Published in final edited form as:

Epilepsy Res. 2011 March ; 94(0): 102–109. doi:10.1016/j.epilepsyres.2011.01.011.

3D visualization of subdural electrode shift as measured at craniotomy reopening

Peter S. LaViolette^{a,*}, Scott D. Rand^b, Benjamin M. Ellingson^b, Manoj Raghavan^{c,d}, Sean M. Lewd^e, Kathleen M. Schmainda^b, and Wade Muellerd^e

^a Department of Biophysics, Medical College of Wisconsin, 8701 Watertown Plank Rd., Milwaukee, WI 53226, United States

^b Department of Radiology, Medical College of Wisconsin, 8701 Watertown Plank Rd., Milwaukee, WI 53226, United States

^c Department of Neurology, Medical College of Wisconsin, 8701 Watertown Plank Rd., Milwaukee, WI 53226, United States

^d Department of the Comprehensive Epilepsy Program, Medical College of Wisconsin, 8701 Watertown Plank Rd., Milwaukee, WI 53226, United States

^e Department of Neurosurgery, Medical College of Wisconsin, 8701 Watertown Plank Rd., Milwaukee, WI 53226, United States

Summary

Purpose—Subdural electrodes are implanted for recording intracranial EEG (iEEG) in cases of medically refractory epilepsy as a means to locate cortical regions of seizure onset amenable to surgical resection. Without the aid of imaging-derived 3D electrode models for surgical planning, surgeons have relied on electrodes remaining stationary from the time between placement and follow-up resection. This study quantifies electrode shift with respect to the cortical surface occurring between electrode placement and subsequent reopening.

Methods—CT and structural MRI data were gathered following electrode placement on 10 patients undergoing surgical epilepsy treatment. MRI data were used to create patient specific post-grid 3D reconstructions of cortex, while CT data were co-registered to the MRI and thresholded to reveal electrodes only. At the time of resective surgery, the craniotomy was reopened and electrode positions were determined using intraoperative navigational equipment. Changes in position were then calculated between CT coordinates and intraoperative electrode coordinates.

Results—Five out of ten patients showed statistically significant overall magnitude differences in electrode positions (mean: 7.2 mm), while 4 exhibited significant decompression based shift

© 2011 Elsevier B.V. All rights reserved.

* Corresponding author. Tel.: +1 414 456 7490; fax: +1 414 456 6103. plaviole@mcw.edu (P.S. LaViolette).

Conflict of interest statement

The authors report no conflicts of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epilepsyres.2011.01.011.

(mean: 4.7 mm), and 3 showed significant shear displacement along the surface of the brain (mean: 7.1 mm).

Discussion—Shift in electrode position with respect to the cortical surface has never been precisely measured. We show that in 50% of our cases statistically significant shift occurred. These observations demonstrate the potential utility of complimenting electrode position measures at the reopening of the craniotomy with 3D electrode and brain surface models derived from post-implantation CT and MR imaging for better definition of surgical boundaries.

Keywords

Epilepsy; iEEG; Electrocorticography; ECoG; Brain compression

Introduction

Epileptic patients with medically intractable seizure disorders often require implantation of subdural electrodes for the purpose of seizure localization (Behrens et al., 1994; Engel et al., 1990; Jayakar et al., 1994; Luders et al., 1992) and electrical stimulation mapping of eloquent cortices (Lesser et al., 1987; Luders et al., 1985). Patients undergo a craniotomy for placement of grids and/or strips of electrodes, and the openings are closed for a period of intracranial EEG (iEEG) recording. The duration of the recording can range from a few days to well over a week, throughout which time the grid and strip electrodes are assumed to be stationary relative to the underlying cortical surface.

Planning resection boundaries around epileptogenic zones can be especially challenging in the vicinity of eloquent cortex due to the uncertainty associated with subdural electrode positions and the limitations of techniques for electrode localization. Several techniques have been employed to visualize electrode placement *in vivo* including artifact localization (Bootsveld et al., 1993; Silberbusch et al., 1998), three-dimensional reconstruction and X-ray derived location projection (Dalal et al., 2008; Winkler et al., 2000), automated template MRI transformation and projection (Kovalev et al., 2005), X-ray co-registration (Dalal et al., 2008; Miller et al., 2007; Winkler et al., 2000), curvilinear reformation (Schulze-Bonhage et al., 2002), CT/MRI co-registration (Grzeszczuk et al., 1992; Nelles et al., 2004; Tao et al., 2009), computer aided stereo-tactic model creation (Morris et al., 2004; Wagner et al., 2009) as well as digital 2D photography co-registered to 3D reconstructed MRI (Mahvash et al., 2007; Wellmer et al., 2002).

