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JOURNAL OF MAGNETIC RESONANCE IMAGING 13:93–98 (2001)

Original Research

Registration in Interventional Procedures With Optical Navigator

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Performing interventional procedures in the close proximity to an MR scanner widens the range of operations available for an optical tracking system. In order to gain the full benefits from both unrestricted use of surgical instruments outside the magnet and intraoperative imaging, a method for transferring the registration data of the optical navigator between two locations is required. An optical tracking system, which provides such a transfer method and tracks patient position during a surgical procedure, has been developed, tested, and demonstrated with two patient cases. J. Magn. Reson. Imaging 2001;13:93–98. © 2001 Wiley-Liss, Inc.

Index terms: interventional MRI; optical navigator; co-ordinate registration; neurosurgery; brain tumor

INTRAOPERATIVE MR IMAGING has been proven effective in detecting and sampling pathological tissue, as well as in assessing progress in the minimally invasive treatment of tumors (1). MR-guided procedures should be performed inside the homogeneous imaging volume of a magnet to guarantee high accuracy. However, space constraints create the need for staged procedures, where the procedure is performed outside the magnet. Combining both intraoperative imaging and staged procedures would be beneficial on several occasions, such as in biopsies and neurosurgical procedures.

Most of the musculoskeletal biopsies are well suited for MR facilitated guidance, since MRI provides the best soft-tissue contrast to differentiate between pathological and normal tissue of muscle or bone (2,3). However, a purely intra-operative approach within the scanner may result in inconvenient needle handling. For example, force needs to be applied on the sampling apparatus in bone biopsies, and the needle insertion angle is restricted with obese patients.

In neurosurgery, ergonomics require that surgery be performed outside the scanner. Also the safety of operations is increased with the patient lying outside the magnet, within easy reach of the anesthesia team, surgeon, nurse, and interventional radiologist. For intraoperative procedures, the current lack of MR-compatible equipment and instruments can be a limiting factor. Many of the standard tools used in neurosurgery, like drills and microscopes, are not MR-compatible and must be operated outside the 20mT or 0.5mT lines (4,5). And not only must individual MR-compatibility issues of auxiliary devices be considered, but also the MR-compatibility of the system as a whole; safety related issues become exceedingly difficult to solve when sophisticated, interconnected electromechanical devices are brought into close proximity to the strong electromagnetic fields present in and close to the scanner.

Intraoperative MR imaging of anatomical and pathological structures, together with well-controlled artifacts from MR-compatible surgical tools, provide valuable guidance during a procedure. Outside the magnet, image guidance requires a navigator independent of the imaging capabilities, such as a mechanical arm, an ultrasonic wand, or an optical tracking system (6–8). All of these can be used both in and outside the magnet, but a passive optical tracking system, being frameless and wireless, has superior maneuverability. A passive optical navigator consists of a stereo-vision camera and tools (“trackers”) with optical markers. The navigator software is able to precisely calculate in real time both the position and orientation of the trackers. Optical navigator-generated co-ordinate data can be applied in different ways. For example, a tracker attached to an instrument may be used in intraoperative imaging as a pointer to define the position and orientation for the next image set. With staged procedures, a graphic symbol representing the instrument can be displayed as an overlay, moving in real time on already-acquired MR images.

Calibrating a rigid instrument to its tracker is relatively straightforward (9,10), and allows us to obtain a specific tip-point for the instrument tracker in navigator co-ordinates. To be useful, these co-ordinates must be converted into the co-ordinate system used by the

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Received July 19, 2000; Accepted August 30, 2000.

images. This is accomplished through a calibration procedure called “registration.” Registration must be repeated every time there is an unplanned change in the relative positions of the navigator and patient. Consequently, the controlling software needs to regain information about the new positions of the patient and navigator through re-registration.

Algorithms and methods for registration during MR-guided procedures in open-configuration magnets have been proposed and successfully applied (11), e.g., fiducial markers can be attached on a patient at positions visible on MR images. Registration is then implemented by pointing at the markers both in physical space with a tracker and on the images (12). Alternatively, distinct and invariant anatomical features can be utilized as markers (13), or more elaborate computer vision solutions (14) may be used to provide translation, rotation, and scaling information associated with the patient co-ordinate system.

