Frameless Stereotactic Surgery Using Intraoperative High-Field Magnetic Resonance Imaging

Christopher NIMSKY*, Atsushi FUJITA*,**, Oliver GANSLANDT*, Boris von KELLER*, Eiji KOHMURA**, and Rudolf FAHLBUSCH*

*Department of Neurosurgery, University Erlangen-Nürnberg, Erlangen, Germany; **Department of Neurosurgery, Kobe University Graduate School of Medicine, Kobe

Abstract
This study evaluated the clinical validity of frameless stereotaxy using high-field intraoperative magnetic resonance (iMR) imaging combined with an in-room neuronavigation system. A 1.5 Tesla MR scanner in conjunction with a ceiling-mounted neuronavigation system was used during 32 frameless stereotaxy procedures consisting of 19 brain biopsies and 13 catheter placements between April 2002 and mid-October 2003. Evaluation of the procedure was based on either the rate of histological diagnostic yield or the ability to accurately position the catheter in the target region. This technique allowed successful registration with a mean error of $1.2 \pm 0.8$ mm and resulted in successful placement of the instrument within the target tissue. Intraoperatively, frozen section analysis showed all biopsy samples contained pathological tissue and locations of sampling points were confirmed by iMR imaging. Specific final diagnosis was made in all 19 brain biopsies. The tip of the catheter was successfully placed into the target in all 13 patients confirmed by iMR imaging. The catheter was repositioned based on iMR imaging in four of 13 patients, increasing the rate of successful placement. There were no procedure-related neurological deficits or mortality, but we encountered two cases of wound infection, one needing surgical revision. Total additional procedure time related to the induction of iMR imaging was $76.7 \pm 23.3$ minutes. This initial experience of the combination of conventional frameless stereotaxy and high-field iMR imaging improved the quality of frameless stereotaxy with low morbidity and mortality, but did not translate into a significant reduction of procedure-related time.

Key words: brain biopsy, frameless stereotaxy, functional neuronavigation, intraoperative high-field magnetic resonance imaging

Introduction
The development of computers and advances in technology have allowed increased clinical implementation of stereotactic techniques for various neurosurgical procedures, including brain biopsy, placement of catheters, and insertion of electrodes. Initially, these techniques required a rigid head frame, which is associated with some discomfort for the patients, and complicated calculation of positioning data for accurate targeting. The frameless stereotaxy technique can eliminate the cumbersome head frames, including the time for application, and achieved an accuracy comparable to frame-based stereotaxy.\textsuperscript{1,3,4,14,22}

Intraoperative magnetic resonance (iMR) imaging...
in our operating theater in April 2002, we have developed this concept for application to clinical stereotactic procedures with scalp-applied fiducial markers.

Here we describe our initial experience of frameless stereotaxy using high-field iMR imaging in conjunction with a fiducial marker-based neuronavigation system, and evaluate this system with an emphasis on clinical feasibility and validation.

**Subjects and Methods**

I. Patients

A total of 239 patients underwent neurosurgical procedures between April 2002 and mid-October 2003 in the operating theater of the Department of Neurosurgery at the University Erlangen-Nürnberg using high-field iMR imaging. This study retrospectively reviewed 32 patients, 20 men and 12 women aged 18 to 74 years (mean 48.4 ± 16.3 years) who underwent stereotactic procedures (e.g. brain biopsy and correct placement of catheter) based on their medical records, including the discharge and operative summaries, histological examination, and neuroimaging data. Nineteen patients underwent stereotactic brain biopsy and 13 patients placement of a catheter for intracranial cystic lesions. The indications for stereotactic brain biopsy were suspected intracranial tumor-like lesions in eloquent areas, multifocal lesions, and diffuse lesions. The local ethical committee approved high-field iMR imaging and signed informed consent from each patient was obtained.

II. Set up of the operating theater

All stereotactic procedures were carried out in a radiofrequency-shielded operating theater (Fig. 1) containing a 1.5 Tesla MR scanner (Magnetom Sonata Maestro Class; Siemens Medical Solutions, Erlangen, Germany) and a specially designed rotating surgical table (Trumpf, Saalfeld, Germany). The superconductive active shielded magnet has a 160-cm bore length with 60-cm inner bore diameter equipped with a gradient system with a field strength of up to 40 mT/m (effective 69 mT/m) and a slew rate of up to 200 T/m/sec (346 T/m/sec effective). For safety reasons, both the 5-Gauss and 200-Gauss lines were marked on the floor and the latter was also marked by a raised stainless steel strip as a mechanical threshold. The principal surgical position of the surgical table was located at 160 degrees to the longitudinal axis of the scanner, with the patient’s head at the 5-Gauss line, where all standard neurosurgical instruments can be used. Intraoperatively, the rotating surgical table allowed safe patient transportation into the scanner. Once the rotating mechanism was locked, the height of the table, the angle of tilt, as well as the lateral tilt could be adjusted by a remote control. Only the rotation about the table axis to turn the table into the axis of the scanner was performed manually for safety reasons. An alternative surgical position for stereotactic procedures was located at the opposite opening of the magnet, where only MR imaging-compatible instruments could be used. At this position, the patient could be withdrawn from the scanner for the burr hole procedure, then moved into the scanner for the brain biopsy under continuous imaging.

