then registered to the skin surface of the MRI segmentation. The surgeon is provided with augmented reality visualizations, in which all of the internal structures of the MRI segmentation are overlaid in exact alignment with a live video view of the patient, taken from the perspective of the surgeon (usually with a camera looking in over his shoulder).</td>
</tr>
<tr>
<td>Throughout the surgery</td>
<td>Tracking and display of sterile surgical probes within the 3D volume of MRI data, with segmented structures overlaid (see Fig. 11). The surgeon is able to visualize his surgical position relative to other nearby structures at any point in the procedure.</td>
</tr>
</tbody>
</table>
Table 2

<table>
<thead>
<tr>
<th>Biopsy in MRT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>100</td>
</tr>
<tr>
<td>Head/neck, other</td>
<td>108</td>
</tr>
<tr>
<td>Drainage procedures</td>
<td></td>
</tr>
<tr>
<td>Subdural collection</td>
<td>3</td>
</tr>
<tr>
<td>Brain</td>
<td>9</td>
</tr>
<tr>
<td>Cryoablation</td>
<td></td>
</tr>
<tr>
<td>Abdominal</td>
<td>5</td>
</tr>
<tr>
<td>Laser ablation</td>
<td></td>
</tr>
<tr>
<td>Brain</td>
<td>4</td>
</tr>
<tr>
<td>Liver</td>
<td>2</td>
</tr>
<tr>
<td>Brachytherapy</td>
<td>38</td>
</tr>
<tr>
<td>MRI-guided surgery</td>
<td></td>
</tr>
<tr>
<td>Cranietomy</td>
<td>254</td>
</tr>
<tr>
<td>Cranietomy and brachytherapy</td>
<td>3</td>
</tr>
<tr>
<td>Ventricular shunt</td>
<td>2</td>
</tr>
<tr>
<td>Pituitary (transspinosid)</td>
<td>10</td>
</tr>
<tr>
<td>Spine</td>
<td>12</td>
</tr>
<tr>
<td>ENT</td>
<td>19</td>
</tr>
<tr>
<td>Breast lumpectomy</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>573</td>
</tr>
</tbody>
</table>

desired targeted tissue. The existing system at the Brigham and Women’s Hospital at Harvard Medical School has already been used in neurosurgical cases (n ≥ 250) and for functional imaging (n = 59) with excellent results [25] (Table 2).

Currently, several vendors offer open configuration magnets (Table 3), which permit access to the patient and some systems are equipped with instrument tracking systems to provide an interactive environment in which biopsies, percutaneous or endoscopic procedures, and minimally invasive interventions or open surgeries can be performed.

In addition, various thermal ablations with image-based control of energy deposition can be performed to exploit the intrinsic sensitivity of MRI to both temperature and tissue integrity [26].

Details of the interventional MRI system used at our institution are presented in [27]. The interventional MR scanner has two separated superconducting magnetic coils with an 1840 mm outer diameter. The coils are placed with a 560 mm gap between them. This allows the surgeon access to the interventional field by placing the operative bed in the gantry. The main magnet field strength is 0.5 T and the homogeneity is 12.3 ppm over 300 mm and 1.6 ppm over 200 mm.

The interventional MRI system (Fig. 4) developed by General Electric Medical Systems (SIGMA SP) and the interventional-surgical suite in which it resides, combines the key enabling technologies: superconductive MR system, flexible transmit/receive coils, computer workstations, position sensors, intraoperative display, audio- and video equipment [28]. The facility is equipped with MR-compatible anesthesia delivery and monitoring devices and instruments for biopsies, thermal ablations, endoscopies and open surgical procedures [29]. It incorporates and integrates functions related to imaging, image-guidance, and therapy. The system was installed at the Brigham and Women’s Hospital in 1994. Although the initial application domain included primarily percutaneous biopsy, the capability ultimately evolved into a broad range of interventional and surgical applications in which the combination of direct imaging and real-time image guidance were consolidated.

