Intracranial electrode implantation is widely practiced in the workup for epilepsy surgery in patients with medically refractory seizures. Subdural arrays and depth electrode assemblies with multiple stainless steel or platinum contacts are inserted using frame-based or frameless image guidance techniques, as well as under direct view following a craniotomy. A wide variety of techniques have evolved for documenting and assessing electrode locations, ranging from artist’s sketches, photographs, and plain x-ray films, to postimplant imaging with MR or CT studies.

In our opinion, despite the use of state-of-the-art stereotactic techniques for implantation, the most accurate information comes from imaging of the electrodes after they are implanted. Although postimplant MR imaging can be done safely, it generally produces images that obscure and distort the anatomy in the vicinity of electrodes, especially in the case of subdural grids, where sulci and gyri are completely obscured by electrode artifact. A number of groups have used interactive techniques to mark and transfer electrode positions manually to preoperative MR images or normative atlases. We experimented with this approach some years ago (unpublished data), but found it highly subjective, and had problems with achieving good coregistration accuracy between pre- and postimplant MR images. More recently, Studholme et al. described a quantitative approach to aligning and assessing the nonlinear distortion between pre- and postimplant MR images. This approach is attractive, but is relatively complex to implement, and furthermore, it remains the case that the postimplant MR imaging mainly gives a distorted view of electrode locations, which are most easily assessed using CT scanning. The major downside of CT scanning is the radiation dosage, but there are significant advantages in terms of precise visualization of the electrodes (and cabling) in 3D space, simplicity of automation, rapid assessment of complications, and repeat scanning without disconnection of electrode cabling.

Methods

Patients with medically intractable epilepsy and stereotypical seizures of unclear localization typically have
Implanted electrode localization

undergone multiple MR imaging studies prior to electrode implantation. The most recent high-resolution volumetric scan (spoiled gradient–recalled acquisition or magnetization-prepared rapid acquisition gradient echo sequence, 1 mm in plane resolution, 1- to 1.5-mm slices, 124–140 slices) is most often used as the base image for coregistration and fusion with the postimplant CT scan. If scanning with fiducials or a stereotactic frame is done on the day of implant surgery, those images would typically be used. Use of the most recent images is particularly important in pediatric cases and other instances in which there is potential for ongoing brain distortion. Similar registrations can be performed with other types of anatomical scans by using the same techniques described later in this paper. Coregistrations with other modalities such as SPECT, PET, or functional MR imaging are typically done using the same base image or a previously fused image derived from the same base image. A postimplant CT scan (3 mm, whole head, 0.5 mm in plane resolution, zero gantry tilt) is typically obtained after the patient leaves the postanesthesia care area and before he or she arrives in the seizure monitoring unit, but could be taken or repeated at any time during the implant period. We prefer to have this done as soon as possible after implantation, because it is also an excellent screen for rare implant complications such as bleeding or misplacement of electrodes. The downside to early scanning is the fact that brain shift from the electrode implantation surgery is probably maximal at this time and thus affects coregistration accuracy. As discussed later, we believe that the advantages of early scanning outweigh the disadvantages, and still achieve an accuracy that exceeds that obtainable from postimplant MR imaging. Some suggestions for possible accuracy improvements are also given in the Discussion.

Although we have implemented the following steps in a particular image analysis package, ANALYZE (Mayo Clinic, Biomedical Information Resource), the various steps are generally simple, and generic image processing and visualization procedures that are easy to implement are available in other packages.

Step 1 is to convert the images from the Digital Imaging and Communications in Medicine (DICOM) format and interpolate them (3D linear or spline) to isotropic voxels. This is not a necessary step but facilitates later visualization.

Step 2 is to perform rigid body coregistration by using the MR image as the base and CT scan as the matching image. The choice of base and match images is potentially important, because the base image will not be changed when fusions are performed, whereas the match image will be resampled. This can become a major issue when one of the images is low resolution, in which case it is usually preferable to use the higher-resolution image as base to avoid excessive downsampling. Because in the end the CT is only used to identify electrode locations and facilitate coregistration, we favor avoidance of resampling of the MR imaging. Coregistration is performed using a relatively standard maximization of the mutual information approach between the base and match images, and produces a homogeneous transformation matrix with rigid body rotation, translation, and scaling parameters that can be used to reformat the match image into the same coordinates as the base image.