A ceiling mounted navigation system (Vector-VisionSky; BrainLAB, Heimstetten, Germany) in combination with a touch screen monitor allowed the surgeon to use the neuronavigation system at any time during the procedure. Ceiling mounted in-room displays (Iiyama, Nagano) were located in the fringe field of MR scanner for optimal viewing during surgery. Anesthesia gas inlets and compressed air for surgical drills were integrated in the wall of the radiofrequency-shielded room. Service outlets and sockets were connected to individual electrical circuits so that selected devices could be switched off from a switchboard in the MR control room to prevent artifacts generated by individual devices. The ceiling outlet for laminar airflow was located above the main operating position (Luwa, Frankfurt, Germany). The laminar airflow output was surrounded by a band of fluorescent lamps for optimal illumination. The entire operating theater...
has MR-compatible spot lighting. Two ceiling-mounted surgical lamps (Heraeus Med, Hanau, Germany) were installed at the main surgical position. All equipment not completely MR-compatible, such as the height adjustable surgeon’s chair, is mechanically secured to the wall of the radiofrequency-shielded operating room as a safety precaution. The instrument table and the various rotating stools were fully MR-compatible (Trumpf).

For safe administration of anesthesia, a MR-compatible ventilator (Servo Ventilator 900C; Siemens Medical Solutions) and MR-compatible monitors (Invivo Research, Orlando, Fla., U.S.A.) were used. The monitoring data were transferred to the remote display, which allowed continuous monitoring during scanning from outside the radiofrequency-shielded operating room, using a wireless 2.4 GHz connection. Three infusion pumps (model 2010; Medfusion Inc., Duluth, Ga., U.S.A.) were shielded in a MR-compatible carrier (MRI-Caddy; MIPM, Mammendorf, Germany) for continuous infusion of drugs. The anesthesia equipment was located beyond the 200-Gauss line.

III. Frameless navigation-guided stereotactic procedures

All patients underwent stereotactic procedures under general anesthesia because their heads had to be fixed with a head holder for accurate neuronavigation. For intraoperative use, a MR-compatible 4-point head fixation device made of glass fiber-reinforced plastic was integrated into the head coil. The upper part of the head coil could be sterilized using plasma sterilization. Sterile adapters were used to bridge between the nonsterile and sterile surgical areas to assure sterile draping. This unique system allowed wide variability of the patient’s position, except for the sitting position. After induction of general anesthesia, the scalp was shaved and skin fiducial markers were glued to the head for preoperative scanning. We used data sets of 1.0 mm isotropic three-dimensional (3D) magnetization prepared with a rapid acquisition gradient echo sequence (MPRAGE; field of view [FOV] 250 mm, repetition time [TR] 2020 msec, echo time [TE] 4.38 msec, matrix 256 × 256, voxel size 1.0 × 1.0 × 1.0 mm, scan time 8 min 39 sec) for patient registration. Our unique concept for functional neuronavigation-guided stereotactic procedure added two sets of data. The functional data from functional MR (fMR) imaging or magnetoencephalography (MEG) were integrated into the 3D MPRAGE navigational data set for functional neuronavigation, which allowed correct alignment of the trajectory of the biopsy needle. In patients with diffuse lesions, the data from MR spectroscopy and positron emission tomography (PET) were also integrated into the anatomical 3D MPRAGE data set, which facilitated accurate target selection, resulting in improvement of diagnostic yield.