For imaging, the interventional MRI (iMRI) has two modes called “standard scan” and “interactive scan” - the former is similar to that available in conventional diagnostic scanners. The latter is the interactive oblique mode in which surgeons and radiologists can interactively select the position and orientation of the scanning plane. For this interactive mode, the system is equipped with an optical scan plane locator and its detector (Flashpoint, ISG, Boulder, CO). The locator has 2 to 3 Light-Emitting Diodes (LED) which are tracked by 3 CCD cameras attached on the rail above the interventional field. The locator can be mounted on surgical devices like a biopsy needle holder, a suction tube or a sinus endoscope. The scan plane locator is calibrated to the imager, thus its spatial relationship is known.

This mode resembles sonography except that the three orthogonal planes can be displayed without changing the actual position of the probe. In the localizing mode, the probe is used as a virtual pointer with a computer-displayed icon that can point to or outline an anatomic object within the body. This mode can also be used to trace contours of organs or margins of lesions or to obtain points or surfaces from inside the body for registration [30].

Using the targeting mode, the tip or the shaft of a virtual

<table>
<thead>
<tr>
<th>System Vendor</th>
<th>Field-strength (T)</th>
<th>Type of magnet</th>
<th>Access</th>
<th>Opening (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetom Open Viva Siemens AG</td>
<td>0.2</td>
<td>Resistive</td>
<td>Horizontal</td>
<td>41</td>
</tr>
<tr>
<td>Outlook Picker-Nordstar</td>
<td>0.23</td>
<td>Resistive</td>
<td>Horizontal</td>
<td>46</td>
</tr>
<tr>
<td>SIGNA Profile General Electric</td>
<td>0.2</td>
<td>Permanent</td>
<td>Horizontal</td>
<td>44</td>
</tr>
<tr>
<td>Aries Hitachi</td>
<td>0.3</td>
<td>Permanent</td>
<td>Horizontal</td>
<td>43</td>
</tr>
<tr>
<td>OPART Toshiba</td>
<td>0.35</td>
<td>Super-conductive</td>
<td>Horizontal</td>
<td>55</td>
</tr>
<tr>
<td>SIGNA SP General Electric</td>
<td>0.5</td>
<td>Super-conductive</td>
<td>Vertical and axial</td>
<td>vertical 56, axial 55</td>
</tr>
<tr>
<td>QUAD12000 Fornar</td>
<td>0.6</td>
<td>Super-conductive</td>
<td>Horizontal</td>
<td>51</td>
</tr>
<tr>
<td>Magnetom Harmony Siemens AG</td>
<td>1.0</td>
<td>Super-conductive</td>
<td>Axial</td>
<td>60</td>
</tr>
<tr>
<td>Magnetom Symphony Siemens AG</td>
<td>1.5</td>
<td>Super-conductive</td>
<td>Axial</td>
<td>60</td>
</tr>
<tr>
<td>Gyroscan ACS NT Philips</td>
<td>1.5</td>
<td>Super-conductive</td>
<td>Axial</td>
<td>60</td>
</tr>
</tbody>
</table>
into the target. Using the tracking mode, the trail of instruments or the motion of body parts can be followed and displayed on the images [24]. Images are acquired using optical tracking of surgical instruments in order to establish accurate intraoperative correlations between instrument position and anatomic structures. The images can be viewed on monitors located conveniently within the vertical gap of the magnet. The neurosurgeon is thereby equipped with a near real-time, interactive navigational device [23].

Interactive image-guidance within the interventional MRI system using optical or other tracking systems can be applied to a wide variety of interventional and surgical procedures (see Fig. 5).

This method has some aspects in common with frameless stereotactic or navigational systems. In particular, it provides direct control of scan plane location, orientation and angulation with enough flexibility and convenience to perform freehand procedures and enough accuracy for stereotactic biopsies [26,29].

The definition of real-time imaging or dynamic image update is relative and contingent upon the time constants of the procedures or processes being imaged. Imaging needle placement may require update of multiple slices or planes. For interactive image guidance, the images are generated and displayed quickly enough (within 1.5–13 s) to be utilized without disrupting or slowing down the procedure and before considerable changes occur within the operational field. Most localization, targeting, tracking and monitoring requirements can be satisfied by the commonly available fast imaging techniques (fast spin echo, gradient echo) (Fig. 6) [31].