Step 3 is to segment the MR imaging study to isolate the brain from its coverings. This is done with a mostly automatic sequence of thresholding, erosion, and dilation steps commonly used to segment the brain contour.

Step 4 is to threshold the CT image to isolate the electrodes from the rest of the image. This is an easy matter with the typical platinum electrodes used for implantation today (we use platinum subdural and depth electrodes from Ad-Tech Medical Instrument Corp., and which have a distinctly higher density and brightness in CT than bone, connector wires, and brain. Intermediate thresholds or intensity ranges could be used to isolate these other elements if needed, for example if questions arise regarding external electrode connections.

Step 5 is to edit away any remaining extraneous high-intensity voxels such as electrode wires or cables, and high-density areas of bone. This step is optional, but is a convenient and quick way to ensure that the remaining nonzero voxels represent electrode contacts only. After this, all electrode voxels are set to 1.

Step 6 is to intensify the electrode-only image to exceed the intensity range of the MR image, so that electrode contacts will stand out as bright spots in the fused images. A typical multiplier we use here is 2000.

Step 7 is to apply the homogeneous transformation matrix to resample the electrodes-only CT image and fuse it (by addition) with the MR image. This fusion is done with both the segmented and unsegmented versions of the MR image. The segmented MR image is appropriate for subdural grid surface renderings, whereas the unsegmented MR image works best for depth electrode visualization. One can also just transform the CT scan into MR imaging space as a separate registered image, which is useful for importation into image guidance systems, in which temporary blending of multiple modalities with the base image (usually the MR imaging study with fiducials) is desirable.

Once the aforementioned steps have been performed, the composite image can be visualized in a variety of ways. For convexity electrodes, we favor volume renderings of the segmented MR/CT fusion by using a ray tracing method that averages surface voxels and nicely visualizes cortical electrodes and adjacent cortical surface with sulci and gyri. Maximum intensity projections ("glass brains") are helpful in locating depth electrodes, and 3D visualization with triaxial orthogonal views is helpful for understanding the relationship of individual electrodes to adjacent structures. Oblique cut planes from the unsegmented MR/CT fusion are particularly helpful in visualizing depth electrode trajectories. Examples of these forms of visualization are shown in Fig. 1.

Results

The approach described here has been used routinely at our medical center, and our experience comprises on the order of 200 electrode implants since 1995. We have also used the technique for postimplant localization of deep brain stimulator (Medtronic, Inc.) and neurostimu-
lator (RNS; NeuroPace, Inc.) implants. The aforementioned steps take approximately 60 minutes to complete in ANALYZE, and most of the steps could be automated with scripting and minimal user interaction. The resulting fused image quality can be poor if the MR image is poor due to movement or artifacts, making for difficult segmentation (sometimes requiring some manual steps) and inadequate renderings. Automated coregistration is occasionally difficult, and manual adjustment may be required due to incomplete or sparse imaging of the head, and low-resolution CT (> 3-mm slices) may not adequately image all implanted electrodes. Our epileptologists find the visualizations extremely helpful in electroanatomical correlations of spike and seizure data, in which it is essential to know the position of electrodes with respect to one another and to adjacent brain structures. Combined knowledge of individual brain geometry and EEG field topography make possible the qualitative assessment of source topography and localization. For example, if a sharp polarity reversal is seen between 2 electrodes, it is helpful to know if there is a sulcus between them and how the sulcus traverses the electrode array. Similarly, data from electrodes traversing deeper brain nuclei or structures like the hippocampus are more easily interpreted when intra- and extrahippocampal electrodes are distinguishable.

In terms of the accuracy of our technique, we are aware that there is always some degree of brain shift between the postimplant CT scanning and preoperative MR imaging. As has been mentioned, CT scanning is typically done shortly after completion of the implant, at which point CSF loss is probably maximal. This shift is evident in the fused images and is typically manifested in the vicinity of larger grid assemblies, which are somewhat less convex, or are flattened along with the brain postoperatively, and thus appear to be somewhat below the cortical surface. Still, these electrodes were easily visualized in the rendered surface projection, which averages voxels to a specified depth. When seen, this usually amounts to no more than a few millimeters in the radial direction, but we have seen shifts of 1 cm or more in some instances. On occasion, we have performed repeat CT scanning 24 hours or more after initial implantation, and have noted that the prior brain shift was largely resolved, presumably due to reconstitution of CSF. In those cases, there was little or no indication of translational shift of the electrode array on the cortical surface, but rather a radial dilation of the brain. In such cases, we have seen little difference in the resulting rendered visualizations of surface electrodes, and no significant differences in the relationship of electrodes to sulci and gyri.

