Quantification of Subdural Electrode Shift Between Initial Implantation, Postimplantation Computed Tomography, and Subsequent Resection Surgery

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BACKGROUND: Subdural electrodes are often implanted for localization of epileptic regions. Postoperative computed tomography (CT) is typically acquired to locate electrode positions for planning any subsequent surgical resection. Electrodes are assumed to remain stationary between CT acquisition and resection surgery.

OBJECTIVE: To quantify subdural electrode shift that occurred between the times of implantation (Crani 1), postoperative CT acquisition, and resection surgery (Crani 2).

METHODS: Twenty-three patients in this case series undergoing subdural electrode implantation were evaluated. Preoperative magnetic resonance and postoperative CT were acquired and coregistered, and electrode positions were extracted from CT. Intraoperative positions of electrodes and the cortical surface were digitized with a coregistered stereovision system. Movement of the exposed cortical surface was also tracked, and change in electrode positions was calculated relative to both the skull and the cortical surface.

RESULTS: In the 23 cases, average shift of electrode positions was 8.0 ± 3.3 mm between Crani 1 and CT, 9.2 ± 3.7 mm between CT and Crani 2, and 6.2 ± 3.0 mm between Crani 1 and Crani 2. The average cortical shift was 4.7 ± 1.4 mm with 2.9 ± 1.0 mm in the lateral direction. The average shift of electrode positions relative to the cortical surface between Crani 1 and Crani 2 was 5.5 ± 3.7 mm.

CONCLUSION: The results show that electrodes shifted laterally not only relative to the skull, but also relative to the cortical surface, thereby displacing the electrodes from their initial placement on the cortex. This has significant clinical implications for resection based upon seizure activity and functional mapping derived from intracranial electrodes.

KEY WORDS: Epilepsy, Cortical shift, Functional mapping, Intraoperative stereovision, Optical flow, Subdural electrode

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In surgical resection for the treatment of medically intractable epilepsy, accurate localization of epileptogenic foci can be incomplete and challenging using scalp electroencephalography (EEG), medical imaging, and other noninvasive approaches. Accordingly,

subdural electrodes are often implanted for seizure localization in these instances.^{1–3} A first craniotomy (Crani 1) is typically performed for implantation of subdural grid and/or strip electrodes, and intracranial electrocorticography (ECoG) is recorded over a period of time (~7 d or more) while the patient is monitored. Postoperative computed tomography (CT) images are acquired after Crani 1 to locate the electrodes and to coregister them with preoperative magnetic resonance (pMR).⁴ The patient then typically undergoes a second craniotomy (Crani 2) for follow-up resection surgery where the ECoG and other behavioral results are used to plan and guide the resection boundaries.

ABBREVIATIONS: 3D, 3-dimensional; CT, computed tomography; ECoG, electrocorticography; EEG, electroencephalography; GTC, generalized tonic-clonic; IRB, institutional review board; ISV, intraoperative stereovision; OF, optical flow; pMR, preoperative magnetic resonance

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Although various techniques have been developed to localize and visualize electrodes relative to medical images⁵⁻¹¹ to assist in identification of resection boundaries, the electrode grids/strips are assumed to remain stationary during monitoring. However, they can shift in directions both perpendicular and lateral to the cortical surface.¹² In a previous study, LaViolette et al¹³ measured shifts in electrode positions between CT and Crani 2, and found significant overall electrode movement (mean: 7.2 mm) in 5 of 10 patients evaluated. Four of these showed sizeable displacements in the direction normal to the cortical surface (mean: 4.7 mm) and 3 had significant lateral shifts (mean: 7.1 mm). However, electrode displacements were not measured relative to the cortical surface and the brain is known to shift between the times of pMR, postoperative CT, and craniotomy reopening.

In this study, we localized electrodes in the open cranium at time of implantation and resection, respectively, using an intraoperative stereovision (iSV) system, and extracted their locations from postoperative CT scans coregistered to the intraoperative data to measure changes in electrode positions between time points. We also acquired the 3-dimensional (3D) surface of

the exposed cortex intraoperatively with iSV in order to quantify electrode movement relative to the cortex from time of implantation to time of removal. We report results from 23 clinical patients, and analyze characteristics of the measured displacement patterns.

METHODS

Surgical Cases and Procedure

Image data obtained from 23 patients undergoing craniotomy between July 2013 and June 2016 for subdural electrode implantation (ie, Crani 1) and cranial reopening for removal of electrodes (ie, Crani 2) were evaluated. Criteria for case selection were (1) subdural grid and/or strip electrodes implanted, and (2) features such as blood vessels and gyri/sulci patterns available on the exposed cortical surface for spatial tracking. The image analysis study was approved by the institutional review board (IRB), and the IRB waived the patient consent requirement per 45 CFR 46.116(d). Subject gender, age, location, and size of craniotomy are reported in Table 1 (columns 2-5), along with information on the number of days patients were monitored (column 6), the number of subdural electrodes (column 7 with the total number of