Recent advances have made it possible for subdural electrodes to be visualized on patient-specific 3D cortical models derived from post-implantation imaging (LaViolette et al., in press). These 3D models are unique in that they are created using MR imaging acquired following the placement of intracranial electrodes. This method gives clear visualization of compression effects on the cortex resulting from electrode grid placement, leaving cortical anatomy intact beneath the grid.

Here we relate CT measured electrode positions obtained shortly after implantation to measurements made in the operating room (OR) during follow-up surgical resection of epileptogenic zones in order to quantify shifts of electrode positions accrued during iEEG

monitoring, or during the reopening of the craniotomy. We present results from 10 patients in whom 3D models of electrode placement were created, and subsequent electrode positions were measured in the OR at the time of resective surgery using intra-operative stereotactic navigation.

Methods

Ten adult patients (S1—S10) with medically intractable epilepsy undergoing surgical implantation of subdural electrodes for epileptic zone localization were enrolled in this study. Patients were sampled randomly from our clinical population, as they were acquired sequentially. This HIPAA-compliant study was approved by our institutional review board (IRB). All patients gave informed written consent to participate in the study.

Electrode implantation

Implanted platinum—iridium alloy electrode discs (4 mm diameter) were arranged in a grid (8×8), partial grid (8×2), strip (4×1 or 6×1), and/or a combination of each (Ad-Tech Medical Racine, WI). Electrodes were placed in the subdural space via both craniotomies and burrhole craniectomies. The current analysis was limited to grid electrodes exposed visually at the time of craniotomy reopening. In some cases, as shown in Fig. 1a S3 and S5 top, grids were trimmed of unnecessary electrodes at the discretion of the neurosurgeon (WM). During implantation, the subdural electrodes were sewn to the dura to limit movement during the course of iEEG monitoring. The craniotomy bone flap was not replaced during the monitoring period and was stored frozen in a sterile environment. The flap was replaced after completing the second-stage surgery for resection of tissue. Each wire from the subdural electrodes was tunneled out a separate stab incision through the scalp where it was secured a second time with a purse-string suture. A head wrap bandage was applied and changed as needed.

Medical imaging

Patients underwent two imaging studies for epilepsy (resective) surgery planning following electrode implantation. Clinical information on each patient is displayed in Supplementary Table 1. Structural 3D T1-weighted spoiled gradient echo (SPGR) MR images were gathered using a 1.5T MR unit (GE Healthcare, Waukesha, WI) with commercially available hardware and software, voxel size $1.25 \text{ mm} \times 1.25 \text{ mm} \times 1.3 \text{ mm}$, repetition time (TR) = 8.74 ms, echo time (TE) = 1.66 ms, field of view (FOV) = 320 mm, and flip angle = 15° . A high-resolution CT scan was also acquired with commercially available multi-detector hardware and helical scan software, voxel size of $0.5 \text{ mm} \times 0.5 \text{ mm} \times 0.625 \text{ mm}$, tube voltage of 140 kV, 250 mm FOV, current 250—325 mA, and gantry angle 0— 27.5° (GE Healthcare, Waukesha, WI). In patients S1—5 and S7—8 an additional high resolution MRI was acquired prior to resective surgery for use in a StealthStation intraoperative stereo-tactic navigational system (Medtronic Inc. Minneapolis, MN). In the remaining 3 patients, MRI gathered the day prior to resective surgery was used in both stereotactic navigation and construction of 3D models. This eliminated the need for an additional MRI.

MRI processing

MRI data was processed as previously described (LaViolette et al., in press) using Freesurfer (www.surfer.nmr.mgh.harvard.edu) to produce patient-specific 3D cortical surface models (Dale et al., 1999; Fischl et al., 1999, 2002). The automated skull-stripping tool BET (FMRIB tool library) was also used in cases where part of the skull remained following freesurfer's skull strip algorithm (7/10 patients). In the analysis of one patient (S10), the 3D renderings of cortex could not be created due to confounding superficial enhancing venous anatomy, as the post-implant MRI was obtained with a gadolinium contrast agent. As an alternative, overlays from this patient were displayed on a template brain.