Coregistration errors are also a potential source of inaccuracy in electrode localization. The postimplant CT scan contains a number of items not included in the preimplant MR image, including the electrodes, connector wires, and skull defects (bur holes and craniotomies). The mutual information coregistration technique we use seems to be remarkably unaffected by these items, with little change evident in the homogeneous transformation matrix when these items are masked out or removed from the CT. We speculate that there is sufficient mutual information in the whole brain images away from the areas of mismatch to dominate and stabilize the coregistration. We estimate the overall localization accuracy of surface electrodes placed under a craniotomy to be 3 mm or less, approximately the size of an electrode contact and considerably less than their typical spacing of 1 cm. The localization accuracy is probably better for depth and strip electrodes that are inserted through twist drill or bur holes and are less subject to CSF leakage. A formal ac-

**Fig. 1.** Illustrations of fused MR/CT images and visualization. Panels A and B show maximum intensity projections of postimplant CT scans, in which the platinum electrode contacts are clearly seen and in high contrast to other elements of the image. The remaining panels show the visualized electrodes as typically seen for neocortical grids and strips (D), interhemispheric grids (E), and depth electrodes (G and F).
Implanted electrode localization

curacy assessment of our electrode localization method would be desirable but difficult to perform. One possibility would be with a comparison of cortical renderings from MR/CT fusions, with the direct visualization of cortical anatomy from images of the cortical surface obtained with the electrodes in place. Ideally, one would compare stereo pairs of the electrodes in situ with cortical renderings from the same viewing angle. An assessment of depth electrode localization accuracy would probably need to rely on a comparison of postimplant CT and MR imaging studies.

Although MR imaging with implanted electrodes is safe to perform (prior to the attachment of connectors and cabling), the void artifacts in postimplant MR imaging essentially obliterate and distort anatomical details in the vicinity of implanted electrodes, to the extent that sulci and gyri are invisible. We know of no MR imaging sequence that overcomes this problem, and we believe that reference to the preoperative MR images for these anatomical details is unavoidable. In terms of accuracy in locating implanted electrodes in 3D space, CT scanning is undoubtedly superior in terms of direct, undistorted visualization as opposed to the indirect visualization via MR imaging void artifacts. The postimplant CT scan also gives a direct assessment of brain shift relative to the preimplant MR image and can be repeated or postponed until later in the implant period if more accuracy is desired. As has been mentioned, the brain shift associated with implantation appears to be mainly radial and almost exclusively manifested over larger grid assemblies, which are seen slightly (a few millimeters) below the cortical surface. In any case, the visualized surface projections of these electrodes appear to be highly accurate reflections of the actual cortical position, to the extent that we have been able to assess this by occasional repeat CT scanning, postimplant MR imaging, and direct visualization of cortical anatomy. The most accurate image-guided surgery at the end of an implant period would probably rely on a repeat CT just prior to the operation, and on using the electrodes themselves as fiducials.

Discussion

The composite images produced by the described technique bring essential anatomical context to the electroclinical analysis performed using video-EEG recordings of spontaneous seizures. It is also useful for the interpretation of brain stimulation procedures, which in our center include Penfield-style 50-Hz stimulation, 500-Hz triggered electromyography motor mapping, and a variety of evoked potential techniques. The data obtained during the implant procedure can then be brought to the operating room and used to guide the resection. The electrodes from which the data were obtained may be used as fiducials for image guidance or as reference points to define resection margins. We also frequently coregister preoperative subtraction SPECT scans with fused MR imaging electrode images, and we find this useful in making final resection decisions.

Conclusions

The technique described here is easy to implement and use, and addresses the dual purpose of risk management in the assessment of implant complications, and accurate 3D localization of the implanted electrodes with respect to brain anatomy. An obvious improvement to the technique would be to switch from rigid body coregistration to nonlinear warping techniques that could correct for postimplant brain shift. We expect that the most accurate result would come from warping of the preoperative MR image to match the postimplant CT scan. Quantitative electrode localization giving the cartesian coordinates of all electrodes in MR imaging space would also be useful for quantitative inverse source modeling of EEG and evoked potential data, as well as modeling of current fields produced by electrical stimulation.

Disclosure

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

References


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