TABLE 1. Summary of Patient Information

Patient ID	Gender	Age (years)	Craniotomy Location	Craniotomy size (cm × cm)	ECOG monitoring period (Days)	Subdural electrodes (Total)	iSV visible electrodes (Crani 1, Crani 2)	GTC seizures
1	M	23	Left temporal	5.7 × 4.8	11	60 (103)	16 (17, 17)	1
2	M	23	Right temporal	4.7 × 4.2	9	68 (68)	16 (17, 16)	3
3	M	37	Right temporal	5.9 × 4.4	8	88 (88)	13 (14, 23)	0
4	F	39	Right temporal	4.8 × 3.8	9	76 (96)	11 (18, 13)	0
5	M	26	Left frontal	8.2 × 5.2	9	116 (116)	45 (53, 45)	0
6	F	31	Right temporal	5.0 × 4.0	10	72 (96)	12 (20, 14)	3
7	F	46	Left temporal	7.7 × 6.1	9	68 (128)	24 (26, 26)	1
8	F	28	Right temporal	6.7 × 5.5	9	76 (112)	38 (45, 39)	1
9	M	21	Left temporal	5.9 × 4.6	23	76 (112)	22 (24, 26)	1
10	M	26	Left frontal	7.6 × 6.1	23	88 (112)	29 (30, 32)	1
11	M	41	Left frontal	7.1 × 5.5	9	104 (116)	36 (37, 40)	1
12	M	64	Right temporal	5.4 × 3.7	9	56 (88)	15 (22, 15)	0
13	F	51	Left frontal	3.3 × 2.2	8	72 (96)	3 (8, 6)	1
14	M	28	Right occipital	3.8 × 3.4	9	48 (52)	5 (8, 14)	0
15	F	47	Left temporal	3.8 × 3.1	14	72 (96)	8 (13, 9)	1
16	F	24	Left occipital	4.1 × 3.1	10	52 (64)	13 (16, 15)	0
17	F	39	Left frontal	7.3 × 5.7	9	88 (124)	34 (40, 41)	3
18	F	43	Left temporal	5.4 × 5.1	32	76 (100)	11 (13, 12)	0
19	F	38	Right frontal	5.5 × 4.9	11	74 (74)	14 (26, 15)	0
20	M	37	Left frontal	3.4 × 2.0	14	88 (88)	6 (7, 6)	4
21	M	38	Left temporal	3.4 × 3.1	12	48 (60)	6 (19, 10)	0
22	F	36	Left temporal	4.6 × 3.0	28	68 (80)	11 (13, 11)	0
23	M	20	Right frontal	5.1 × 4.7	11	108 (132)	19 (29, 23)	0

ECOG: electrocorticography.

Subdural electrodes: total number of subdural and depth electrodes in parenthesis.

iSV: intraoperative stereovision.

iSV visible electrodes: Number of common electrodes visible with iSV in both Crani 1 and Crani 2. Numbers visible in Crani 1 and Crani 2 in parenthesis, respectively.

GTC: secondary generalized tonic-clonic seizures.

FIGURE 1. Cortical surface (A and C) and electrode grids (B and D) acquired from iSV during Crani 1 (A and B) and Crani 2 (C and D), respectively, overlaid with pMR.

electrodes = depth + subdural in parenthesis), the number of subdural electrodes sampled by iSV (column 8 including the number measured during Crani 1 and Crani 2, respectively, in parenthesis), and the number of secondary generalized tonic-clonic (GTC) seizures recorded (column 9).

T1-weighted pMR images were acquired prior to the Crani 1 procedure following standard of care with scalp fiducial markers (scan size = 256×256 with pixel size $0.9375 \text{ mm} \times 0.9375 \text{ mm}$, or 512×512 with pixel size $0.4688 \text{ mm} \times 0.4688 \text{ mm}$, 104-144 slices with slice thickness 1.5 mm). At time of surgery, fiducial-based patient registration was performed on a commercial navigation system (StealthStation S7, Medtronic, Dublin, Ireland) using pMR for intraoperative navigation and optical tracking. A surgical microscope (OPMI Pentero Carl Zeiss Surgical GmbH, Oberkochen, Germany) was connected to the StealthStation and was tracked optically throughout the procedure. An iSV system was attached to the microscope and draped together in a sterile bag at the beginning of surgery. It consisted of 2 charge-coupled device cameras (Flea2 FL2G-50S5C, Point Grey Research, Inc, Richmond, British Columbia, Canada; image resolution: 1024×768 pixels) and was precalibrated for 3D surface reconstruction.¹⁴⁻¹⁶ After

dural opening but before electrode implantation, an iSV image pair of the exposed cortical surface was acquired. Then, at the end of the implantation surgery, after all subdural electrode grids were placed and secured but before closing the dura, another iSV image pair of the surgical field was recorded. Textured 3D profiles of the surgical surface were reconstructed and coregistered with pMR using tracking information obtained from the navigation system through the Medtronic StealthLink communications framework. For accuracy assessment, a sterilized stylus probe (Microscope Probe, Medtronic) was used to digitize the center of each electrode that was visible in the surgical field, and the average distance between the coordinates of tracked points and their counterparts determined from iSV is measured. Four bony features (pinpoint holes) around the boundary of craniotomy were identified using the stylus probe, and stored as registration locations (ie, “checkpoints”) on the StealthStation using a built-in re-alignment tool for coregistration purposes.¹⁷ Electrodes that showed visible displacement, typically at the time of surgical closure, were tacked to the adjacent dura with 1 or 2 sutures; if no displacement was noted, no sutures were placed apart from those securing the proximal electrode leads at their exit through the scalp, as is typically performed for depth and subdural strip electrodes.

Postoperative CT scans were acquired after Crani 1 on the same day. Patients were monitored (9-32 d, Table 1, column 6), and iEEG and seizure activities were recorded (0-4 GTC seizures, Table 1, column 9). At time of the Crani 2 procedure, the same system was set up. The 4 checkpoints were localized using the sterile stylus probe in the same order, and patient registration was updated automatically on the StealthStation for optical tracking. At the second surgery, an iSV image pair of the surgical field was acquired after dural opening but before removing the electrodes, and positions of exposed electrodes were digitized with the stylus probe for accuracy assessments. After the electrodes were removed but before resection, another iSV image pair of the cortical surface was acquired. The reconstructed 3D surfaces were coregistered with pMR using the updated patient registration and tracking data obtained from the StealthStation. Figure 1 illustrates the iSV surfaces acquired from Crani 1 and Crani 2 with and without electrodes from patient 11 overlaid with pMR.