After finishing the preoperative imaging, the patients were transferred to the principal surgical position and registration was performed using the pointers and rigid reference points within minutes. The optimal entry point and trajectory to the lesion were determined on the VectorVision Autopilot view. A small incision and a burr hole were made at the entry point determined by navigation. The MR imaging-compatible trajectory guide (NeuroGate set; DAUM, Schwerin, Germany) was inserted into the burr hole and tightly affixed by its screw (Fig. 2A). Then the 14-G biopsy needle (NeuroCut; DAUM) with an attached instrument adapter with three mounted reflective markers (BrainLAB) (Fig. 2B, C) was inserted and pivoted until the previously planned trajectory was achieved. After the proper trajectory for biopsy target was determined, the

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locking nut was securely tightened to fix the needle (Fig. 2D). The needle was advanced in a stepwise fashion along the planned pathway with the aid of continuous imaging on the navigation monitor. After confirming the tip of the cannula within the targeted lesion, serial biopsy samples were aspirated using a 5-ml syringe. Since the needle had a side cut window, specimens could be obtained from different portions by rotating the needle. Frozen section analysis was performed to confirm the presence of pathological tissue. During examination by a neuropathologist, the needle was withdrawn and intraoperative imaging was performed to assess the accuracy of sampling portion and exclude hemorrhagic complication. Once the diagnostic tissue was identified, the burr hole-mounted trajectory guide was removed and the wound was closed. For placement of a catheter, a different trajectory guide, a guiding tube with an attached instrument adapter, was held by a flexible Leyla fixation device to maintain the correct trajectory and the catheter was inserted through the tube. This guide had to be removed prior to intraoperative imaging. Cyst puncture was performed with standard silicone catheters containing a straight inner stylet as for ventricular puncture (35 cm radiopaque silicone ventricular catheters, 1.5 mm inner diameter, 3.1 mm outer diameter; 36 cm straight stylet; Codman, Raynham, Mass., U.S.A.).

All patients underwent at least three imaging procedures, i.e. before surgery, after induction of anesthesia, and following the actual stereotactic procedure. The position values in every sequence during imaging studies before starting surgery were recorded for subsequent scanning. This technique enabled identically positioned anatomical slices comparable to preoperative imaging. We preferred to use the T2-weighted turbo spin echo sequence (slice thickness 4 mm, FOV 230 mm, TR 6490 msec, TE 98 msec, scan time 5 min 59 sec at 3 acquisitions) for intraoperative imaging. Other sequences were also used for accurate assessment such as half-Fourier acquisition single-shot turbo spin-echo (slice thickness 5 mm, FOV 230 mm, TR 1000 msec, TE 89 msec, scan time 25 sec), fluid-attenuated inversion-recovery (slice thickness 4 mm, FOV 230 mm, TR 10000 msec, TE 103 msec, scan time 6 min 2 sec at 1 acquisition), T1-weighted spin echo (slice thickness 4 mm, FOV 230 mm, TR 525 msec, TE 17 msec, scan time 3 min 59 sec at 2 acquisitions), and echo planar imaging dark fluid (slice thickness 5 mm, FOV 230 mm, TR 9000 msec, TE 85 msec, scan time 1 min at 1 acquisition).

**Results**

Thirty-two patients underwent stereotactic procedures in the operating theater with high-field iMR imaging during the study period. We did not observe any technical difficulties or untoward events attributable to application of high-field iMR imaging, or ferromagnetic accidents owing to the use of standard instruments at the 5-Gauss line. Intraoperative patient transport with the rotating surgical table was uneventful, with only a delay of about 2 minutes until imaging could start. Patient access during imaging is of course limited by the presence of the magnet, but during surgery the access is the same as in conventional surgery. Intraoperative imaging was technically possible in all cases. No imaging artifacts were observed as the fluorescent lamps and specific power outlets were turned off from the MR control room during scanning. The high-field scanner provided greatly superior intraoperative image quality compared to previous low-field scanners. There were no observable differences in image quality between preoperative and intraoperative MR imaging.

The results of patients who underwent stereotactic brain biopsy are summarized in Table 1. Most lesions were primary brain tumors (6 glioblastoma multiforme, 3 malignant lymphoma, 5 astrocytoma, 2 gliomatosis cerebri, 1 oligodendroglioma, 1 oligoastrocytoma, and 1 leucodystrophy). We were able to localize the correct placement of the biopsy needle within the target lesion, as confirmed by intraoperative imaging in all cases. Therefore, the overall diagnostic yield was 100%. Additional imaging modalities (5 fMR imaging, 4 PET, 2 MEG, 1 MR spectroscopy, and 5 diffusion-weighted imaging) were integrated into the MPRAGE data sets for correct target selection in 11 patients. During the stereotactic procedure, the co-registered information was displayed on the navigation monitor. In patients with diffuse lesions (Cases 8 and 10), PET data were used to direct the target to the region of highest fluorodeoxyglucose uptake within the lesion. The application of the navigation system in this series provided satisfactory accuracy. Mean registration error (MRE) in cases of brain biopsy was $1.0 \pm 0.8$ mm (mean ± standard deviation). Figures 3 and 4 show examples of brain biopsy using iMR imaging.

