Neuronavigation applied to epilepsy monitoring with subdural electrodes

Technical note

ROUKOUZ B. CHAMOUN, M.D., VIKRAM V. NAYAR, M.D., AND DANIEL YOSHOR, M.D.

Department of Neurosurgery, Baylor College of Medicine, Houston, Texas

Accurate localization of the epileptogenic zone is of paramount importance in epilepsy surgery. Despite the availability of noninvasive structural and functional neuroimaging techniques, invasive monitoring with subdural electrodes is still often indicated in the management of intractable epilepsy. Neuronavigation is widely used to enhance the accuracy of subdural grid placement. It allows accurate implantation of the subdural electrodes based on hypotheses formed as a result of the presurgical workup, and can serve as a helpful tool for resection of the epileptic focus at the time of grid explantation. The authors describe 2 additional simple and practical techniques that extend the usefulness of neuronavigation in patients with epilepsy undergoing monitoring with subdural electrodes. One technique involves using the neuronavigation workstation to merge preimplantation MR images with a postimplantation CT scan to create useful images for accurate localization of electrode locations after implantation. A second technique involves 4 holes drilled at the margins of the craniotomy at the time of grid implantation; these are used as fiducial markers to realign the navigation system to the original registration and allow navigation with the merged image sets at the time of reoperation for grid removal and resection of the epileptic focus. These techniques use widely available commercial navigation systems and do not require additional devices, software, or computer skills. The pitfalls and advantages of these techniques compared to alternatives are discussed.

KEY WORDS • epilepsy surgery • frameless stereotaxy • neuronavigation • subdural electrode grid

Abbreviations used in this paper: EEG = electroencephalography; EMU = Epilepsy Monitoring Unit; EZ = epileptogenic zone; MEG = magnetoencephalography.
tion to enhance the accurate localization of the hypothesized EZ. Thus, the use of neuronavigation can be helpful in surgery for patients with epilepsy who require evaluation with a subdural grid, during grid implantation as well as during the resective surgery.

There are several previous reports that describe the use of neuronavigation in conjunction with epilepsy surgery involving subdural electrodes. We review the relevant literature in this area and describe the techniques we use to operate a StealthStation (Medtronic, Inc.) system for neuronavigation in this setting. Our techniques include the following: 1) standard image-guided surgery using preoperative images to guide electrode implantation; 2) fusion of a postimplantation CT scan with a preoperative MR image to localize electrode positions accurately; and 3) reregistration of the preoperative MR image (and fused postimplantation CT) during the second stage of surgery (explantation/resection) by using the StealthStation’s “realign” feature and 4 small drill holes previously placed at the craniotomy margins at the time of grid implantation. Collectively, these techniques enhance the accuracy of electrode placement, post hoc electrode localization, and epileptic focus resection, and obviate the need for a postimplantation MR image. Moreover, these methods are simple and use resources that are readily available in the vast majority of epilepsy centers.

Surgical Technique

Neuronavigation-Guided Subdural Grid Implantation

A standard high-resolution volumetric MR image is acquired before surgery and transferred to the navigation workstation. The MR imaging data are obtained using T1-weighted fast field echo images (1.5-mm thickness, 256 × 256 matrix, 220-mm field of view). We use the Stealth Treon system (Medtronic, Inc.), but the technique described is probably applicable to other commercially available neuronavigation systems. A FLAIR sequence (3-mm thickness, 256 × 256 matrix, 220-mm field of view) is frequently used in addition to the T1-weighted sequence because the former allows a better visualization of the abnormality for some types of lesions (for example, cortical dysplasia). For patients without identifiable lesions in whom electrode grids are implanted based on PET, SPECT, or MEG data, an image set of the functional study can be fused to a structural MR image to allow grid placement to be tailored to the location of the relevant metabolic focus or dipole. This method has been described in detail elsewhere.

After induction of anesthesia, the patient’s head is fixed of the preoperative MR image (and fused postimplantation CT) during the second stage of surgery (explantation/resection) by using the StealthStation’s “realign” feature and 4 small drill holes previously placed at the craniotomy margins at the time of grid implantation. Collectively, these techniques enhance the accuracy of electrode placement, post hoc electrode localization, and epileptic focus resection, and obviate the need for a postimplantation MR image. Moreover, these methods are simple and use resources that are readily available in the vast majority of epilepsy centers.