These methods, which originated from computed tomography, pose limitations in MRI. They tend to require large amounts of 3D image data where specific anatomical details or markers are visible. Faster, custom-made sequences for locating fiducials decrease imaging time, but registration still involves pointing with a tracker on three or more pre-defined spots on the patient or stereotaxic frame. Imprecise pinpointing or inadvertent movement of the fiducials attached to the patient can also cause misregistration, as can significant peripheral distortion of the images (15), which is typical for MRI.

Our goal is to present a neurosurgical system that makes the combination of intra-operative and staged procedures faster and more feasible. The system calculates registration data automatically, using two co-ordinate reference frames for the navigator, each time the patient is moved in or out of the magnet, or when the navigator itself is moved. The primary frame (“magnet tracker”) is an immovable part of the magnet. It allows free movement of the optical navigator by fixing the origin and axes of the navigator co-ordinate system to the magnet. The secondary frame (“patient tracker”) is an auxiliary tracker that is attached to a head frame. The head frame is fixed to the skull of the patient, and the patient tracker constantly updates patient position information for the navigator. Thus patient movement can be taken into account.

THEORY

In image-guided navigation, an elementary process is to transform a point in physical space, $\mathbf{p}_p$, to a corresponding point, $\mathbf{p}_i$, in image space. Such transformation requires rotation, scaling, and translation:

$$\mathbf{p}_i = \mathbf{A}_{p\to i}\mathbf{R}_{p\to i}(\mathbf{p}_p - \mathbf{p}_p^i) \quad (1)$$

where $\mathbf{p}_p^i$ is the image-space origin expressed in physical space co-ordinates, matrix $\mathbf{R}_{\mathrm{p\to i}}$ rotates from physical to image space co-ordinate system, and matrix $\mathbf{A}_{\mathrm{p\to i}}$ scales the co-ordinate axes. Scaling is needed to compensate image distortions arising from non-idealities.

For MR imaging, the natural origin for physical space is the magnet, because the origin of image space is also fixed to its iso-center. An optical navigator introduces another co-ordinate convention to physical space, see Figure 1.

The conversion from physical to image co-ordinates requires a transformation from navigator to image set co-ordinate system. The constants for transformation must be recalculated every time the navigator is moved. Therefore, it is beneficial to fix the navigator co-ordinate system to the magnet by attaching an immobile magnet tracker to it. Because the optical navigator provides both the rotation and translation data from the tracker, the tracker can be thought of as having its own co-ordinate system. A point $\mathbf{p}_{\mathrm{on}}$, detected by the navigator, can then be represented in immobile magnet tracker co-ordinate system:

$$\mathbf{p}_{mt} = \mathbf{R}_{on\to mt}(\mathbf{p}_{on} - \mathbf{p}_{on}^{mt}) \quad (2)$$

Above $\mathbf{p}_{on}^{mt}$ is the observed position of the magnet tracker. Both points are expressed in optical navigator co-ordinates. The rotation matrix, $\mathbf{R}_{\mathrm{on\to mt}}$, from optical navigator to the magnet tracker co-ordinate system, comes directly from the observed orientation of the magnet tracker.

For the navigator to be able to guide imaging, the link between a magnet tracker and image co-ordinates must still be found. Here, registration with fiducial markers attached to a phantom can be used: the phantom is imaged and the fiducials identified from the images, yielding three points, $\{\mathbf{p}_{is}\}$, in image set co-ordinates. Pointing at the fiducials with an instrument tracker gives the corresponding points in physical space. Using equation (2), observed points can be expressed in the co-ordinate system of the magnet tracker. These two point sets, $\{\mathbf{p}_{is}\}$ and $\{\mathbf{p}_{mt}\}$, make it possible to calculate the transformation data presented in equation (1), which, in this case, comprises the constants $\mathbf{A}_{\mathrm{mt\to is}}$, $\mathbf{R}_{\mathrm{mt\to is}}$, and $\mathbf{p}_{mt}^{is}$. The calculation remains valid as long as new image distortions are not introduced and the magnet tracker remains immobile. In Figure 1, locating the instrument on images corresponds to traversing the route “instrument tracker–navigator–magnet tracker–image set.” If the patient remains inside the homogeneous volume of the magnet and the navigator has a line of sight (LOS) to both the instrument and magnet trackers, the instrument tracker position is available in image space, and navigator-controlled image guidance is possible.