The results of patients who underwent placement of a catheter are summarized in Table 2. All cystic lesions were detected by the navigation system and the catheter tips were successfully placed into the cysts, but intraoperative imaging revealed inappropriate placement of the catheter tip in four of 13...
Table 1  Summary of patients who underwent stereotactic brain biopsy

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age/Sex</th>
<th>Histology (WHO grade)</th>
<th>Location</th>
<th>Maximum diameter (mm)</th>
<th>Cyst or necrosis</th>
<th>Enhancement</th>
<th>MRE (mm)</th>
<th>Images used during procedure</th>
<th>Additional images</th>
<th>Complication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>58/F</td>
<td>malignant lymphoma*</td>
<td>lt basal ganglia</td>
<td>37</td>
<td>—</td>
<td>homo</td>
<td>1.4</td>
<td>T1WI-Gd</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>74/M</td>
<td>glioblastoma (IV)</td>
<td>lt frontal (central)</td>
<td>24</td>
<td>+ (necrosis)</td>
<td>hetero</td>
<td>2.0</td>
<td>fMR imaging</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>69/F</td>
<td>astrocytoma (II)</td>
<td>lt frontal (Broca)</td>
<td>32</td>
<td>+ (cyst)</td>
<td>homo</td>
<td>1.5</td>
<td>T1WI</td>
<td>MEG</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>63/M</td>
<td>astrocytoma (II)</td>
<td>rt parietal</td>
<td>32</td>
<td>—</td>
<td>—</td>
<td>1.2</td>
<td>T1WI</td>
<td>fMR imaging</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>68/F</td>
<td>glioblastoma (IV)</td>
<td>—</td>
<td>49</td>
<td>+ (necrosis)</td>
<td>hetero</td>
<td>0.3</td>
<td>T1WI-Gd</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>62/F</td>
<td>malignant lymphoma*</td>
<td>—</td>
<td>36</td>
<td>—</td>
<td>homo</td>
<td>3.2</td>
<td>T1WI</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>67/F</td>
<td>malignant lymphoma*</td>
<td>rt frontal, lt frontal</td>
<td>30</td>
<td>—</td>
<td>homo</td>
<td>0.8</td>
<td>T1WI</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>8</td>
<td>67/M</td>
<td>gliomatosis cerebri (III)</td>
<td>bil occipital</td>
<td>88</td>
<td>—</td>
<td>—</td>
<td>0.4</td>
<td>T1WI, T2WI, FLAIR, PET, DWI</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>44/F</td>
<td>leucodystrophy**</td>
<td>rt cerebellar hemisphere</td>
<td>18</td>
<td>—</td>
<td>—</td>
<td>0.9</td>
<td>T1WI, T2WI</td>
<td>PET + ***</td>
<td>—</td>
</tr>
<tr>
<td>10</td>
<td>50/F</td>
<td>gliomatosis cerebri (III)</td>
<td>bil frontal</td>
<td>75</td>
<td>—</td>
<td>—</td>
<td>2.5</td>
<td>T1WI-Gd</td>
<td>MR spectroscopy, PET</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>29/M</td>
<td>oligodendroglioma (II)</td>
<td>lt frontal (central)</td>
<td>35</td>
<td>—</td>
<td>—</td>
<td>0.4</td>
<td>T1WI, T2WI</td>
<td>fMR imaging, MEG</td>
<td>—</td>
</tr>
<tr>
<td>12</td>
<td>39/F</td>
<td>glioblastoma (IV)</td>
<td>rt parieto-temporal</td>
<td>37</td>
<td>+ (necrosis)</td>
<td>hetero</td>
<td>0.2</td>
<td>T1WI-Gd, T2WI</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>13</td>
<td>52/M</td>
<td>glioblastoma (IV)</td>
<td>lt frontal (pericallosal)</td>
<td>42</td>
<td>+ (necrosis)</td>
<td>hetero</td>
<td>0.7</td>
<td>T1WI-Gd</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>14</td>
<td>23/M</td>
<td>astrocytoma (II)</td>
<td>rt frontal diffuse</td>
<td>65</td>
<td>—</td>
<td>—</td>
<td>0.2</td>
<td>T1WI, T2WI</td>
<td>PET, DWI</td>
<td>—</td>
</tr>
<tr>
<td>15</td>
<td>18/M</td>
<td>astrocytoma (II)</td>
<td>rt parietal</td>
<td>33</td>
<td>—</td>
<td>—</td>
<td>1.5</td>
<td>T1WI, T2WI</td>
<td>DWI, fMR imaging</td>
<td>—</td>
</tr>
<tr>
<td>16</td>
<td>56/M</td>
<td>oligo-astrocytoma (II)</td>
<td>lt parietal</td>
<td>45</td>
<td>—</td>
<td>—</td>
<td>0.5</td>
<td>T1WI, T2WI</td>
<td>DWI, fMR imaging</td>
<td>—</td>
</tr>
<tr>
<td>17</td>
<td>48/F</td>
<td>astrocytoma (III)</td>
<td>lt parietal</td>
<td>38</td>
<td>—</td>
<td>hetero</td>
<td>0.9</td>
<td>T1WI, T2WI</td>
<td>DWI</td>
<td>—</td>
</tr>
<tr>
<td>18</td>
<td>36/M</td>
<td>glioblastoma (IV)</td>
<td>rt parieto-occipital</td>
<td>41</td>
<td>—</td>
<td>hetero</td>
<td>0.3</td>
<td>T1WI-Gd</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>19</td>
<td>52/F</td>
<td>glioblastoma (IV)</td>
<td>rt occipital</td>
<td>35</td>
<td>—</td>
<td>hetero</td>
<td>0.6</td>
<td>T1WI, T2WI</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>