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Neuronavigation in patients with subdural grid electrodes

using a Mayfield 3-point fixation clamp and the Stealth reference arc is attached to the clamp. The registration process is performed in standard fashion by using either previously placed stick-on scalp fiducials or surface anatomical landmarks. The location and extent of the craniotomy is individually planned based on the suspected epileptic focus. The skin incision and craniotomy are then tailored with navigation guidance. After performing the craniotomy, 4 holes 1.5 mm in width are drilled in the skull around the craniotomy site and are registered as well (Figs. 1 and 2). This step will allow subsequent realignment of the registration by using the preoperative MR image when the patient is brought back to the operating room for the explantation and resection. The subdural grid is applied to the surface of the brain as dictated by the preoperative workup. Finally, the incision is closed in multiple layers, the head is wrapped, and the patient is awakened from anesthesia. After a brief period of observation in the post-

![Fig. 3. Preimplantation MR image (left) and postimplantation CT scan (right) viewed during the fusion process.](image)

![Fig. 4. Preimplantation MR image fused with postimplantation CT scan allowing the surgeon to localize the subdural grid on the MR image, obviating the need for postoperative MR imaging.](image)
anesthesia care unit, the patient undergoes a CT scan of the head that includes a thin-cut volumetric sequence. The patient is then transferred to the EMU for video-EEG monitoring and, when indicated, for extraoperative cortical mapping.

**Electrode Localization**

While the patient is connected to the recording equipment in the EMU, the postimplantation CT scan is merged with the preoperatively obtained MR image set (Fig. 3) by using the “Auto Merge” function that is included in the Medtronic StealthStation software suite. The fusion software (Stealth Merge, Medtronic, Inc.) searches automatically for optimal image-to-image registration between the CT and MR imaging data sets without the need for manual correction. It has the ability to merge data sets independent of acquisition orientation. Alternatively, if the automatic fusion is found to be unsatisfactory, the “Point Merge” feature, which relies on manual identification of several points on each image set, can be used. In spite of the fact that there are overt differences between the pre- and postimplantation image sets, our experience with this technique in > 50 patients suggests that the “Auto Merge” is nearly always highly effective in accurately fusing the 2 image sets.

Once the 2 image sets are fused and the merged images are visually inspected at multiple slices to confirm a good fusion, the electrode positions are easily defined on the MR image by blending the 2 image sets to a level that allows visualization of the electrodes from the CT scan while permitting good visualization of the adjacent anatomy on MR images (Fig. 4). Our use of this technique in numerous patients has confirmed that it is a very simple and accurate way to pinpoint the electrode locations without obtaining a postimplantation MR image, which may be difficult to obtain and has electrode-induced artifacts. We subsequently use the StealthStation’s “Annotation” feature to mark the important electrode locations on the MR image for subsequent use during the resection procedure.

**Resective Surgery**

During the course of video-EEG monitoring in the EMU, which varies according to the rate at which the patient’s seizures are captured, the electrographic data are studied by the epilepsy team in an attempt to formulate a plan for resection. If a resectable focus is defined, the patient is taken again to the operating room for grid explantation and resection of the epileptic focus. The Stealth Station is prepared by setting the previously used preimplantation MR image as the “reference image set,” and the fused postimplantation CT scan is set as the “working image set.” Once again, the patient’s head is fixed in standard Mayfield 3-point fixation and the Stealth reference arc is attached to the Mayfield adapter. The previous skin incision is reopened and the previous craniotomy is reelevated. The StealthStation registration from the prior implantation surgery is aligned to the patient’s head by using the realign feature on the StealthStation to register to the four 1.5-mm drill holes that were previously fashioned at the craniotomy margin (Fig. 5). This allows us to reuse the previous registration to the preimplantation MR image to navigate in relation to MR anatomy, and we also use the fused CT scan to navigate in relation to specific electrode locations, without obtaining any new imaging studies and with a very simple means for registration. In our experience, the neuronavigation system reregisters to the 4 pinpoint drill holes with good accuracy in craniotomies ~ 5 × 5 cm or larger.

The subdural grid is then removed and the resection is done with navigation guidance. The fusion between the postimplantation CT scan and preimplantation MR image allows visualization of structural abnormalities depicted by the MR image and localization of the grid on the brain surface. During surgery, navigation is often used repeatedly to
tailor the resection according to the structural and/or electrographic abnormalities detected on the MR image and the EEG monitoring conducted using the subdural grid electrodes. We have found this technique to be very helpful and accurate, because in a significant number of such patients the surgeon cannot rely on macroscopic appearance and tissue consistency to guide the resection.

Obviously the surgeon should be aware of any brain shift during surgery. Brain shift is a well-known limitation of neuronavigation. Particularly in this setting, when large subdural grids are used, the amount of cortical displacement can reach several millimeters in the center of the grid. This can lead to a potential error in the CT/MR image fusion. As a consequence the grid may seem to be below the cortical surface in some cases. However, in accordance with the experience of other groups, this displacement is mainly perpendicular to the surface of the grid and does not lead to substantial error in the large majority of cases. If the surgeon suspects significant brain shift at the time of resection, surgical adjuncts such as ultrasonography or intraoperative MR imaging may be useful. Anatomical lesions may be readily identified with these imaging modalities, and the surgeon can verify the completeness of resection.