Several novel imaging techniques offer improved temporal resolution achieved by less redundant spatial encoding and without considerably affecting spatial resolution and signal-to-noise. MR fluoroscopy and other dynamic

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**Fig. 4.** The interventional MR System allows access to the patient from both sides during neurosurgery. Reprinted with kind permission from Der Radiologe. Springer Verlag, Aufbau, klinische Eignung und Zukunftsspekte eines 0.5 T MR-Spezialsystems für den interventionellen Einsatz. Kettenbach J, Silverman SG, Schwartz RB, Hsu L, Koskinen SK, Kikinis R, Black P McL, Jolesz FA. Radiologe 1997;37:825–834.

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**Fig. 5.** Interactive image-guidance using optical tracking of the needle holder. Frameless stereotactic targeting procedure for brain biopsy (malignant glioma). Three orthogonal views acquired with a T1 weighted fast spin echo sequence (FSE 400/17) obtained after intravenous contrast administration: (a) image demonstrating the virtual needle (predicted needle path) as a segmented line; (b) the virtual needle-tip (cross hair) displayed on the view perpendicular to the predicted needle path; (c) actual biopsy needle is seen as a metallic artifact behind the segmented line. The needle was introduced along the predicted path. Reprinted with kind permission from the RSNA, Jolesz, FA et al. Image-guided procedures and the operating room of the future. Radiology 1997;204:601–12.
Fig. 6. shows the configuration of the IMRI system. The IMRI system is connected to two major computers: an IMRI front-end workstation dedicated for scan control and a research workstation. Each workstation and the scanner are connected to an Ethernet network that operates nominally an 10 Mbits/s. The roles of each workstation are presented in the next section.

imaging approaches are also available to utilize preexisting information for adaptive encoding of changing image data.

2.2.1. Configuration of the IMRI system (IMRI front-end workstation)
Most of IMRI system specific functions are controlled by the IMRI front-end workstation (SPARCstation 20 model 612MP, Sun Microsystems, Mountain View, CA). The functions include the real-time imaging control, temperature monitoring to prevent overheating of the magnets, plus an audio and video switcher.

2.2.1.1. Research workstation. Since the front-end workstation is dedicated for imaging control and its computational resources may not be affected by research- software processes, a research workstation (Sparc 20 TZX, Sun Microsystems, Mountain View, CA) with high-performance graphics capability, dedicated for image registration and a 3D visual interactive interface was used. For further computation the sequentially acquired images were then transferred from the image buffer of the MR console via the Ethernet network to the research computer workstation, placed beside the MR console and the IMRI front-end workstation.

2.2.2. Intraoperative MRI
Interactive localization and targeting have not only provided on-line planning of optimal trajectories for biopsies but also real-time image feedback during the needle advancement and tissue sampling. Using this method lesions within deep and high risk regions (e.g. hypothalamus, pineal region or brainstem) have been biopsied [24]. Unavoidable hemorrhagic complications were immediately recognized, localized and treated surgically by open craniotomy within the magnet. Intraventricular, relatively mobile and unstable targets have been reached safely, and cystic structures in various locations have been drained under continuous image control (Fig. 7).

The most exciting and potentially rewarding neurosurgical application of interventional MRI-guidance is resection of malignant intraxial tumors (Fig. 8).

When viewing the exposed brain surface without imaging, the neurosurgeon can not define the spatial extent of the tumor, and even after surgically entering the brain tissue, the tumor is indistinguishable from normal cerebral tissue in most patients. Preoperative image data may help to demonstrate the extent of the tumor in some instances. During resection of large, deep tumors, however, brain