Patient Tracker

Procedures facilitated by use of the magnet tracker have a disadvantage in the fact that, if the patient has moved, the instrument is not shown in the correct position on previously acquired images. New images must be obtained, which may take a considerable amount of time, particularly when large image sets are needed. To prevent this invalidation and allow the patient to be taken outside the magnet, where conductive, ferromagnetic tools can be used (16), a patient tracker can be attached to the patient. Transformation data from pa-

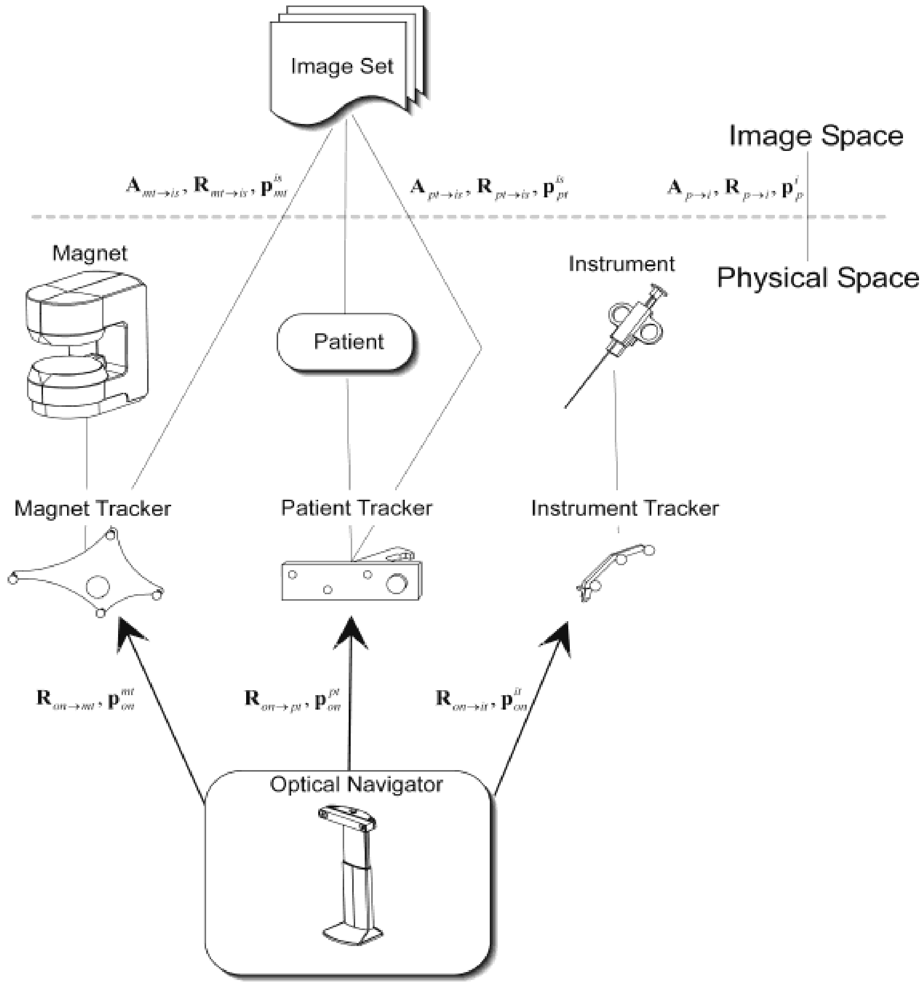

Figure 1. Diagram of co-ordinate systems. Arrows designate direct relationships, e.g., the co-ordinates of the magnet tracker are directly available to the navigator. Solid lines show associative relations between items. If an item is only connected with association lines, registration must be performed to deduce its co-ordinates. The following super- and subscripts have been used: *i* (image space), *is* (image set), *it* (instrument tracker), *mt* (magnet tracker), *on* (optical navigator), *p* (physical space), and *pt* (patient tracker).