**Discussion**

Neuronavigation is currently widely used in epilepsy surgery for planning and guidance of both diagnostic and resective procedures. When the EZ is related to a clear anatomical lesion, the advantages of using neuronavigation during resection include a smaller craniotomy precisely tailored to the location and size of the lesion, and potentially a better outcome because it allows one to maximize resection while minimizing the risk of injury to eloquent structures. Many times, however, the presurgical workup reveals an ill-defined anatomical lesion or metabolic/magnetic abnormalities are seen on functional neuroimaging (MEG, PET, and SPECT) requiring invasive monitoring performed using subdural electrodes. Accurate placement of the subdural grid is crucial in these cases. Fusion techniques between structural MR imaging and different functional imaging modalities have been previously described, and the fused images can be used for the purpose of navigation for precise grid positioning over the metabolic and/or magnetic abnormalities identified.

Accurate information about the position of the subdural grid with respect to the cortex is very important for the neurologist and neurosurgeon in the planning of the resective surgery. Traditionally, the grid position is indicated on schematic drawings of standardized brains. More recently, a number of techniques have been described to provide a better visualization of the grid on the surface of the brain. Postimplantation MR imaging is one option; however, the electrodes may cause significant image distortion.

Besides, obtaining an MR image soon after grid implantation is often not very practical, especially in pediatric cases. Alternatively, postimplantation multiplanar radiographs or CT scans are relatively easier and quicker to obtain and can be fused with the preimplantation MR images. A CT scan/MR image fusion in particular is widely available, because it can be obtained using the neuronavigation system and no additional digitizer or software is needed.

Visualization of the subdural electrode on high-resolution 3D MR images is interesting and might offer an additional advantage in the understanding of the position of the grid. However, this typically requires complex software and analysis that may not be readily available in many epilepsy centers. Besides, neurosurgeons are very familiar with cross-sectional multiplanar MR imaging, making the additional value of 3D images potentially modest in the clinical setting.

The technique described in this paper is simple and should be readily available in the vast majority of epilepsy centers. The first step includes using neuronavigation based on a preoperatively acquired MR image for grid placement. The second step consists of accurate anatomical localization of the subdural electrodes by using preimplantation MR imaging/postimplantation CT scan image fusion. By allowing visualization of the electrodes on the cortical surface of the brain, the fused images play an important role during the monitoring period and in the planning of the second surgery. The third step includes using neuronavigation based on the CT/MR fused images during the resective surgery. Neuronavigation use during resection has several advantages: it helps maximize the extent of resection of abnormal lesions identified on the MR image, and it also allows continuous tracking of the position of the subdural electrodes on the brain surface after the actual removal of the grid, thus allowing accurate resection of epileptogenic foci identified during the invasive monitoring. In addition, it helps minimize the risk of neurological deficit by identification of eloquent cortical areas through either known anatomical landmarks on the MR image or as a result of the cortical mapping done during the monitoring period.

Image registration for navigation during the resective surgery using preimplantation MR images is done using the realign feature. Scalp fiducials and surface anatomy are inaccurate for registration at the time of resection because typically there is an interval of several days between grid implantation and resection: fiducials are unlikely to remain in the same position while the patient is being monitored for epilepsy, and surface anatomy is distorted by postoperative swelling. This is why, during the first surgery (for grid implantation), we use pinpoint holes drilled in the skull and register them. This feature is available in the navigation system, and it was designed to verify and/or realign registration during the procedure if need be (for example, in case of suspected movement between the reference arc and the patient’s head). Although rarely used routinely, in the context of resective surgery after grid implantation it allows us to use the preimplantation MR image and to have the same registration accuracy as that obtained during grid implantation.

**Conclusions**

In our experience the technique herein described allows accurate grid placement and precise planning and guidance during the resective procedure. It is simple, relies on a preoperative MR image and a postimplantation CT scan, and is used routinely in our service. It allows us to avoid the need for a postimplantation MR image. The registration process using the realign feature and the CT scan/MR image fusion are available in the navigation workstation, so no additional device, software, or computer skills are required. Because most neurosurgeons nowadays are
familiar with navigation, its use is not associated with a significant increase in the operating time, and its benefits outweigh this small disadvantage.

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

References

Address correspondence to: Daniel Yoshor, M.D., BCM Faculty Center, 1709 Dryden, Suite 750, Houston, Texas 77030, email: dyoshor@bcm.tmc.edu.