Fig. 7. Image-guided drainage of a pineal cyst using MRI guidance: (a) The tip of the needle (arrow pointing to the needle artifact) within the cyst. T1 weighted 3D fast spoiled gradient echo sequence (FSPGR 28/12, flip angle 30°); (b) 3D rendering from the volumetric dataset demonstrating the cyst, the thalami, and the surrounding veins. The needle was introduced into the cyst between the internal cerebral vein and the vein of Rosenthal. Reprinted with kind permission from the RSNA, Jolesz, FA et al. Image-guided procedures and the operating room of the future. Radiology 1997;204:601-12.
structures may move and become deformed, negating the value of preoperative images. Using intraoperative optical tracking and refreshing the volumetric images, surgeons are able not only to locate the tumor margins but completely resect the tumor while preserving the integrity of surrounding normal brain. Similar methods can be applied to resection of other intraparenchymal tumors such as breast cancer or soft tissue sarcoma where the margins are difficult to define with the naked eye.

The potential advantage of precise localization and optimized access route has also been demonstrated by combining an operative microscope with MRI-guided resection of deep-seated small tumors and cavernous hemangiomas. Surgical removal of extraaxial tumors may benefit from the delineation of surrounding, directly invisible anatomy. In addition, intraoperative MRI-guided laminectomies in the lumbar and cervical spine may represent a new minimally invasive approach to this high risk area.

2.3. Future applications of image-guidance

The Image Guided Therapy Program of Brigham and Women’s Hospital represents a concentrated effort of radiologists, surgeons and computer scientists to introduce advanced imaging, image processing and image controlled therapy techniques into interventional radiology and surgery. Here the already implemented image-guided procedures provide a glimpse to the future and demonstrate that the enabling technologies are present even now.

Using these advances surgeons have developed new procedures and techniques. Diagnostic and interventional radiologists have also been involved in the therapeutical process and their relationship with their surgical colleagues has extended beyond the constraints of the traditional consultation. By entering together into the “operating room of the future” they have developed a closer interaction. This association has resulted in a more pronounced understanding of the interplay between diagnosis and treatment and a more profound appreciation of each other’s role in patient care.

2.3.1. Surgical navigation with enhanced graphics interface within a real-time interventional MRI system

Recently, we have developed a method to fuse multi-modality (pre- and intra-operative) images for the interventional MRI guided surgery. The preliminary work included the engineering setting of a high-performance computing, the use of the hospital network and the integration of the interactive guidance system of the open-configuration MRI scanner [32].

We concluded that highly accurate and complex surgical procedures are possible using an interactive 3D graphics display (Fig. 9) in which we integrate multiple modalities (MRI [T1,T2,MRA], CT, SPECT, and intraoperative MRI data). Coregistration of CT, MRA and MRI is especially helpful in skull base surgery. The combination of functional MRI with cortical physiology is invaluable for executing surgical resection without sacrificing critical brain functions. SPECT registration to intraoperative MRI distinguishes metabolically active tumor parts from necrotic areas.

Using this method surgeons and interventional radiologists not only plan but also execute the procedure, i.e. localize a trajectory path that is minimally invasive to critical anatomical structures such as vessels and critical cortical functional areas (Fig. 10).

2.3.2. Monitoring and control of MR-guided ablation therapy with interventional MRI

One of the greatest potentials of MRI consists in monitoring and even delivery of various energies by means of
thermal probes. MRI is clearly the modality of choice for these procedures, because it can be used both to guide placement of the ablation probes and monitor the thermal treatment. Techniques for creating thermal ablation lesions were discussed in detail previously [33–35], and will therefore only be briefly mentioned. Thermal ablation methods include laser, radiofrequency (RF), ultrasound (US), and microwave energy. Temperatures above 56–60°C cause irreversible tissue damage, and the pathophysiology is similar regardless of the energy source [36].

Laser energy, delivered to tissue by optical fibers, has the advantage of small diameter and efficient energy delivery to the treatment site. Being non-metallic, the laser fibers are MRI compatible. The major disadvantage of lasers is the relatively limited penetration depth and therefore relatively small lesion size. RF energy can be delivered simply through needles implanted in the target lesion. Large lesions can be created with this technique by implanting a tight array of needles, by cooling the needles, and by pulsing RF power [37]. One disadvantage of RF heating is the interference between the energy source and the MRI system, precluding imaging while the RF device is on, although some groups are addressing this problem. Microwave energy has the potential to penetrate deeper into tissues than either laser or RF methods, but small implantable antennas are much more complex to design, and this technique is not in common use at this time.