CT image processing

Post-implantation, gantry angle-corrected CT data was processed as described previously (LaViolette et al., in press). Briefly, CT data was co-registered using a linear affine transformation to post-implant MRI data using FLIRT (FMRIB software library <http://www.fmrib.ox.ac.uk/fsl>). A Board Certified Radiologist (SDR) visually verified co-registration on all patients. The CT data was then thresholded and binarized to limit the image information to the electrodes only (Morris, O'Brien, Cook, Murphy and Bowden 2004). The threshold value was chosen manually to eliminate streak (beam hardening) artifact from the electrodes (Silberbusch et al., 1998).

Intra-operative electrode localization

During surgical resection the Stealth navigation system was calibrated for each patient using a high resolution MRI scan acquired as described above. Once calibrated with fiducial markers present in the MRI, the patient's craniotomy defects were carefully reopened. Upon exposure, the surgeon placed the Stealth navigational probe in the center of each electrode and coordinates were recorded from the navigation system monitor. In each case, electrode positions were gathered only on visible electrodes within direct reach of the navigational probe. In two cases, time constraints limited the number of electrode coordinates gathered to measure grid position (S2 and S5) at the discretion of the surgeon. Stealth coordinates were then transformed into the same coordinate space as the Freesurfer-rendered cortical surfaces using a rigid affine transformation calculated by co-registration of the two MRI datasets. In the cases where the same MRI was used for generating cortical surface models and used in navigation, no affine transform was necessary. Rather, a simple resampling scheme was used to transform the data from Stealth navigation image resolution to Freesurfer image resolution.

3D grid model creation

A 3D mesh was created connecting the electrode coordinates measured with the Stealth probe (Fig. 1a and b 2nd row, red sheets) using Matlab (MathWorks Inc. Natick, MA) and custom developed software. A second 3D mesh sheet was also created based on the CT measured coordinates (Fig. 1a and b 2nd row, yellow sheets) for visual comparison with Stealth measurement based sheets. For ease of comparison, the sheet lying farthest out laterally was displayed transparently making overlap appear as orange in color (Fig. 1a and

b, 2nd row). This procedure was done following the resective surgery, and required approximately an hour of processing per patient.

Measurement of electrode shift

The centroid location was found for each of the CT measured electrodes and compared to the coordinate measured in the Stealth system intra-operatively to quantify the differences in electrode location. The *magnitude*, *compression*, and *shear* displacements were calculated for each electrode, defined as the absolute change in position, the difference in distance between the brain's centroid and each electrode, and the movement along the brain surface, respectively (Fig. 2). The brain's centroid was found using the skull stripped MRI.

3D Model creation and display—Freesurfer-generated pial surfaces were loaded into 3Dslicer (<http://www.slicer.org>) for viewing (LaViolette et al., in press). 3D tessellations were then rendered around thresholded CT electrodes (Fig. 1a and b top row). Pial surfaces were also overlaid with the two grid sheet models for visualization of rotation and translation.

Reference electrode validation of modality registration

In six patients additional intraoperative coordinates were measured by sampling 2-contact reference electrodes screwed into the skull. These coordinates were then transformed using the same transformation as the Stealth measured grid electrode positions and compared to CT derived screw head locations found visually in the high-resolution CT (Supplementary Fig. 1). Since these electrodes were firmly secured to bone, these measurements provided estimates of electrode shift error manifested through co-registration of CT to MRI and the transformation from the Stealth space Cartesian coordinate system to the Freesurfer space Cartesian coordinate system.

Statistical analysis of electrode shift

Measures of magnitude, compression, and shear for each patient were compared to the estimated errors gathered from the reference electrodes anchored on the skull. It was assumed that the error in our measurement procedure was well captured by the empirically observed shifts of the reference electrodes. Individual measures of shifts in magnitude, compression, and shear were considered significant if they differed statistically from the group's control (reference electrodes) measurements as a whole using a one-way ANOVA. Differences were considered significant for $p < 0.01$.