tient tracker to image co-ordinate system is then required. Instead of doing explicit registration, as was the case with the magnet tracker, the patient tracker can utilize the already registered magnet tracker to provide the data. If the patient has not yet invalidated the images by moving, registration information can be transferred from magnet tracker to patient tracker coordinate system. A validation for this claim can be found in Figure 1. A direct transformation from patient tracker to image co-ordinate system produces identical results with transformation through the path "patient tracker–navigator–magnet tracker–image set," where all transformation constants are known. Therefore, at the moment of transfer, the following holds:

$$\begin{cases} \mathbf{p}_{is} = \mathbf{A}_{pt\to is}\mathbf{R}_{pt\to is}[\underbrace{\mathbf{R}_{on\to pt}(\mathbf{p}_{on} - \mathbf{p}^{pt}_{on})}_{\mathbf{p}_{pt}}\mathbf{p}_{pt} - \mathbf{p}^{is}_{pt}] \\ \mathbf{p}_{is} = \mathbf{A}_{mt\to is}\mathbf{R}_{mt\to is}\{\underbrace{\mathbf{R}_{on\to mt}[\underbrace{(\mathbf{R}^{-1}_{on\to pt}\mathbf{p}_{pt} + \mathbf{p}^{pt}_{on})}_{\mathbf{p}_{on}} - \mathbf{p}^{mt}_{on}]}_{\mathbf{p}_{mt}} - \mathbf{p}^{is}_{mt}\} \end{cases} \tag{3}$$

and solving unknowns $\mathbf{A}_{\mathrm{pf}\to\mathrm{is}}$, $\mathbf{R}_{\mathrm{pf}\to\mathrm{is}}$, and $\mathbf{p}^{is}_{pt}$ is straightforward. A registration transfer requires that we have an LOS to both the magnet and patient trackers at the moment of the transfer. After the transfer, it is possible to start using the patient tracker as the reference and lose the LOS to the magnet tracker. The instrument tracker can now be displayed correctly on the previously acquired images. Patient movement does not cause problems, given that the patient tracker remains rigidly fixed to the patient and the optical navigator sees both the instrument and patient trackers. It is also possible to take the patient out of the magnet and reposition the navigator to gain better access to the patient.

Methods

A patient tracker was constructed for an open-configuration, 0.23T Proview scanner (Marconi Medical Systems, Cleveland, Ohio) equipped with commercially