Finally, one of the most promising techniques for thermal ablation, when combined with MR imaging, may be high intensity focused ultrasound (HIFU). A system has been incorporated into a standard 1.5T MRI system (GE Medical Systems, Milwaukee, WI) at Brigham and Women's Hospital [38]. An MRI compatible 1.5 MHz ultrasound transducer is coupled to the body surface by a water bath and focused to a deep tissue target. The focal spot is controlled by computer based on MR imaging, and permits irregular volumes to be precisely treated. It has been shown that MRI can readily detect temperature changes of 7–8°C, therefore detecting temperature elevations below the threshold for causing irreversible tissue damage. This permits a low power sonication to be used to verify the treatment focus prior to increasing the ultrasound power to ablate the tissue. A precise spatial control of the tissue ablation beyond what is possible with interstitial methods is achieved. In addition, this technique requires no needle insertions and is therefore the least invasive of the minimally invasive therapies. The major disadvantages with the technique are: (1) inability of ultrasound to penetrate gas or bone; (2) small treatment volume (focus is only several millimeters in size) of each focused ablation, making treatment times longer than for other methods; and (3) patient motion is more problematic, since probes are not physically positioned within the target lesion.

Several MR techniques are available for determining temperature changes from thermal ablation procedures. Molecular diffusion methods can be used, but are sensitive to patient motion, making this technique less desirable [39]. Small temperature-dependent shifts in proton resonant frequency can be evaluated with fast spoiled gradient echo sequences [40–42]. Using this technique, Cline and Hynynen et al. [43] found the temperature coefficient for the frequency shift to be 0.011 ppm/°C in rabbit brain. This allows temperature changes to be related to phase changes observed on the gradient echo images. Using this technique, temperature elevations below the threshold for tissue damage can be detected for localization and verification of the ultrasonic focus prior to therapeutic sonication.
Irreversible tissue damage caused by temperatures exceeding 60°C are evident on T1W and T2W conventional spin-echo images.

Based upon our extensive experience in thermal imaging and MR guided thermal ablations [33–35,43], we have developed a computer assisted MR temperature imaging interface for interstitial laser therapy. Clinical applications involving tumor ablation in the brain and liver have already been initiated (Fig. 11). The interventional MR imaging system was used to guide and monitor the accurate placement of the laser source (needle with optical fiber) at the targeted lesion. T1-weighted and 2D-SPGR with phase mapping of the water proton chemical shift images, transferred to a research workstation from the MR scanner, were used to reconstruct temperature mapping for monitoring the effect of the laser ablation. Newly developed software in the imaging system and the research workstation enabled rapid (27–221 ms) and on-line temperature image reconstruction. In the highlighted brain tumor case, subtraction images from T1-weighted scans and proton chemical shift images clearly showed the signal intensity peak at the tip of the laser guide. The preliminary study indicated that the presented system design is feasible for real-time and on-line monitoring of interstitial laser therapy (Fig. 12).

2.3.3. IMRI and physiological data acquisition

In addition to the data provided by MRI scans, additional valuable information can be obtained from functional mapping of anatomic data sets, which can then be incorporated directly into the three dimensional MRI reconstruction. These include Thallium-201 CI and Technetium-99m-HMPAO (or ECD) dual isotope SPECT (single photon emission computed tomography) three dimensional imaging, or FDG or methionine PET (Positron Emission Tomography). Various motor, speech or visual areas might be mapped using SPECT or transcranial magnetic stimulation (TMS). Other modalities might be incorporated into the enhancement of three dimensional and functional data. Electrocorticography with three-dimensional definition of epileptiform activity is another possibility.

All of this data can be merged into a single unified model for presentation to the surgeon.