Patients. The rigid capsule led to an initial displacement of the catheter in three of the four patients, all with suprasellar craniopharyngiomas. In the fourth patient (Case 32), the catheter pathway was corrected, because after aspiration of some cyst fluid the intraoperative imaging revealed compartmentalization of the cyst, which was not visible before, so that the drainage would otherwise have been incomplete, but correction of the catheter path allowed satisfactory cyst aspiration. The re-registration technique using intraoperative imaging could adjust the catheter tip position to the correct location. Two patients (Cases 26 and 32) required another attempt whereas two (Cases 22 and 25) required two further attempts. MRE was 1.5 ± 0.7 mm in these patients, and overall MRE was 1.2 ± 0.8 mm. The differences in MRE between patients with or without repositioning of the catheter were not significant (1.6 ± 0.7 mm for one attempt versus 1.1 ± 0.4 mm for several attempts, p = 0.12, Welch’s t-test). Figures 5, 6, and 7 show examples of correct placement of a catheter using iMR imaging.

The mean time for setup (from positioning of the patient to skin incision) was 52.8 ± 19.2 minutes,
including the time for head fixation, preoperative imaging, image processing, planning, and registration of navigation. The most frequent preoperative imaging sequence was the MPRAGE data set, which is necessary for the registration of the navigation system, with or without T2-weighted imaging. The mean time for intraoperative imaging (from the decision to perform iMR imaging to the end of the scanning) was 23.9 ± 10.5 minutes. The most frequent intraoperative imaging sequence was T2-weighted imaging. The total additional procedure time including preoperative and intraoperative imaging, image transfer, image processing, planning, and registration was 76.7 ± 23.3 minutes.

There were no new neurological deficits or deterioration of preexisting deficits in any patient. However, one patient undergoing biopsy group developed local wound infection, which could be treated by antibiotics, and a catheter had to be removed one month after implantation due to meningitis in a patient with craniopharyngioma. The overall morbidity and mortality was 0%. The differences in maximum diameter of the target between the two groups were not significant (41.7 ± 17.2 mm in patients who underwent brain biopsy versus 35.2 ± 12.9 mm for catheter placement, p = 0.23, Welch’s t-test) and MRE between the two groups was also not significant (1.5 ± 0.7 mm in patients who underwent brain biopsy versus 1.0 ± 0.8 mm for catheter placement, p = 0.10, Welch’s
Discussion

Frameless stereotactic systems have been under development and implementation since the mid-1980s. The frameless technique avoids the use of stereotactic head frames, complicated calculations, and the additional time and cumbersome task of application of the frame. However, frameless systems require preoperative imaging oriented to a constant set of fiducial markers, which is usually performed at least one day before the planned operative procedure. This time lag between imaging acquisition and surgery is thought to be one of the major factors causing registration error. Our approach to obtain preoperative imaging data after induction of anesthesia and head fixation avoids movement of the skin markers compared to the conventional approach in frameless stereotaxy. The