Results

Quantifying electrode shift

Resulting measures of magnitude, compression, and shear shifts are shown in Fig. 3 and Table 1. Half (5/10) of the patients showed a magnitude shift significantly greater than expected from the grounded electrode control measures (average magnitude of 7.2 mm vs. control mean of 2.3 mm, $p < 0.01$). Four patients exhibited significant compression (mean: 4.7 mm vs. 0.4 mm, $p < 0.01$), while three displayed significant shear shift in electrodes (mean: 7.1 mm vs. 1.9 mm, $p < 0.01$). One patient (S4) showed significantly greater shear

measures with a mean rotational and translational electrode shift of 12.4 mm (min 4.6, max 21.2 mm). A detailed assessment is displayed in Fig. 4, where electrode models are compared to photographs taken in the OR. In addition, patient S2 showed statistically significant shear shift, detailed in Supplementary Fig. 2. Patient S9 showed the greatest compression change of 6.8 mm (min 1.4, max 12.9 mm). Measures of electrode shift are displayed in Fig. 3. Skull reference electrode shifts derived from our co-registration procedures are also displayed for each subject (where available) as + signs.

Visualizing electrode shift

3D representations of CT based electrode placement are displayed for each patient in Fig. 1a and b top row. Electrodes are shown in yellow. Sheet representations of CT and Stealth measured electrode positions are shown in Fig. 1a and b 2nd row (CT images are shown only for electrodes also measured with Stealth.). A representative coronal and axial slice are also shown in the 3rd and 4th rows with sheet models depicted as red and yellow lines. Both slices are also shown in the above 3D models.

Discussion

The purpose of this study was to quantify subdural electrode shift (magnitude, compression, and shear components) between the time of placement and subsequent resective surgery during iEEG studies performed for medically refractory epilepsy. Without reliable methods to detect shift during iEEG monitoring, clinicians practice under the assumption that the electrodes remain stationary relative to the underlying cortical surface. We demonstrate that brain compression and sliding of grid electrodes over the brain surface routinely occur, and are both quantifiable and visualizable using 3D electrode models created with post-grid CT and MR imaging combined with intra-operative navigational measures of electrode positions.

Numerous techniques have been invented to attempt to adequately localize intracranial electrodes using medical imaging. None have directly measured compression of brain tissue and the electrode shifts along the brain surface (shear) that occur during invasive EEG monitoring. We find that electrodes shifted an average of 5.4 mm in magnitude including 2.0 mm of compression and 4.0 mm of shear shift across all 264 measurable electrodes in 10 patients. The magnitude of shift is slightly over half the distance between the typical electrode spacing of 1 cm. The average error in such measures was 2.3 mm as assessed using grounded electrodes anchored to the skull with screws.

Measurements were limited to 1 mm isotropic voxel resolution in the co-registered CT + MRI imaging space. The Stealth Station reported accurate co-registration of the MR imaging space to the operative field to within 1 mm in all cases. These figures represent image acquisition and surgical navigational resolution limits. Sub-millimeter resolution for image acquisition would be preferred, but may be impractical due to longer imaging times.

Stereotactic measurement error was estimated in 6 of 10 patients through measurement of the position of 2-contact reference electrodes screwed onto the skull. The differences between the CT measured reference electrode coordinates and coordinates measured in the

OR was considered to represent the overall error accrued in the co-registration of the CT and MRI, and the transformation of the MRI from Stealth space to Freesurfer space. Unfortunately, the control (reference) electrode measurements were not gathered intraoperatively on four patients. In all patients, CT to MRI co-registration was verified by the careful visual inspection of a board certified radiologist (S.D.R.). The patient that showed the greatest shift in electrodes (S4) did have control (reference electrode) data gathered, which did align well with the CT acquired positions.

Four out of ten patients exhibited statistically significant compression effects as measured using intraoperative stereotactic navigational equipment, while three patients demonstrated statistically significant shifts in electrode rotation and translation along the brain's surface (shear). This shift occurred in spite of precautionary measures taken prior to and during the reopening of the craniotomy, implicating shift prior to reopening. The compression findings are not surprising and are influenced by extra-axial fluid, brain shift with positioning, and loss of cerebrospinal fluid during re-opening. Though statistically significant, compression shift in electrode position is likely not clinically significant, as anatomy beneath electrodes generally remains stationary. The shear measurements however are of particular clinical relevance as these observed shifts raise concerns about the precision with which subdural electrodes can provide information about underlying brain physiology. These shear shifts place an empirical limit on the precision with which resection boundaries defined by prolonged iEEG studies can be realized. Clinical significance of shear shift would be difficult to assess, and would require long-term follow up of post-surgical clinical outcomes in a carefully controlled study.