Localization of Electrodes in iSV and CT

The center of each electrode visible in the iSV images was identified, and its 3D coordinates in the coregistered pMR image space were extracted and stored along with other identifying information (eg, type and location of the grid, contact number on the grid, etc). Electrode contacts visible within the craniotomy area could be evaluated with iSV whereas those tucked underneath the dura were not visible, and thus not included in the data analysis. Postoperative (to Crani 1) CT images

were first processed using the StealthViz Advanced Visualization Application (Medtronic), where the CT image stack was coregistered with pMR using a mutual information-based rigid registration, contrast was adjusted to enhance electrode visualization and suppress other features, and electrodes were segmented. The centroid of each segmented electrode was then computed automatically, and its 3D coordinates were recorded. Figure 2 shows an example of electrode positions extracted from iSV and CT overlaid on the segmented brain.

Measurement of Cortical Shift

Two iSV surfaces of the exposed cortex from Crani 1 and Crani 2 were registered using optical flow (OF) motion tracking to measure cortical shift, as illustrated in Figure 3. The technical details of the surface registration method have been published previously.¹⁸ Briefly, the 2 surfaces were projected along a common axis and resampled to generate 2D projection images with the same pixel resolution. The OF algorithm was applied to detect lateral shift of the cortical surface (ie, misalignment between the 2 projection images), and the resulting 2D displacement map was used to generate a 3D displacement field from the iSV spatial information for each pixel.

Data Analysis

All data analysis was performed on a Windows computer (3.30 GHz, 40 GB RAM) in MATLAB (MATLAB 2015b, the Mathworks, Natick,

Massachusetts). Electrode shift between Crani 1 and postoperative CT was quantified. Since CT images and iSV surfaces were both coregistered with pMR, electrode locations were available in pMR image space. Each electrode location visible during the implantation surgery was compared with its counterpart extracted from CT, and a 3D displacement vector was computed ($\text{shift}_{Cr1-CT}^{3D}$). Similarly, the 3D electrode shift between postoperative (to Crani 1) CT and Crani 2 was quantified ($\text{shift}_{CT-Cr2}^{3D}$). Electrode shift between Crani 1 and Crani 2 as measured by the iSV system was also computed ($\text{shift}_{Cr1-Cr2}^{3D}$). Both iSV surfaces were coregistered with pMR through skull-based checkpoint registration; thus, $\text{shift}_{Cr1-Cr2}^{3D}$ measured from iSV represented movement with respect to the skull. To quantify the electrode shift relative to the cortical

surface, the 2 iSV surfaces were registered, and the 3D displacement vector of each pixel (shift_{Cort}^{3D}) was computed. To investigate patterns of shift, the average surface normal was determined, and 3D displacement vectors were decomposed into their components parallel (indicating brain collapse or distension; shift^n) and perpendicular (indicating lateral shift; shift^l) to the surface normal. Then, for each electrode visible in both Crani 1 and Crani 2, the displacement relative to the cortical surface was estimated by subtracting the local lateral cortical shift at the electrode location from the overall lateral displacement with respect to the skull measured from iSV ($\text{shift}_{Rel} = \text{shift}_{Cr1-Cr2}^l - \text{shift}_{Cort}^l$), as illustrated in Figure 4. In addition, the amount of brain shift between the times of pMR and Crani 1 as well as postprocedure CT was measured,

respectively, as the average surface to surface distance along the surface normal direction.

Correlations were explored between the amount of shift relative to the cortical surface and patient age, craniotomy size, duration of monitoring (days), number of subdural electrodes implanted, number of secondary GTC seizures that occurred during the time of monitoring, and the amount of brain shift between the times of Crani 1 and postprocedure CT. Kendall rank correlation coefficients were calculated for each factor, where $\tau = 0$ indicates no correlation and $\tau = 1$ indicates perfect correlation, and a P -value below .05 rejects the null hypothesis (at a significance level of .05) that the 2 variables are statistically independent.

RESULTS

The accuracy of patient registration reported on the StealthStation (Medtronic) in Crani 1 and Crani 2 was 1.6 ± 0.3 and 1.9 ± 1.5 mm on average, respectively, and is listed in Table 2, columns 2 and 3 for each case. The accuracy of iSV was 1.9 ± 0.4 and 1.8 ± 0.4 mm on average in Crani 1 and Crani 2, respectively, and is reported in Table 2, columns 4 and 5 for each case. Quantitative results from 23 patients are presented in Table 3 and Figure 5. Magnitudes of electrode shift and their directional components between Crani 1 and postoperative CT are listed in

Table 3, columns 2 to 4 and displayed graphically in Figure 5, column 1. The average 3D shift was 8.0 ± 3.3 mm and 83% of cases (19/23) showed 3D shift greater than 5 mm. Shift in the normal direction, shift_{Cr1-CT}^n , ranged from 2.0 ± 0.9 to 11.2 ± 2.1 mm with an average of 5.8 ± 2.7 mm, and 56% of cases (13/23) showed brain collapse/distension of 5 mm or more. Shift in the lateral direction, shift_{Cr1-CT}^l , was 4.6 ± 3.4 mm on average, smaller than the component in the normal direction in 70% of cases (16/23).