Table 2 Summary of patients who underwent stereotactic placement of catheters

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age/ Sex</th>
<th>Histology (WHO grade)</th>
<th>Location</th>
<th>Target</th>
<th>Maximum diameter (mm)</th>
<th>MRE (mm)</th>
<th>Images used during procedure</th>
<th>Result of iMR imaging</th>
<th>Further treatment</th>
<th>Complication</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>27/M</td>
<td>craniopharyngioma</td>
<td>suprasellar cyst</td>
<td>48</td>
<td>1.8</td>
<td>T1WI</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>21</td>
<td>42/M</td>
<td>craniopharyngioma</td>
<td>suprasellar cyst</td>
<td>27</td>
<td>2.2</td>
<td>T1WI-Gd</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>22</td>
<td>57/M</td>
<td>craniopharyngioma</td>
<td>suprasellar cyst</td>
<td>31</td>
<td>0.9</td>
<td>T1WI</td>
<td>catheter placement corrected twice</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>23</td>
<td>26/M</td>
<td>craniopharyngioma</td>
<td>suprasellar cyst</td>
<td>29</td>
<td>1.6</td>
<td>T1WI</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>24</td>
<td>40/M</td>
<td>glioblastoma (IV)</td>
<td>rt temporal cyst</td>
<td>38</td>
<td>1.4</td>
<td>T1WI, T2WI</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>25</td>
<td>23/M</td>
<td>craniopharyngioma</td>
<td>suprasellar cyst</td>
<td>33</td>
<td>0.6</td>
<td>T1WI</td>
<td>catheter placement corrected twice</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>26</td>
<td>61/M</td>
<td>craniopharyngioma</td>
<td>suprasellar cyst</td>
<td>26</td>
<td>1.3</td>
<td>T1WI</td>
<td>catheter placement corrected once</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>27</td>
<td>40/F</td>
<td>brain abscess</td>
<td>rt parietal cyst</td>
<td>26</td>
<td>0.5</td>
<td>T1WI</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>28</td>
<td>45/F</td>
<td>neurofibromatosis, isolated fourth ventricle</td>
<td></td>
<td>30</td>
<td>2.9</td>
<td>T1WI, T2WI</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>29</td>
<td>61/M</td>
<td>glioblastoma</td>
<td>lt temporal cyst</td>
<td>34</td>
<td>2.0</td>
<td>T2WI</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>30</td>
<td>64/M</td>
<td>craniopharyngioma</td>
<td>suprasellar cyst</td>
<td>27</td>
<td>1.2</td>
<td>T2WI</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>31</td>
<td>64/M</td>
<td>brain abscess</td>
<td>lt basal ganglia</td>
<td>35</td>
<td>1.2</td>
<td>T1WI, T2WI</td>
<td>correct catheter placement</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>32</td>
<td>23/M</td>
<td>astrocytoma (I)</td>
<td>lt parietal cyst</td>
<td>73</td>
<td>1.6</td>
<td>T2WI</td>
<td>catheter placement corrected once*</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

*Catheter pathway was corrected after intraoperative imaging revealing unexpected compartmentalization of the cyst, which may have caused insufficient drainage. **Wound infection after 1 month, necessitating catheter removal. iMR: intraoperative magnetic resonance, MRE: mean registration error, T1WI: T1-weighted imaging, T1WI-Gd: T1-weighted imaging with gadolinium, T2WI: T2-weighted imaging, WHO: World Health Organization.

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Fig. 5 A 64-year-old man (Case 31) with a deep-seated paraventricular brain abscess. During planning of the trajectory, angulations and entry point of the trajectory passing to the target were verified using the virtual line of the tracking system (A), using axial (B), coronal (D), and sagittal (E) T1-weighted magnetic resonance (MR) images with contrast medium and the axial T2-weighted MR image (C).

Fig. 6 Same patient as in Fig. 5. Co-registered preoperative T1-weighted magnetic resonance (MR) image with contrast medium (A) and T2-weighted MR image (B) and corresponding intraoperative T1-weighted (C) and T2-weighted (D) MR images after evacuation of the pus demonstrate the successful placement of the catheter into the abscess without perforation into the lateral ventricle.

Review of the largest published series of 7471 stereotactic brain biopsies found the average diagnostic yield was 91% (80–99%), the mortality was 0.7% (0.5–2.6%), and the morbidity was 3.5% (0–13%). In our series, none of the biopsy samples yielded normal brain tissue, and a final histological diagnosis was obtained in all cases. This overall diagnostic yield of 100% is only a preliminary value based on 19 patients, but falls within the range for conventional frameless stereotaxy and iMR imaging, with a diagnostic yield of 96–100%. The morbidity and mortality in our series were both 0%, but we observed two cases of wound infection, one needing surgical revision. The incidence of surgical site infection is 4% in patients who underwent craniotomies in conventional operating rooms. Our study included too few patients to detect any increase in the number of wound infections caused by iMR imaging. However, we observed only four wound infections among 239 patients (1.7%) operated under high-field iMR imaging since April 2002. iMR imaging could exclude early postopera-
Fig. 7 A 45-year-old woman (Case 28) with neurofibromatosis associated with an isolated fourth ventricle. The planned trajectory of the needle (bold line) passing to the ventricle is displayed on the in-room navigation screen and adjusted using the axial (A, C) and sagittal (B) T1-weighted, and axial T2-weighted (D) magnetic resonance (MR) images. The line between the two dots in Figures A–D indicates the planned entry point and the target. Preoperative (E) and intraoperative (F) axial T2-weighted MR images confirm the tip of the catheter was successfully placed into the fourth ventricle.