There are a number of possible factors that may contribute to electrode shifting. Blood and cerebrospinal fluid accumulation can occur in the epidural or subdural spaces causing migration of the electrodes. One would expect this to contribute to changes in compression (relationship between electrodes and center of brain) and have limited effects on shear. However if fluid were to accumulate between the surface of the brain and the electrodes, this may allow the electrodes to “float” with subsequent shear effect. Wires being inadvertently pulled could potentially cause electrode shift. Our technique involves securing the wires in a tension-free manner at both the level of the scalp, and the dura, so this would seem unlikely in the absence of a broken suture (which was not identified). Some seizures result in violent movement of the head, which could potentially result in disruption of the relationship between the electrodes and the surface of the brain. It is the preference of our epilepsy center to remove the craniotomy bone flap during the monitoring period; it is unclear whether the presence or absence of the bone flap makes electrode shift more or less likely. This is a possible area of future research. Finally, one cannot rule out human error as a source of shift during opening of the dura although certainly great care was taken in each case to avoid any iatrogenic forces on the electrodes and wires.

Another possible explanation for shear shift would be that the brain and electrodes shift together with respect to the brain's centroid, and our subsequent measurements lack clinical significance when cortical anatomy remains physically and spatially coupled to shifting electrodes. We have shown photographic evidence to the contrary for patient S4, in Fig. 4, and patient S2 in Supplementary Fig. 2. Electrodes in both cases slide along the brain's

surface moving from one gyrus to the next adjacent gyrus (for example, see electrodes 18 and 21 in Fig. 4, and electrodes 17—20 in Supplementary Fig. 2 that cross the Sylvian fissure). In the case of patient S9 ideal photographs were not obtained in the OR, so no photographic comparison was made.

Fortunately in the case of Patient S4, whose measurements showed the greatest rotational and translational (shear) shift in electrode position (Fig. 4), the surgical outcome remained positive, and the patient is currently seizure free at 13 months following resection. The surgical resection was an anterior temporal lobectomy. The reason for such a large shift in electrode position in this patient is not clear. The patient was monitored for two days following the grid placement and two complex partial seizures without secondary generalization were recorded during iEEG monitoring. Also notable in Fig. 1b, patient S9s CT data was acquired following electrode placement, and the MRI was gathered 3 days later, prior to resection. During this time the brain surface decompressed (expanded) substantially causing the CT data to appear well beneath the brain's surface. This patient also had a positive outcome, currently at 8 months seizure free. A summary of each patient's clinical details is presented in Supplementary Table 1, including outcome status at the time of publication.

Accurate localization of intracranial electrodes is not only of significance for refining the current practice of epilepsy surgery, but is also relevant to several emerging diagnostic and therapeutic methodologies. Precise modeling of the relationship of electrodes and cortical surface geometry is an essential step in computing the cortical sources of electrical activity recorded at the electrodes using sophisticated source modeling methods (Fuchs et al., 2007; Zhang et al., 2008). Neuromodulation therapies involving cortical electrodes, such as responsive neurostimulation for epilepsy (Kossoff et al., 2004), or cortical stimulation for pain and tinnitus would also benefit from precise localization of electrode positions and estimation of shifts after initial implantation. A future direction in refining our methods could be to undertake more computationally intensive methods to model gyral and sulcal deformation patterns with techniques such as finite element modeling. Serial brain surface and electrode models at different time points with paired MRI and CT datasets could also help monitor electrode shifts relative to the cortical surface. The potential of these 3D models to improve the topographical definition of planned surgical targets, resection margins, and surgical outcomes in epilepsy surgery is yet to be explored.

One current disadvantage of our technique is that the shift analysis is done post hoc, and not in real time in the operating room. Due to this limitation the surgeries were all done without knowledge of the shift measurements. Current limitations of the Stealth Navigation unit prevent real time feedback to our research software for comparison. One potential solution is the import of these 3D models into the navigation unit. Research is under way to determine the feasibility of this methodology.