Electrode shifts between CT scans and Crani 2 are reported in Table 3, columns 5 to 7 and shown graphically in Figure 5, column 2. The 3D shift, $\text{shift}_{CT-Cr2}^{3D}$, was 9.1 ± 3.7 mm on average and greater than $\text{shift}_{Cr1-CT}^{3D}$ in 74% of cases (17/23), and more than 5 mm on average in 87% of cases (20/23). The shift along the surface normal direction, shift_{CT-Cr2}^n , was 6.6 ± 4.2 mm, greater than 5 mm in 65% of cases (15/23). The lateral shift, shift_{CT-Cr2}^l , was 5.0 ± 3.3 mm on average, smaller than the component in the normal direction in 56% of cases (13/23).

Electrode shift between Crani 1 and Crani 2 procedures, as measured by the iSV system, is summarized in Table 3, columns 8 to 10, and presented graphically in Figure 5, column 3. The average 3D shift, $\text{shift}_{Cr1-Cr2}^{3D}$, was 6.2 ± 3.0 mm, and

TABLE 2. Accuracy of Patient Registration and Stereovision

Patient ID	Registration (mm)		iSV (mm)	
	Crani 1	Crani 2	Crani 1	Crani 2
1	1.1	0.7	1.6 ± 0.6	2.0 ± 0.6
2	1.9	5.3	1.9 ± 0.9	2.0 ± 0.7
3	1.8	1.0	2.5 ± 1.6	2.0 ± 1.3
4	1.9	1.0	2.0 ± 0.9	2.1 ± 0.6
5	1.7	5.6	1.3 ± 0.5	2.0 ± 0.5
6	2.0	4.2	2.3 ± 1.4	1.8 ± 0.7
7	1.7	0.7	1.5 ± 0.6	1.3 ± 1.3
8	1.8	0.9	1.7 ± 0.9	1.9 ± 0.5
9	1.9	1.8	1.5 ± 0.8	1.4 ± 1.5
10	1.8	4.2	1.5 ± 0.9	1.3 ± 0.6
11	0.9	1.0	2.2 ± 1.2	2.3 ± 1.0
12	1.1	0.5	2.6 ± 1.5	1.4 ± 1.0
13	1.4	1.2	0.9 ± 0.2	2.1 ± 0.8
14	1.9	1.4	1.9 ± 1.5	1.8 ± 1.1
15	1.6	1.6	1.7 ± 1.1	1.8 ± 0.4
16	1.9	1.6	1.4 ± 1.1	1.4 ± 0.6
17	1.7	1.1	2.1 ± 0.6	2.7 ± 1.0
18	1.8	1.0	2.3 ± 0.9	2.3 ± 1.2
19	1.8	1.7	2.4 ± 0.8	2.6 ± 1.2
20	1.2	2.1	1.8 ± 1.4	1.7 ± 0.2
21	1.9	2.4	2.5 ± 1.0	1.2 ± 0.6
22	1.6	1.1	1.5 ± 0.8	1.8 ± 0.4
23	1.5	0.8	2.1 ± 1.5	1.4 ± 1.0
Average	1.6 ± 0.3	1.9 ± 1.5	1.9 ± 0.4	1.8 ± 0.4

iSV: intraoperative stereovision.

smaller than the averages for shift $_{Cr1-CT}^{3D}$ (8.0 ± 3.3 mm), and shift $_{CT-Cr2}^{3D}$ (9.1 ± 3.7 mm). The component along the surface normal direction, shift $_{Cr1-Cr2}^n$, was also smaller (3.4 ± 1.6 mm), and only 22% of cases (5/23) showed shift greater than 5 mm. The lateral displacement was 4.6 ± 3.3 mm on average, and similar to shift $_{Cr1-CT}^l$ (4.6 ± 3.4 mm), as well as shift $_{CT-Cr2}^l$ (5.0 ± 3.3 mm).

The measured cortical shift between Crani 1 and Crani 2 is reported in Table 3, columns 11 to 13, and plotted in Figure 5, column 4. The average magnitude of 3D shift was 4.6 ± 1.4 mm, and only 26% of cases (6/23) showed shift greater than 5 mm. The shift in direction to the surface normal was 3.2 ± 1.5 mm, and the lateral shift was 2.9 ± 1.0 mm on average, and smaller than 5 mm in every case. The cortical shift between pMR and Crani 1 is reported in Table 3, column 14 (+/- signs indicate displacements outward/inward, respectively), and ranges from -7.8 to 4.8. The cortical shift between pMR and CT is reported in Table 3, column 15. All cases showed brain depression at time of CT acquisition (-5.8 ± 3.7 mm on average) due to subdural extra-axial collections, which is a common phenomenon.¹²

Electrode shift relative to the cortical surface is listed in Table 3, column 16 and presented in Figure 5, column 5, and Figure 6. The average displacement was 5.5 ± 3.6 mm, and 43% of cases

(10/23) resulted in shifts greater than 5 mm. This movement was larger than the shift relative to the skull in 65% of cases (15/23). Furthermore, we found that the electrodes did not shift in the same direction relative to gravity in the 23 cases. Specifically, we decomposed the gravitational vector (acquired at time of surgery based on patient position) into components parallel and perpendicular to the direction normal to the brain surface, respectively, and calculated the angle between the overall lateral shift (by averaging lateral shift vectors of all electrode contacts) and the lateral component of gravity for each patient. The average angle was $81^\circ \pm 56^\circ$ (range: 1° to 159°), and 8 out of 23 cases showed angles $> 90^\circ$, indicating that the electrodes shifted in directions opposing gravity in these cases.