Intraoperative use of a high-field MR scanner may eliminate the limitations such as low imaging quality and long acquisition time of a low-field scanner. However, we should clearly emphasize that with our described setup a smooth intraoperative workflow is guaranteed and updating of neuronavigation with intraoperative data for repeated biopsy attempts is possible. Just to place catheters in cysts would not justify purchasing a high-field magnet because such procedures should be possible either with low-field MR scanners or mobile computed tomography (CT), which have a clear advantage over the high-field MR scanner in view of cost effectiveness. Moreover, a high-field MR system has the potential for additional imaging modalities, such as fMRI imaging, MR spectroscopy, and diffusion-weighted imaging, which cannot be easily achieved by low-field MR scanners. MR spectroscopy is now increasingly used to distinguish between tumor and non-tumor tissue in clinical practice, but rarely in the field of interventional MR imaging. In one case, we also used this spectroscopic information to determine the optimal targeting site to obtain a biopsy specimen and achieved diagnostic yield. Our approach enabling both MR spectroscopy and conventional MR imaging for registration in a single procedure, without requiring patient repositioning, was very
useful for brain biopsy, especially in diffuse or heterogeneous lesions. Furthermore, it is also possible to take these spectroscopic images during the surgical procedure and integrate the data into the neuronavigation as an intraoperative update, thus aiding subsequent attempts.

Interventional MR imaging has recently been developed, so there is no proof of biological effects related to the exposure of persons working in a magnetic field, especially in the fringe-field of a high-field (1.5 T) scanner. Compared with stereotactic procedures using real-time imaging within a high-power magnetic field, our approach provided safety advantages over other implementations of iMR imaging for real-time imaging. Procedures in our environment were mostly performed outside the 5-Gauss line, which eliminated unnecessary long-lasting exposure to high magnetic fields for both surgeons and other staff.

There are some limitations that have to be discussed. First, whereas our frameless stereotaxy method using iMR imaging provided superb effects in clinical practice, the overall procedure time, including planning, registration, and intraoperative imaging, is relatively long. The mean additional time (76.7 min) required was longer than reported in series of frameless stereotaxy procedures with low-field iMR imaging or without intraoperative imaging modalities. One of the most cited restrictions of this technology is the lengthening of the image acquisition time compared with other modalities such as mobile CT, which requires less imaging time. Additional anesthetic time is difficult to dissociate from image acquisition time in our approach, so the overall procedure time is difficult to decrease to a period comparable to conventional stereotaxy. We believe, however, that the smooth workflow with our set up and shortening of image acquisition time generated by a high-field scanner can obtain additional imaging information as described before compared with the low-field scanner. Because there is a learning curve to performing these unique procedures, optimal management of this problem may be achieved by surgeons familiar with this technique. At present, the introduction of iMR imaging for stereotactic procedures does not translate into significant reductions in operative time in comparison with conventional frameless stereotaxy. Therefore, careful patient selection of the type of intraoperative imaging is necessary to reduce the procedure-related time. In the near future, we expect that improvement of the speed of the image acquisition technology will probably solve these problems.

Second, one disadvantage of both frame-based and frameless biopsy techniques is the potential risk for brain shifting after the dura mater has been opened and the cerebrospinal fluid drained, which can result in displacement of the target. Frameless stereotaxy has been performed interactive with near-real time iMR imaging that allowed for direct visualization of the instruments. In our series, the aim of the procedure was not affected by brain shift in any patient. Moreover, if intraoperative shift of the target occurred and histological yield was not achieved, iMR imaging could depict the reasons for failure of targeting and allowed us to visualize the correct target by re-registration of neuronavigation within few minutes.