The tremendous benefit gained by bringing stereotactically linked MR, CT, SPECT, functional mapping, etc. data into the active field of perception of the neurosurgeon during a neurosurgical operation is tremendous. The efforts of the Surgical Planning Laboratory, especially...
as they apply in the intraoperative MR (MRT) project, are actively addressing these particular challenges at multiple levels. The benefit to the operating neurosurgeon and his patient has been increasingly clear to the neurosurgical community worldwide.

2.3.4. Conclusion

Image-guidance as a concept demands a strategic shift in the focus of medical imaging from diagnosis to treatment. Continuous commitment from imaging experts, radiologists and neurosurgeons is necessary to expedite technology development in our rapidly changing healthcare environment. Image-guided therapy offers the possibility of improving safety, efficacy and cost-effectiveness of existing procedures, and it may result in new procedures that cannot be conceived outside of this environment.

Computers become a more integral part of the surgical process, and the need to provide information to the surgeon in a convenient and intuitive way becomes greater. Nowhere is this relationship more true than in the Interventional MRI system (IMRI), where image information acquired by MRI and augmented and annotated by computer data is a powerful tool for intra-operative planning and guidance.

The use of novel dynamic imaging techniques, and the integration of various usage modes and procedure classes, will further expand the application of intraoperative MRI. This and the integration of computer-based registration techniques allow an intuitive interface to both pre- and intra-procedural information.

Thus, the emerging field of intraoperative MRI has the potential to profoundly reduce the morbidity, mortality and cost associated with neurosurgical procedures. It may significantly impact the available treatment options and can change prognosis for patients with surgically treatable diseases.

3. Summary

The concept of image-guidance demands a strategic shift in the focus of medical imaging from diagnosis to treatment.

Image guidance can reduce the invasiveness of surgery and improve localization and targeting by intraoperative imaging via ultrasound, or more recently, MRI. Alternatively, intraoperative image guidance can be based on previously acquired images using reference frames attached to the patient (frame-based stereotaxy), or images that have been registered to the patient (frameless stereotaxy). In the latter case, computers can navigate the operator through 3D coordinates and thus fulfill the need for enhanced visibility during interventional radiological and minimally invasive surgical procedures. For surgical planning and for subsequent intraoperative navigation, a patients model has to be created from imaging data including the process of imaging, segmentation, 3D-modeling and registration of the imaging data to the actual patient’s position.

There are various methods for patient-to-model registration. In the original, frame-based stereotactic method, 3D points (of the physical frame) are matched with 2D points (seen on the images). Alternatively, surface points are matched with selected anatomic landmarks or external fiducial markers visible on both the images and on the patient. In these methods the registration process requires pointers attached to position-sensing devices which establish the relationship between the reference frame of the patient and the images. Other registration techniques match visible anatomic objects, features or shapes represented on both the patient and the reconstructed images.

Most of the navigational systems developed in the last decade are relevant only for interactive image-guided neurosurgery and endoscopic sinus surgery. The use of preoperative images for intraoperative image guidance is limited by the potential intraoperative changes in the anatomy. Due to retraction of tissues, removal of tumor masses, loss of cerebrospinal fluid, hemorrhage, or edema, this can cause substantial errors.

Therefore, the vision that an intraoperative MRI (IMRI) system should provide unlimited access for two physicians, should be equipped with a tracking and navigational system for interactive image guidance and should have a display which is integrated within a surgical microscope initiated research and development in the field of IMRI.

Currently various open MRI systems are utilized for intraoperative image-guidance and have been applied to a variety of neurosurgical applications. Since neurosurgery has been the most aggressive specialty to use image guidance technology, the transition to real time image guidance has been a relatively easy process. In our institution alone, over 250 such procedures have been performed.

Further, the integration of preoperative multimodal information with the intraoperative imaging allows an intuitive interface to both pre- and intra-procedural information. The use of novel dynamic imaging techniques, and the integration of various usage modes and procedure classes, will further expand the application of intraoperative MRI for less invasive procedures.

The emerging field of computer-based image guidance and the intraoperative MRI has the potential to profoundly reduce the morbidity, mortality and cost associated with neurosurgical procedures. It may significantly impact the available treatment options and can change prognosis for patients with surgically treatable diseases.

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References


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