Correlations were determined between the amount of shift relative to the cortical surface and factors that could contribute to electrode shift. For example, electrodes may have more space for shift with a larger craniotomy size, fewer numbers of electrodes, or larger magnitude of brain depression at the end of Crani 1 relative to postprocedure CT; when patients are monitored for longer periods of time, the brain may deform over time, thus leading to larger shift; more secondary GTCs which involve patient movement may cause larger shift. The corresponding correlation coefficient τ and P -values are reported in Table 4. The small τ values demonstrate that shift of electrode grids/strips relative to the cortex was weakly associated with these factors, and P -values $> .05$ demonstrate that none were statistically significant.

DISCUSSION

In this paper, shift of subdural electrodes was measured between implantation (Crani 1), postimplantation CT, and subsequent grid removal at time of the resection procedure (Crani 2) in 23 clinical patients. Results show that electrode displacement occurred between the 3 time points in directions both lateral and normal to the cortical surface. The overall electrode shift was slightly smaller between Crani 1 and postoperative CT than between CT and Crani 2, whereas the overall electrode shift between Crani 1 and Crani 2 was smaller than either of these intermediate movements (8.0 ± 3.3 mm and 9.2 ± 3.7 mm, respectively, vs 6.2 ± 3.0 mm). Displacement patterns were similar for components normal and lateral to the cortical surface. These observations indicate that the shift was likely caused by closing and re-opening of the craniotomy, especially in the normal direction, yielding an overall shift of only 3.4 ± 1.6 mm (Table 3, column 9) in the normal direction between Crani 1 and Crani 2. In addition, the cortical shift between Crani 1 and Crani 2 was measured, and found to be smaller than the electrode displacements. Not surprisingly, the average shift of the cortical surface in the normal direction (Table 3, column 9) was similar to the average normal shift in the electrodes (Table 3, column 12), since the electrodes were largely in direct contact with the cortical surface.