Third, important restrictions of the introduction of iMR imaging for stereotaxy are related to cost effectiveness. Although it is clear that iMR imaging for stereotactic procedures initially increases costs, for the equipment, site, and personnel, we expect that the cost of the iMR imaging system will be easily offset by using the system for pre- and postoperative assessment of patients when not required for intraoperative scanning. Our unique approach did not require completely MR-compatible instruments (excluding the burr hole-mounted trajectory guide), which are necessary in procedures within the fringe field regardless of the strength of the magnet. In our series, we found no early postoperative hemorrhagic complication, which also reduced postoperative imaging costs, as a follow-up CT the next day was unnecessary. Moreover, an uneventful postoperative clinical course certainly reduces both the hospital stay and costs. In the near future, we expect that less costly iMR imaging systems will be available.

Frameless stereotaxy using high-field iMR imaging was safe and effective, and yielded both successful histological diagnosis yields and correct placements of catheters with low morbidity and mortality comparable to those obtained both in conventional and image-guided stereotactic series. However, introduction of this new technique did not translate into significant reduction in operative time.

Acknowledgments

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References


Address reprint requests to: A. Fujita, M.D., Department of Neurosurgery, Kobe University Graduate School of Medicine, 7–5–1 Kusunoki-cho, Chuo-ku, Kobe 650–0017, Japan.
e-mail: afujita@med.kobe-u.ac.jp

Commentary on this paper appears on the next page.
Commentary

The authors have developed a concept of integrating high-field MR imaging with an in-room neuronavigation system for frameless stereotactic intervention. This technique proposes to eliminate the use of cumbersome head frames and extra time for positioning, with preservation of accuracy. They also added new sets of data, since the functional data from functional MR and magneto-encephalography were integrated in the navigational data, and in patients with diffuse lesions, the data from MR spectroscopy and PET were also integrated into the anatomical data set, thus facilitating more accurate target selection and improvement of diagnostic results.

This frameless technique certainly avoids the use of rigid stereotactic frames and their complicated corrections and calculations, using simpler fiducial markers, with comparable accuracy. This technique mainly used for biopsies will also be useful for the placement of catheters in cystic lesions and other locations.

This paper gives us the feeling of the operating rooms of the future, and I am sure that by the middle of the 21st century we will have more computers than people in the operating rooms. The authors, and many other centers, have thus opened the path for the ideal operating room. Unfortunately, not all countries will be able to follow this enormous progress due to its cost.

Raul Marino, Jr., M.D.
Department of Neurosurgery
University of São Paulo Medical School
Instituto Neurologico de São Paulo
São Paulo, Brazil

This paper describes the successful implementation by a well-respected group of an intraoperative high-field strength MRI system and the clinical experience using this form of image-guidance for two common neurosurgical procedures, biopsy and catheter placement. In the spectrum of intraoperative MRI strategies, that described by Nimsky and colleagues is high end, essentially offering the functionality of a state-of-the-art diagnostic scanner. The set-up, methodology, integration with an image-guidance system, and overall operational efficiency of their implementation provide a convenient and powerful surgical environment for a wide variety of neurosurgical procedures. Their experience with these two procedures demonstrates apparent ease-of-use and successful achievement of surgical goals with acceptable morbidity and mortality. They are to be commended on moving this field.

The optimal level of functional capability of neuroimaging in the surgical environment is still to be determined. The described clinical experience shows the feasibility of using a high-field strength MRI more than any specific, actual advantage of this magnet over low-field systems. There are both strengths and weaknesses associated with incorporation of the most sophisticated imaging within the operative room, and we do not know yet how much functionality makes the most sense clinically and financially. Lesser imaging capability relying upon co-registration methodologies to transfer more sophisticated imaging onto intraoperative data-bases represents the more commonly used alternative, but we will be best served by maintaining an open mind in this debate. Should the case for more advanced intraoperative imaging prove compelling on clinical grounds, however, it will likely be difficult for many centers to sufficiently utilize a dedicated diagnostic scanner in a cost-effective manner. Those desiring such capability may have their best chance of acquiring such imaging through a hybrid model in which such equipment is used for diagnostic purposes when it is not in surgical use. As implementations evolve and prove useful, the implications for hospital design and practice behaviors are considerable. In any event, real-time imaging does provide certain advantages as illustrated in some of the cases of their series (although this reader is not convinced that the time-lag between image acquisition and surgery of the nature of biopsy and catheter placement is a major factor causing registration error).

Allocation of resources — be it time, personnel, space, capital equipment, or financial assets — is of critical importance as the cost of ever more sophisticated health care has become a major societal concern. This contribution helps further our understanding of how one such technical implementation might raise our standard of care; it will be of tremendous interest to all of us as financial analyses highlight the less clinical but necessary practical realities of cost, budgetary choice, and value that accompany such practice.

David W. Roberts, M.D.
Section of Neurosurgery
Dartmouth-Hitchcock Medical Center
Lebanon, New Hampshire, U.S.A.