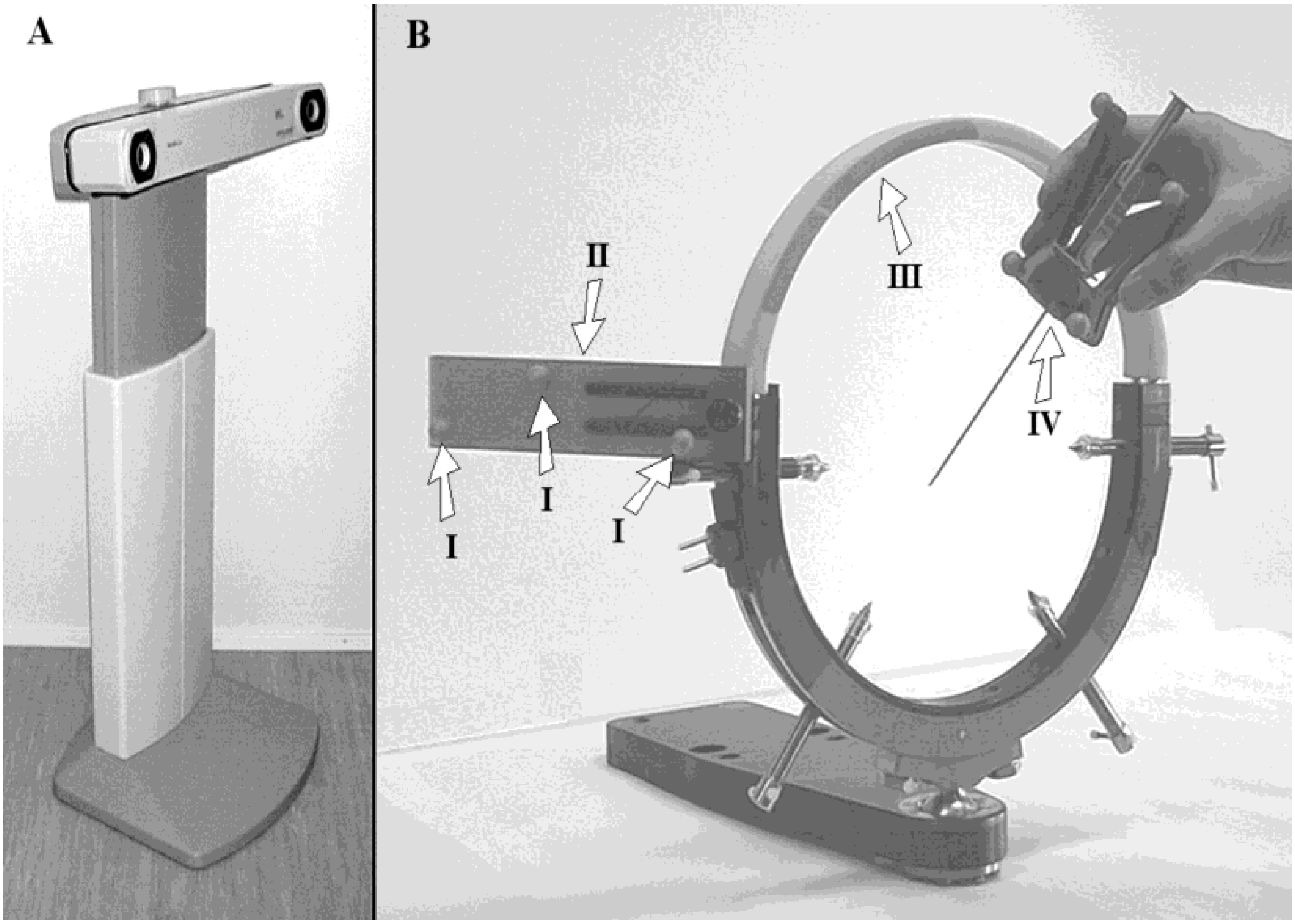

Figure 2. Navigator elements. **A**: Camera head on navigator stand. **B**: Frame with patient tracker (I, II) and detachable upper part (III). Also shown is the instrument tracker (IV).

available MRGP (MR-Guided Procedures) hardware and software suites. The suites have an in-room display, optical navigator, sterilizable trackers, and keyboard and mouse controls as a standard, and also provide the software interfaces for supporting a patient tracker. The tracker itself was designed for a neurosurgical head frame with an integrated receiver coil (see Figure 2). It was made out of Ultem1000 (General Electric Plastics, Massachusetts) to render its surfaces sterilizable. The clamping area was designed to be large enough to avoid difficulties with sterile drapes, which are normally placed over coils and frames. The large area provides the necessary rigidity for the tracker and protects the drapes against tearing.

The infrared (IR) reflecting spheres on the surface of the patient tracker, also shown in Figure 2 marked with "I," form a unique geometrical configuration, allowing the optical navigator to distinguish the patient tracker from other trackers such as those attached to instruments or the magnet. The navigator emits IR pulses and uses a triangulation technique to deduce the position information from detected reflections. At least three spheres are needed to resolve all six degrees of motion. Because of the LOS requirements, a navigator stand equipped with wheels and 15m of cable is used. It can be moved around the magnet for optimal field of view. The stand has manual controls for pitch and height.

Locking of the Patient Tracker

Introducing the patient tracker requires support from the software. When a navigator has LOS to the patient and magnet trackers, the software allows a "locking" operation to be performed. It is a simple procedure in which, by a mouse click on the scan-room console, the operator informs the system that registration data for the patient tracker is needed. The software then converts co-ordinate system transformation data from the magnet tracker to the patient tracker using the temporary knowledge it has on their respective locations. It also starts using the patient tracker as a reference instead of the magnet tracker, and displays the overlay of the instrument path on previously acquired images. Staged operations, where the patient has been moved out for better access, can be performed in this overlay mode.

If more images are needed and the patient is outside the magnet, the operator can select appropriate slices by pointing at the region of interest with the instrument. After selecting the desired type of sequence and moving the patient into the magnet, the operator starts the image acquisition. The software uses the information it has about the previous locking operation and the current positions of the magnet and patient trackers to calculate the requested slice positions.