TABLE 3. Summary of Average Shift in Each Patient Case

Patient	Electrode Crani 1 – CT (mm)			Electrode CT – Crani 2 (mm)			Electrode Crani 1 – Crani 2 (mm)			Cortical Crani 1 – Crani 2 (mm)			Cortical MR – Crani 1 (mm)		Cortical MR – CT (mm)		Relative Crani 1 – Crani 2 (mm)	
	3D	Normal	Lateral	3D	Normal	Lateral	3D	Normal	Lateral	3D	Normal	Lateral	Normal	Lateral	Normal	Lateral	Normal	Lateral
1	6.6 ± 1.5	5.4 ± 1.5	3.6 ± 1.2	8.4 ± 7.7	3.8 ± 1.5	6.8 ± 8.2	2.9 ± 2.2	1.6 ± 1.3	2.4 ± 1.9	3.8 ± 1.7	2.9 ± 1.8	2.0 ± 1.3	2.6 ± 1.4	2.0 ± 1.3	2.6 ± 1.4	2.0 ± 1.3	2.3 ± 1.2	2.3 ± 1.2
2	6.3 ± 1.3	4.6 ± 1.6	3.9 ± 1.6	9.3 ± 1.3	8.8 ± 1.3	3.0 ± 0.5	4.5 ± 1.3	4.0 ± 1.5	1.5 ± 1.1	4.9 ± 1.1	4.7 ± 1.1	1.2 ± 0.6	3.1 ± 2.1	1.2 ± 0.6	3.1 ± 2.1	1.2 ± 0.6	2.1 ± 1.2	2.1 ± 1.2
3	4.7 ± 2.3	4.2 ± 2.3	1.9 ± 1.1	9.8 ± 3.5	1.7 ± 1.8	9.3 ± 4.1	9.9 ± 3.0	3.4 ± 2.1	9.1 ± 2.9	4.5 ± 1.5	3.2 ± 1.8	2.9 ± 0.9	3.0 ± 1.9	2.9 ± 0.9	3.0 ± 1.9	2.9 ± 0.9	8.0 ± 3.5	8.0 ± 3.5
4	8.6 ± 1.7	8.0 ± 1.9	3.0 ± 0.8	9.2 ± 1.0	8.8 ± 1.0	2.7 ± 0.6	2.2 ± 0.9	1.3 ± 0.4	1.7 ± 1.0	3.5 ± 1.0	1.7 ± 1.3	2.9 ± 0.8	0.6 ± 0.8	2.9 ± 0.8	0.6 ± 0.8	2.9 ± 0.8	2.7 ± 1.4	2.7 ± 1.4
5	5.3 ± 0.9	3.1 ± 1.7	3.8 ± 1.1	7.3 ± 1.1	5.2 ± 1.6	4.8 ± 1.6	3.4 ± 1.6	1.6 ± 1.3	2.9 ± 1.3	2.9 ± 1.0	2.0 ± 1.1	1.9 ± 0.8	–5.1 ± 2.9	1.9 ± 0.8	–5.1 ± 2.9	1.9 ± 0.8	2.4 ± 1.2	2.4 ± 1.2
6	8.9 ± 1.1	6.6 ± 2.0	5.7 ± 1.3	5.1 ± 0.6	4.6 ± 0.8	2.1 ± 0.5	7.2 ± 1.2	2.6 ± 1.8	6.5 ± 1.0	3.5 ± 1.8	2.4 ± 1.8	2.3 ± 1.0	–2.4 ± 2.1	2.3 ± 1.0	–2.4 ± 2.1	2.3 ± 1.0	5.7 ± 2.2	5.7 ± 2.2
7	8.6 ± 1.6	5.9 ± 2.4	6.0 ± 0.8	3.9 ± 2.5	2.5 ± 1.6	2.8 ± 2.1	7.8 ± 1.4	4.0 ± 2.3	6.4 ± 0.7	7.2 ± 2.7	6.3 ± 2.8	3.0 ± 1.3	–3.5 ± 2.3	3.0 ± 1.3	–3.5 ± 2.3	3.0 ± 1.3	6.9 ± 1.9	6.9 ± 1.9
8	9.1 ± 1.6	8.3 ± 1.5	3.6 ± 1.3	4.4 ± 1.1	3.2 ± 1.2	2.8 ± 1.1	6.6 ± 1.4	5.4 ± 1.7	3.6 ± 1.3	7.1 ± 2.0	4.6 ± 2.0	4.9 ± 2.2	2.1 ± 1.4	4.9 ± 2.2	2.1 ± 1.4	4.9 ± 2.2	4.4 ± 3.8	4.4 ± 3.8
9	12.5 ± 2.4	11.2 ± 2.1	5.4 ± 1.7	10.3 ± 2.1	6.1 ± 2.7	8.0 ± 1.0	6.9 ± 2.1	6.0 ± 2.3	3.0 ± 1.4	7.0 ± 1.8	5.4 ± 1.6	4.2 ± 1.6	1.8 ± 1.5	4.2 ± 1.6	1.8 ± 1.5	4.2 ± 1.6	6.4 ± 2.1	6.4 ± 2.1
10	4.2 ± 1.6	2.3 ± 1.4	3.3 ± 1.3	6.2 ± 1.0	1.8 ± 0.8	5.9 ± 1.1	6.6 ± 1.3	3.3 ± 2.0	5.2 ± 1.8	6.5 ± 1.4	4.9 ± 2.1	3.7 ± 1.4	–5.5 ± 2.2	3.7 ± 1.4	–5.5 ± 2.2	3.7 ± 1.4	6.6 ± 1.5	6.6 ± 1.5
11	6.8 ± 1.9	6.1 ± 1.8	2.6 ± 1.0	7.8 ± 1.6	7.6 ± 1.7	1.6 ± 0.5	3.2 ± 1.1	2.2 ± 1.5	2.0 ± 0.7	3.9 ± 1.2	2.3 ± 1.5	2.9 ± 0.7	–2.2 ± 1.7	2.9 ± 0.7	–2.2 ± 1.7	2.9 ± 0.7	4.1 ± 0.7	4.1 ± 0.7
12	5.5 ± 1.3	2.0 ± 0.9	5.1 ± 1.2	8.6 ± 1.6	1.5 ± 1.0	8.4 ± 1.5	4.8 ± 1.0	1.1 ± 0.5	4.6 ± 1.1	4.5 ± 1.7	3.0 ± 1.9	3.1 ± 0.8	–7.8 ± 2.7	3.1 ± 0.8	–7.8 ± 2.7	3.1 ± 0.8	4.5 ± 0.7	4.5 ± 0.7
13	16.1 ± 0.3	4.0 ± 0.3	15.5 ± 0.3	9.9 ± 0.2	8.6 ± 0.1	4.9 ± 0.5	16.5 ± 0.0	4.4 ± 0.0	15.9 ± 0.0	3.5 ± 1.7	2.0 ± 1.7	2.5 ± 1.2	4.7 ± 1.5	2.5 ± 1.2	4.7 ± 1.5	2.5 ± 1.2	18.1 ± 0.0	18.1 ± 0.0
14	9.2 ± 2.1	4.8 ± 1.7	7.8 ± 1.6	12.1 ± 2.9	11.1 ± 3.8	3.9 ± 2.1	8.2 ± 3.8	6.6 ± 4.3	4.5 ± 1.2	3.5 ± 2.0	2.4 ± 1.9	2.3 ± 1.3	–3.8 ± 2.8	2.4 ± 1.9	–3.8 ± 2.8	2.4 ± 1.9	6.0 ± 2.4	6.0 ± 2.4
15	9.3 ± 1.1	9.2 ± 1.1	1.1 ± 0.7	13.1 ± 2.2	13.0 ± 2.1	1.3 ± 0.6	5.0 ± 1.3	4.3 ± 1.8	2.2 ± 0.8	3.9 ± 1.4	3.1 ± 1.6	2.1 ± 0.7	3.0 ± 1.0	3.1 ± 1.6	3.0 ± 1.0	2.1 ± 0.7	4.2 ± 0.9	4.2 ± 0.9
16	6.8 ± 1.7	5.8 ± 2.1	3.2 ± 0.6	9.0 ± 1.4	5.7 ± 1.8	6.8 ± 0.6	5.9 ± 0.9	2.3 ± 1.5	5.3 ± 0.7	2.8 ± 0.8	1.8 ± 1.1	1.9 ± 0.7	–1.9 ± 1.4	1.8 ± 1.1	–1.9 ± 1.4	1.9 ± 0.7	3.9 ± 1.2	3.9 ± 1.2
17	12.0 ± 3.6	5.2 ± 2.1	10.7 ± 3.4	16.2 ± 2.1	5.5 ± 1.8	15.2 ± 1.9	5.3 ± 1.6	1.8 ± 1.3	4.8 ± 1.5	4.2 ± 1.1	1.3 ± 1.0	3.8 ± 1.1	4.8 ± 3.8	1.3 ± 1.0	4.8 ± 3.8	3.8 ± 1.1	6.0 ± 1.5	6.0 ± 1.5
18	6.3 ± 1.2	5.5 ± 1.4	2.8 ± 0.5	9.5 ± 0.6	6.4 ± 0.9	7.0 ± 0.5	7.1 ± 0.5	1.0 ± 0.8	7.0 ± 0.6	4.8 ± 1.3	2.2 ± 1.3	4.1 ± 1.1	–3.7 ± 1.1	2.2 ± 1.3	–3.7 ± 1.1	4.1 ± 1.1	2.9 ± 0.6	2.9 ± 0.6
19	5.4 ± 2.2	3.6 ± 2.8	3.5 ± 0.6	7.1 ± 1.8	5.7 ± 2.3	4.0 ± 0.5	3.8 ± 2.3	2.5 ± 2.9	2.4 ± 0.4	3.0 ± 2.1	2.4 ± 2.3	1.4 ± 0.5	–6.8 ± 3.0	2.4 ± 2.3	–6.8 ± 3.0	1.4 ± 0.5	2.0 ± 0.5	2.0 ± 0.5
20	10.6 ± 2.0	10.4 ± 2.0	1.4 ± 0.8	15.5 ± 1.4	15.0 ± 1.3	3.7 ± 0.9	5.3 ± 2.5	4.3 ± 2.5	3.0 ± 0.9	4.9 ± 1.0	2.5 ± 1.0	4.0 ± 1.2	2.4 ± 1.3	4.9 ± 1.0	2.5 ± 1.0	4.0 ± 1.2	6.2 ± 1.5	6.2 ± 1.5
21	14.1 ± 1.5	10.9 ± 1.8	8.9 ± 0.8	17.2 ± 1.2	15.9 ± 1.4	6.5 ± 0.7	9.5 ± 0.9	5.0 ± 2.1	7.7 ± 1.8	4.4 ± 1.2	2.0 ± 1.1	3.6 ± 1.4	–7.0 ± 1.4	2.0 ± 1.1	–7.0 ± 1.4	3.6 ± 1.4	12.4 ± 1.2	12.4 ± 1.2
22	2.7 ± 1.9	2.3 ± 2.1	0.9 ± 0.7	7.7 ± 2.0	7.6 ± 2.0	0.7 ± 0.5	5.2 ± 0.9	5.2 ± 0.9	0.6 ± 0.3	5.7 ± 0.9	5.0 ± 0.9	2.6 ± 0.9	–2.3 ± 1.4	5.0 ± 0.9	–2.3 ± 1.4	2.6 ± 0.9	2.9 ± 0.6	2.9 ± 0.6
23	4.8 ± 2.5	4.0 ± 3.2	2.0 ± 0.6	3.0 ± 0.8	1.1 ± 1.2	2.6 ± 0.4	5.6 ± 2.1	3.8 ± 2.9	3.5 ± 0.3	7.3 ± 3.8	5.7 ± 4.1	3.6 ± 2.3	–6.0 ± 3.6	5.7 ± 4.1	–6.0 ± 3.6	3.6 ± 2.3	4.8 ± 2.3	4.8 ± 2.3
Average	8.0 ± 3.3	5.8 ± 2.7	4.6 ± 3.4	9.2 ± 3.7	6.6 ± 4.2	5.0 ± 3.3	6.2 ± 3.0	3.4 ± 1.6	4.6 ± 3.3	4.7 ± 1.4	3.2 ± 1.5	2.9 ± 1.0	–1.1 ± 3.9	3.2 ± 1.5	–1.1 ± 3.9	2.9 ± 1.0	5.5 ± 3.6	5.5 ± 3.6