In summary, we have demonstrated that electrode shift with respect to the brain surface can occur due to activities of daily inpatient monitoring, fluid collections, seizures, and/or the reopening of the craniotomy. This shift presents a potentially clinically significant constraint in the definition of surgical resection boundaries for partial epilepsy based on iEEG studies.

The combination of 3D surgical planning models that account for post-implantation brain compression using imaging acquired after intracranial electrode placement, and measurement of electrode positions with intraoperative navigation can be used to assess grid shift in cases where high precision is necessary. This should lead to more accurate surgical planning, and presumably, better surgical outcomes.

Statement of ethical coherence

This HIPAA-compliant study was approved by our institutional review board (IRB). All patients gave informed written consent. We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

Acknowledgements

Special thanks to Linda Allen and Sonia Neuberger for administrative support, Staci Gaulke and Jon Callies for OR Stealth Station support, Neha Ahuja for data processing assistance, and to the patients who chose to participate in this study.

Funding

This research was not funded through external sources.

References

- Behrens E, Zentner J, van Roost D, Hufnagel A, Elger CE, Schramm J. Subdural and depth electrodes in the presurgical evaluation of epilepsy. *Acta Neurochir. (Wien)*. 1994; 128:84–87. [PubMed: 7847148]
- Bootsveldt K, Traber F, Kaiser WA, Lauer G, Elger CE, Hufnagel A, Giesecke J, Reiser M. [Intracranial ECoG electrodes Location determination using three-dimensional reconstruction of MR data of the brain as a component of the presurgical diagnosis of epilepsy]. *Radiologe*. 1993; 33:185–188. [PubMed: 8506406]
- Dalal SS, Edwards E, Kirsch HE, Barbaro NM, Knight RT, Nagarajan SS. Localization of neurosurgically implanted electrodes via photograph-MRI-radiograph coregistration. *J. Neurosci. Methods*. 2008; 174:106–115. [PubMed: 18657573]
- Dale AM, Fischl B, Sereno MI. Cortical surface-based analysis I. Segmentation and surface reconstruction. *Neuroimage*. 1999; 9:179–194. [PubMed: 9931268]
- Engel J Jr, Henry TR, Rissinger MW, Mazziotta JC, Sutherling WW, Levesque MF, Phelps ME. Presurgical evaluation for partial epilepsy: relative contributions of chronic depth-electrode recordings versus FDG-PET and scalp-sphenoidal ictal EEG. *Neurology*. 1990; 40:1670–1677. [PubMed: 2122275]
- Fischl B, Salat DH, Busa E, Albert M, Dieterich M, Haselgrove C, van der Kouwe A, Killiany R, Kennedy D, Klaveness S, Montillo A, Makris N, Rosen B, Dale AM. Whole brain segmentation: automated labeling of neuroanatomical structures in the human brain. *Neuron*. 2002; 33:341–355. [PubMed: 11832223]
- Fischl B, Sereno MI, Dale AM. Cortical surface-based analysis II: inflation, flattening, and a surface-based coordinate system. *Neuroimage*. 1999; 9:195–207. [PubMed: 9931269]
- Fuchs M, Wagner M, Kastner J. Development of volume conductor and source models to localize epileptic foci. *J. Clin. Neurophysiol*. 2007; 24:101–119. [PubMed: 17414966]
- Grzeszczuk R, Tan KK, Levin DN, Pelizzari CA, Hu X, Chen GT, Beck RN, Chen CT, Cooper M, Milton J, et al. Retrospective fusion of radiographic and MR data for localization of subdural electrodes. *J. Comput. Assist. Tomogr*. 1992; 16:764–773. [PubMed: 1522271]
- Jayakar P, Duchowny M, Resnick TJ. Subdural monitoring in the evaluation of children for epilepsy surgery. *J. Child Neurol*. 1994; 9(Suppl. 2):61–66. [PubMed: 7806787]