Working in the manner explained above requires that the patient tracker be fixed to the patient at the point of interest. If the patient moves with respect to the tracker, re-registering must be performed; the patient is moved into the magnet, new slices from the region of interest are acquired, possibly under instrument guidance, and locking is done. In this case, previously acquired image sets cannot be used.

RESULTS

The inaccuracy and rigidity of a patient tracker clamped to the head frame were evaluated as follows: an instrument tracker was attached to a head frame, which was in turn attached to a patient couch. The position of the instrument tracker was measured with the optical navigator, with a magnet tracker as the reference. Then, the patient tracker was attached to the frame and covered with drapes. The locking operation was performed, the couch and navigator moved, and the position was measured again with the patient tracker as the reference. The difference between measured positions corresponded to the position error introduced by the patient tracker. The experiment was repeated 25 times. Inside the characterized detection volume of this particular optical navigator, approximately a sphere with a diameter of 1m, the error was ±0.7mm. Compared with the repeatability error of ±0.4mm, typical for the navigator, the increase in error is not significant.

Patient Cases

The use of the patient tracker was demonstrated in a $50m^2$ operating room which was equipped with a Proview magnet and furnished for interventional MR. For example, there is a 2m-wide sliding door to ensure easy patient and device transportation, two operation lights (SQ-240, Steris Corporation, Mentor, Ohio), two customized anesthesia gas outlets in the ceiling (Sa-Va Sairaalavaruste, Helsinki, Finland), and a combustion gas outlet for laser surgery. In staged surgical practice, the patient is moved in the magnet only for the acquisition of new images. The resistive magnet construction allowed the magnetic field to be turned on and off quickly. Imaging was possible in six minutes after turning the field on. Since the magnetic field was turned on only for the duration of imaging, non-MRI-compatible instruments and devices were available to the surgeon while imaging was not in progress. Otherwise, the patient couch was moved approximately 1.5m to get him/her outside the 20mT line. The floor plan is presented in Figure 3, which shows the positioning of auxiliary equipment during a procedure.

The magnet trackers, marked with the letter "Y," were positioned on the upper pole-piece of the "C arm" of the magnet, in order to cover a maximal field of view.

The patient tracker was used with two patient cases, with the aim of assisting in the determination of a maximal, safely achievable tumor resection.

Patient 1

A 38-year-old male presented with a recurrent, right-side, occipitoparietal oligodendroglioma. A palliative reduction of tumor mass was planned with the intention to better control his epileptic seizures and other symptoms. Prior to the operation, functional MR imaging was used to locate primary visual cortex adjacent to the tumor. The neoplasm was recognized after craniotomy by its macroscopically pathological appearance, and the resection proceeded to the point at which it could not be continued safely, based on the preoperative images. The intra-operative MR images revealed tumor residuals in the corpus callosum and the medial temporal lobe, infiltrating the hippocampus. After completion of the imaging session, the patient was moved into the operating position outside the scanner, and the optical navigator, including the patient tracker, was used to localize the resectable tumor remnants. The neurosurgeons used the system to reliably identify anatomical and pathological structures. Further tumor resection was carried out, and the operation was completed, using standard neurosurgical techniques.

The histopathological diagnosis was oligodendroglioma (WHO grade II), confirming the earlier findings and showing no progression to higher malignancy. Nevertheless, the patient was referred for adjuvant oncological treatment.

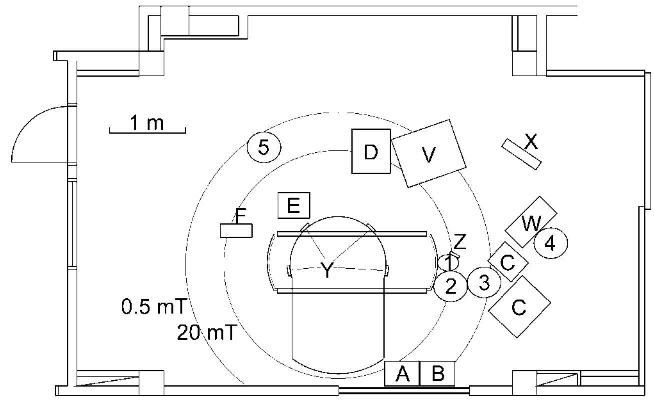

Figure 3. Operating Room Floor Plan. 1, patient's head; 2, neurosurgeon; 3, scrub nurse; 4, radiographer; 5, anesthesiologist; A, suction; B, diathermy; C, nstrument table; D, respirator; E, infusion pumps; F, anesthesia monitor; V, in-room display; W, keyboard & mouse; X, optical navigator; Y, magnet tracker; Z, patient tracker.