More importantly, the electrode shift between Crani 1 and Crani 2 relative to the underlying cortical surface was quantified for the first time. The results show an average relative shift of 5.5 ± 3.6 mm indicating that electrodes do not always remain stationary with respect to the cortical surface in practice. These measurements also differed from the lateral component of displacement relative to the skull (between Crani 1 and Crani 2, Table 3, column 10) suggesting some lateral movement of the cortical surfaces occurred between procedures. As the location and extent of subsequent surgical resection is often based on seizure activity and functional mapping acquired using these electrodes, the magnitude of this displacement easily could be clinically relevant to surgical efficacy and safety. The shift relative to the cortical surface that occurred between Crani 1 and CT, or between CT and Crani 2, was not measured, because cortical features are difficult to extract from CT. While electrodes were localized with respect to the cortical surface in Crani 1 and Crani 2 with iSV, their positions relative to the cortical surface in CT remain uncertain. The methodology used in this study precludes determination of when displacements may have taken place (eg, between the time of postimplantation CT and the second craniotomy). No instances occurred in which discrete electrocorticographic seizure activity was observed to move to adjacent electrode contacts at a subsequent event.

We examined seizure outcomes for cases with large lateral displacements (>10 mm), ie, patients 13 and 21. Patient 13 had a

responsive neurostimulation device implanted which resulted in an Engel class II outcome despite the large displacement (18.1 mm). Patient 21 had an Engel class IV outcome and was the only subject who underwent awake craniotomy. The brain was observed to swell at the time of Crani 2 in this case, which may have contributed to the larger shift. However, whether the outcome was affected by the large shift is inconclusive. Factors that may have been responsible for the large displacements noted with patient 13 and patient 21 were considered but not uniquely identified. The craniotomy size was 3.3×2.2 cm and 3.4×3.1 cm, respectively; these subjects did not experience intraoperative or postoperative intracranial hemorrhage and did not experience a greater number of GTC seizures during monitoring. We explored factors that may contribute to electrode shift, but none was statistically correlated with the magnitude of shift. In the majority of cases, no electrode displacement was observed at the time of implantation, and in these cases, electrodes were secured only at the level of the scalp. Given our experience in this series, securing subdural grid electrodes at the level of the dura is an appropriate strategy for minimizing subsequent movement.