- Kossoff EH, Ritzl EK, Politsky JM, Murro AM, Smith JR, Duckrow RB, Spencer DD, Bergey GK. Effect of an external responsive neurostimulator on seizures and electrographic discharges during subdural electrode monitoring. *Epilepsia*. 2004; 45:1560–1567. [PubMed: 15571514]
- Kovalev D, Spreer J, Honegger J, Zentner J, Schulze-Bonhage A, Huppertz HJ. Rapid and fully automated visualization of subdural electrodes in the presurgical evaluation of epilepsy patients. *AJNR Am. J. Neuroradiol*. 2005; 26:1078–1083. [PubMed: 15891163]
- LaViolette PS, Rand SD, Raghavan M, Ellingson BM, Schmainda KM, Mueller WM. 3D visualization of subdural electrodes for presurgical planning. *Neurosurgery*. in press, PubMed ID: 21206319.
- Lesser RP, Luders H, Klem G, Dinner DS, Morris HH, Hahn JF, Wyllie E. Extraoperative cortical functional localization in patients with epilepsy. *J. Clin. Neurophysiol*. 1987; 4:27–53. [PubMed: 3108315]
- Luders H, Awad I, Burgess R, Wyllie E, Van Ness P. Subdural electrodes in the presurgical evaluation for surgery of epilepsy. *Epilepsy Res. Suppl*. 1992; 5:147–156. [PubMed: 1418444]
- Luders H, Lesser RP, Dinner DS, Hahn JF, Salanga V, Morris HH. The second sensory area in humans: evoked potential and electrical stimulation studies. *Ann. Neurol*. 1985; 17:177–184. [PubMed: 3977299]
- Mahvash M, Konig R, Wellmer J, Urbach H, Meyer B, Schaller K. Coregistration of digital photography of the human cortex and cranial magnetic resonance imaging for visualization of subdural electrodes in epilepsy surgery. *Neurosurgery*. 2007; 344–345:61:340–344. discussion.
- Miller KJ, Makeig S, Hebb AO, Rao RP, denNijs M, Oje-mann JG. Cortical electrode localization from X-rays and simple mapping for electrocorticographic research: the “Location on Cortex” (LOC) package for MATLAB. *J. Neurosci. Methods*. 2007; 162:303–308. [PubMed: 17343918]
- Morris K, O'Brien TJ, Cook MJ, Murphy M, Bowden SC. A computer-generated stereotactic “Virtual Subdural Grid” to guide resective epilepsy surgery. *AJNR Am. J. Neuroradiol*. 2004; 25:77–83. [PubMed: 14729533]
- Nelles M, Koenig R, Kandyba J, Schaller C, Urbach H. Fusion of MRI and CT with subdural grid electrodes. *Zentralbl. Neurochir*. 2004; 65:174–179. [PubMed: 15551181]
- Schulze-Bonhage AH, Huppertz HJ, Comeau RM, Honegger JB, Spreer JM, Zentner JK. Visualization of subdural strip and grid electrodes using curvilinear reformatting of 3D MR imaging data sets. *AJNR Am. J. Neuroradiol*. 2002; 23:400–403. [PubMed: 11901007]
- Silberbusch MA, Rothman MI, Bergey GK, Zoarski GH, Zagardo MT. Subdural grid implantation for intracranial EEG recording: CT and MR appearance. *AJNR Am. J. Neuroradiol*. 1998; 19:1089–1093. [PubMed: 9672016]
- Tao JX, Hawes-Ebersole S, Baldwin M, Shah S, Erickson RK, Ebersole JS. The accuracy and reliability of 3D CT/MRI co-registration in planning epilepsy surgery. *Clin. Neurophysiol*. 2009; 120:748–753. [PubMed: 19264546]
- Wagner S, Kuss J, Meyer T, Kirsch M, Morgenstern U. An integrated tool for automated visualization of subdural electrodes in epilepsy surgery evaluation. *Int. J. Comput. Assist. Radiol. Surg*. 2009; 4:609–616. [PubMed: 20033337]
- Wellmer J, von Oertzen J, Schaller C, Urbach H, Konig R, Widman G, Van Roost D, Elger CE. Digital photography and 3D MRI-based multimodal imaging for individualized planning of resective neocortical epilepsy surgery. *Epilepsia*. 2002; 43:1543–1550. [PubMed: 12460257]
- Winkler PA, Vollmar C, Krishnan KG, Pfluger T, Bruckmann H, Noachtar S. Usefulness of 3-D reconstructed images of the human cerebral cortex for localization of subdural electrodes in epilepsy surgery. *Epilepsy Res*. 2000; 41:169–178. [PubMed: 10940618]
- Zhang Y, van Drongelen W, Kohrman M, He B. Three-dimensional brain current source reconstruction from intra-cranial ECoG recordings. *Neuroimage*. 2008; 42:683–695. [PubMed: 18579412]

Figure 1.