Patient 2

A 61-year-old male was surgically treated for a left temporoparietal intra-axial lesion and a small lesion in the left occipital lobe. Prior to opening of the dura, intraoperative ultrasound imaging was used to visualize the borders of the tumor and to confirm the planned approach. Then the macroscopically visible tumor tissue was resected along the presumed border between infiltrated gliotic brain tissue and tumor bulk. After a macroscopically complete resection of what had shown on the preoperative images as the enhancing tumor mass, the patient was moved into the magnet, where intraoperative MR images were acquired to detect possible contrast-enhancing tumor remnants. The images confirmed the completeness of resection. The optical navigator with a patient tracker was then tested. The

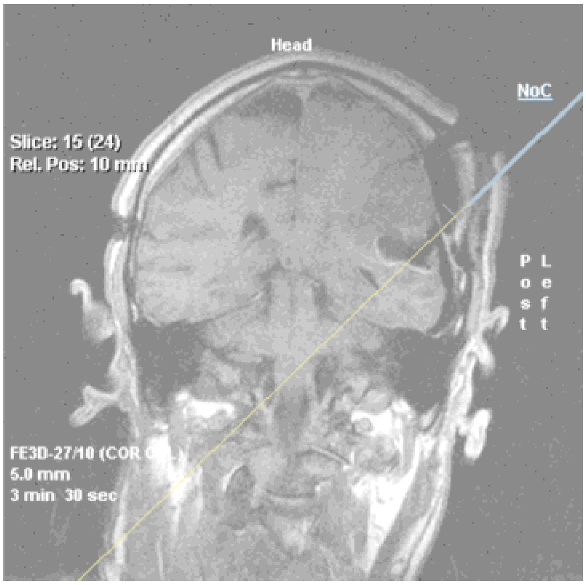

Figure 4. FE3D slice from patient 2. The virtual instrument and its extension line are overlaid on the image in real time with blue and yellow lines, respectively.

magnetic field was turned off and the patient tracker activated. The patient was moved out of the scanner to the operating position, about 1.5m from the scanner's isocenter. Points around and within the depth of the resection cavity were identified with the pointing device, and the locations were compared to the instrument graphics on the large, in-room display (see Figure. 4). Finally, the craniotomy was closed using standard neurosurgical techniques. The histopathological diagnosis was glioblastoma multiforme (WHO Grade IV), and the patient was therefore referred for adjuvant oncological treatment.

The characteristic detection volume of the optical navigator and the positioning capabilities of the patient tracker were sufficient for correct operation of the system. The line of sight to the patient tracker could be arranged with repositioning of the navigator stand.

DISCUSSION

The main benefits of using the patient tracker are simplicity and speed, especially when the access to a patient is restricted inside the magnet. The relative simplicity of the method reduces the chance for human error and the risk inherent in automated, elaborate algorithms. If the patient is operated on near the magnet, as can be the case with low field resistive magnets or when MR compatible equipment is used, the patient tracker makes frequent image acquisitions possible. For example, changes in brain morphology can be detected outside the magnet as in conventional neuronavigational procedures, allowing re-acquisition of image sets. The advantage of shorter procedures, such as biopsies, is also clear.

Patient handling needs to be sophisticated for the method to be effective. The docking mechanism of the couch should be designed to help the operator accurately and smoothly reposition the patient inside the magnet. Immobilization of the patient is a crucial task which is easily achieved in the case of head frames, but more complicated when imaging limbs and soft tissue in general. Rigid fixation of extremities is possible, however (17), and the accuracy needed for musculoskeletal biopsies is not as critical as with neurosurgical operations. It remains to be seen whether this method may also apply to those cases. Using two reference frames with the optical navigator offers a fast and convenient way to acquire images and align minimally-invasive tools in real time in neurosurgical operations.

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