Not all individual electrode contacts were displaced equally within the same patient case. Specifically, for cases with more than 1 grid/strip, the shift pattern may be different for each grid/strip; if rotational shift occurs on the grid/strip, the amount of shift is different on each electrode contact. In this study, we quantified the shift pattern of each electrode contact

TABLE 4. Results of Kendall Rank Correlation Coefficient

	Age	Craniotomy size	Duration	Number of electrodes	Number of GTCs	Brain shift at Crani 1	Brain shift at CT
τ	0.06	-0.01	0.21	-0.05	0.14	0.11	0.08
P	0.71	0.96	0.20	0.77	0.42	0.50	0.60

GTC: secondary generalized tonic-clonic seizures.

FIGURE 6. Average lateral electrode shift relative to the skull (blue) and relative to the cortical surface (red) in each patient case.

individually, in terms of both magnitude and direction, and data were not averaged in the intermediate analysis steps. We report means and standard deviations of the magnitudes of various shifts to summarize overall trends in each case, and the shifts that were calculated were not used to change resection plans in this retrospective study. Cases with larger discrepancies between individual electrode contacts, eg, due to rotational displacement, and/or different shift patterns on individual grids/strips showed higher standard deviations. We also quantified the rotation angle of each individual grid between Crani 1 and Crani 2. The average rotational angle in the 23 cases was $4.3 \pm 3.8^\circ$ (range from 0.2° to 15.7°). Electrode strips were largely tucked underneath the dura in most of the cases. They were visible in 3 of 17 cases that had strips implanted with only 1 to 2 contacts visible in each case, and the shift patterns of these strips could not be quantified, accordingly.

Although iSV has been deployed in neurosurgery to capture 3D profiles of the surgical field,^{15,16} it was used to locate electrode

positions intraoperatively for the first time in this study with a single acquisition that required ~ 1 s to obtain which was far more efficient compared to the stylus probe LaViolette et al¹³ used for intraoperative electrode localization. Here, a sterile stylus probe was used as an independent measurement to assess accuracy, and differences between tracked stylus and coregistered iSV electrode coordinates were 1.9 ± 0.4 mm (combining Table 2, columns 4 and 5). The iSV system was coregistered with pMR through patient registration and optical tracking, and all electrode positions from 3 different time points were transformed into the same coordinate system, ie, the pMR image space. The surface image from the operating room was not used to register or to map to the surface of the MRI brain. The MRI coordinate system was being used only as a common coordinate system for purposes of relating the Crani 1 stereovision data, the postimplantation CT, and the Crani 2 stereovision data. In this study, we did not map the iSV located electrodes onto the pMR brain surface, but rather measured their actual intraoperative locations during Crani 1 and

Crani 2. The electrodes were positioned either above or below the pMR brain surface, indicating brain distention or depression, respectively. Postoperative CT was aligned with pMR using a rigid registration, thus mapping CT-located electrodes into the same image space for quantification of electrode shift between different time points. Lateral shift of the cortical surface (acquired from iSV) was measured, and electrode shift relative to the cortical surface was calculated between Crani 1 and Crani 2, which is the most important finding in this study. This finding is not dependent on the rigid registration per se, since lateral distances between electrode positions and common cortical surface features were available in the iSV views during Crani 1 and Crani 2.

Limitations

Some limitations do exist in the study. First, the measured electrode shift relative to the cortex is subject to inaccuracies from iSV and OF registration, which are on the order of 1 to 2 mm.^{15,16,18} However, it is not influenced by errors from patient registration in Crani 1 or Crani 2, since the cortical surface was aligned using OF registration whereas cortical shift between Crani 1 and Crani 2 and electrode displacements relative to the skull between Crani 1 and Crani 2 include errors from patient registration in Crani 2 (1.8 ± 0.4 mm). Second, the iSV system can only locate electrodes that are visible within the craniotomy, the number of which can be small relative to the total used for iEEG monitoring in some cases (Table 1, column 7). As the electrode positions within each grid are relatively fixed by the silastic grid, this limitation is likely unimportant. Third, the OF algorithm registers features that are found in common between the 2 (Crani 1 and Crani 2) surgeries, and is ineffective when few features are available, eg, if scarring occurs from the previous surgery or the craniotomy is small.

CONCLUSION

In epilepsy surgeries where subdural electrodes are implanted for seizure localization, resection boundaries are typically determined based on the assumption that electrodes remain stationary relative to the cortex between initial implantation and the resection procedure. In this study, we tracked the movement of electrodes with respect to the skull between Crani 1, intersurgical CT, and Crani 2 in 23 patient cases, and showed that subdural grids shifted in directions both lateral and normal to the cortical surface. We also tracked movement of the cortical surface between Crani 1 and Crani 2, and found it did not shift significantly in the lateral direction between surgeries whereas movement of electrodes relative to the cortex was more substantial having an average shift of 5.5 ± 3.6 mm and was greater than the lateral shift relative to the skull in 65% of cases evaluated.

Disclosures

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Pentero operating microscope, respectively. Dr Paulsen, Dr Roberts, and Dr Fan are named inventors on patents and/or patents-pending related to some of the stereovision technology described, the rights to which are currently held by the Trustees of Dartmouth College.

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