(a) Patients S1—S5 grid placement and shift maps. Top row shows CT-derived electrode models overlaid on post-grid MRI-derived 3D brain surface models. Row 2 shows reconstructed grid sheet models overlaid on the 3D brain model. Sheets are limited to those electrodes whose positions were visible and available for measurement in the OR (at the discretion of the surgeon). Yellow sheet indicates CT-derived electrode positions, Red indicates Stealth OR coordinate-derived sheet, and Orange indicates overlap. Rows 3 and 4 show coronal and axial slices indicating location of red and yellow sheets above. Slices shown are included in the 3D rendering in Rows 1 and 2 (b) Patients S6—S10 grid placement and shift maps.

Figure 2.

Illustration depicting the method of electrode shift measurement. Magnitude of shift is measured as the absolute shift. Compression is measured as the difference between the brain's center of the mass to the CT-derived electrode position, and the brain's center to the Stealth-derived electrode position. Shear is defined as the remaining shift along the brain's surface.

Figure 3.

Box plot showing electrode shift measurements for each patient (S1—S10, horizontal axis). Vertical axis indicates shift measurement in mm. Magnitude (M), Compression (C), and Shear (S) are shown. Median measure is indicated by horizontal line within the box, solid black squares indicate the mean, (+) indicate ground electrodes anchored to the skull, indicative of intrinsic error in the measures. Open circles indicate outliers as defined by measurements lying outside 99.5% confidence interval from the mean. Error bars indicate the most extreme value not considered as an outlier. Shaded boxes indicate group mean error in ground electrode comparison for magnitude, compression and shear. **Indicates significantly different from ground electrodes, $p < 0.01$, one way ANOVA.

Figure 4.

(A) Grid shift map for patient S4. Teal electrodes indicate where electrodes were measured via CT. Red dots indicate electrode location as measured in the operating room at the time of resection with navigational unit. Green lines indicate major sulcal patterns visible in the photograph (B). Blue ovals indicate two example electrodes that have shifted across sulci. (B) Photograph of electrodes at the time of resection with green lines analogous to (A) overlaid. (C) Photograph without overlays.

Table 1

Summary table of patient demographics, duration of ECG monitoring, and mean measures of electrode shift.

Patient #	Age (yrs)	Gender	Duration (days)	# Electrodes sampled	Magnitude (mm)	Stdev (mm)	Min (mm)	Max (mm)	Compression (mm)	Shear (mm)	Ground error
S1	37	M	2	27	3.4	1.0	1.4	5.5	1.5	2.8	2.3
S2	18	F	4	11	5.3 ^{**}	0.9	4.1	6.6	-0.5	5.0 ^{**}	—
S3	26	M	3	30	4.8 ^{**}	1.4	1.7	7.7	4.3 ^{**}	1.6	—
S4	44	M	2	33	12.6 ^{**}	4.5	4.6	21.2	-0.6	12.4 ^{**}	3.1
S5	54	F	3	14	5.2 ^{**}	1.1	3.7	7.0	5.3 ^{**}	3.5	—
S6	47	F	2	33	3.6	1.0	1.4	5.7	1.5	2.8	2.3
S7	60	M	3	43	4.0	1.3	1.7	6.4	-0.6	3.6	3.0
S8	47	F	4	32	3.8	1.6	1.4	7.3	2.4 ^{**}	2.1	1.7
S9	46	M	4	24	8.1 ^{**}	2.2	3.6	13.5	6.8 ^{**}	4.0 ^{**}	—
S10	21	M	1	17	3.3	1.0	1.4	5.1	1.6	2.5	1.6
Mean	40.0		2.8	26.4	5.4	1.6	2.5	8.6	2.2	4.0	2.3
Mean w/o S4	S4		2.9	25.7	4.6	1.3	2.3	7.2	2.5	3.1	$p < 0.01$ ^{**}

^{**} Indicates measurements significantly different than skull imbedded screw heads of grounded electrodes $p < 0.01$.