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Perioperative Brain Shift and Deep Brain Stimulating Electrode Deformation Analysis: Implications for rigid and non-rigid devices

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Abstract—Deep brain stimulation (DBS) efficacy is related to optimal electrode placement. Several authors have quantified brain shift related to surgical targeting; yet, few reports document and discuss the effects of brain shift after insertion. Objective: To quantify brain shift and electrode displacement after device insertion. Twelve patients were retrospectively reviewed, and one post-operative MRI and one time-delayed CT were obtained for each patient and their implanted electrodes modeled in 3D. Two competing methods were employed to measure the electrode tip location and deviation from the prototypical linear implant after the resolution of acute surgical changes, such as brain shift and pneumocephalus. In the interim between surgery and a pneumocephalus free postoperative scan, electrode deviation was documented in all patients and all electrodes. Significant shift of the electrode tip was identified in rostral, anterior, and medial directions ($p < 0.05$). Shift was greatest in the rostral direction, measuring an average of 1.41 mm. Brain shift and subsequent electrode displacement occurs in patients after DBS surgery with the reversal of intraoperative brain shift. Rostral displacement is on the order of the height of one DBS contact. Further investigation into the time course of intraoperative brain shift and its potential effects on procedures performed with rigid and non-rigid devices in supine and semi-sitting surgical positions is needed.

Keywords—Brain shift, Deep brain stimulation (DBS), Electrode displacement, Subthalamic nucleus (STN), Parkinson's disease (PD), Rigid catheter, Non-rigid catheter.

INTRODUCTION

Since its introduction, deep brain stimulation (DBS) has been proven to be an effective and widely used symptomatic treatment for Parkinson's disease (PD). A recent randomized trial of DBS surgeries targeting the subthalamic nucleus (STN) has shown evidence of superiority over the alternative best medical management for the treatment of PD.[2] In the future, much broader application of DBS is expected in the treatment of movement disorders, psychiatric disorders, epilepsy, pain, in addition to having other emerging indications.[4]

Standard protocol for neurostimulation with DBS involves a quadrapolar electrode placed within a target area of the brain, commonly the STN. The individual DBS electrode contacts are mounted within a non-rigid insulating carrier and delivered with a rigid stylet through an insertion tube, using stereotactic technique. Once the electrode is in the appropriate location, the insertion tube is removed, the electrode is fixated at the burr hole, and the rigid internal stylet is removed.

Although DBS is a well-accepted treatment, its rate of success is ultimately limited by the overall accuracy of electrode insertion and final placement in the appropriate target. Depending on the surgical center, targeting is performed either with historical imaging sets obtained preoperatively or with imaging obtained intraoperatively.[5] If imaging and targeting are not performed intraoperatively, there exists the possibility of a change in the location of intended implantation in the brain with respect to the historic imaging sets.

In order to minimize the aforementioned targeting error, thoughtful studies have been published with the recommendation of using microelectrode recording in place of intraoperative imaging to arrive at the target location.[1,6,9] Implanting centers commonly use intraoperative microelectrode recording (MER) to provide additional information and to better ensure placement at the desired target.[7] In addition, many centers obtain high-resolution images postoperatively in order to

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document electrode location and the presence or absence of intraoperative complications, such as a hemorrhage,[10] but few have published follow-up imaging documenting the resolution of acute intracranial processes.

Despite the use of intraoperative MER and the fact that the electrode is radially constrained within the surrounding brain tissue after implantation, acute processes introduced in the operation, such as pneumocephalus, have not yet resolved. Both the introduction of these acute processes and their resolution results in a phenomenon known as brain shift. Defined as the displacement and/or deformation of the brain during intracerebral procedures, shift is hypothesized to occur laterally (toward the ear) and caudally (toward the feet) with respect to the burr hole and is due to a combination of forces on the subject's brain, including gravity, cerebrospinal fluid egress, pneumocephalus, and the mechanical process of intracerebral insertion of a device. The shift begins occurring once the skull and dura are opened and is hypothesized to be at its maximum at the time of surgery. As intracranial pneumocephalus resolves during the days to weeks after surgery and reversal of perioperative brain shift is complete, the brain is hypothesized to return to its approximate preoperative condition (Fig. 1).

In spite of improvements in imaging technology, brain shift due to intraoperative processes remains a hurdle that hinders the precision of final electrode placement. It is a significant cause of decreased navigational accuracy during neurosurgical procedures that rely heavily on preoperative imaging. Implantation variance may decrease the efficacy of delivered neurostimulation and therefore, has the potential to limit therapy.

Several previous publications[3,9,17] have reported perioperative brain shift in the setting of implant accuracy. They report the direction of intraoperative brain shift to be caudal and lateral to varying degrees in relation to the stereotactic frame, immediately following the surgery. Some have discussed the relative position of the head in a sitting vs. supine surgery and the potential effects of these surgical positions on the resultant brain shift.[4] Their results demonstrate the direct effect of brain shift on targeting error. Recent discussion from two publications[10,17] regarding the potential for electrode cranial migration resulting from large amounts of intracranial pneumocephalus and brain shift has determined the possibility of over 3 millimeters of secondary ''shift'' as acute processes resolve (Fig. 2). Once pneumocephalus has resolved and the brain has shifted back to its preoperative position, the implanted electrode is found to be complexly deformed into a partial ''question mark'' shape, resulting in retraction of the electrode tip from its original target location (Fig. 3).

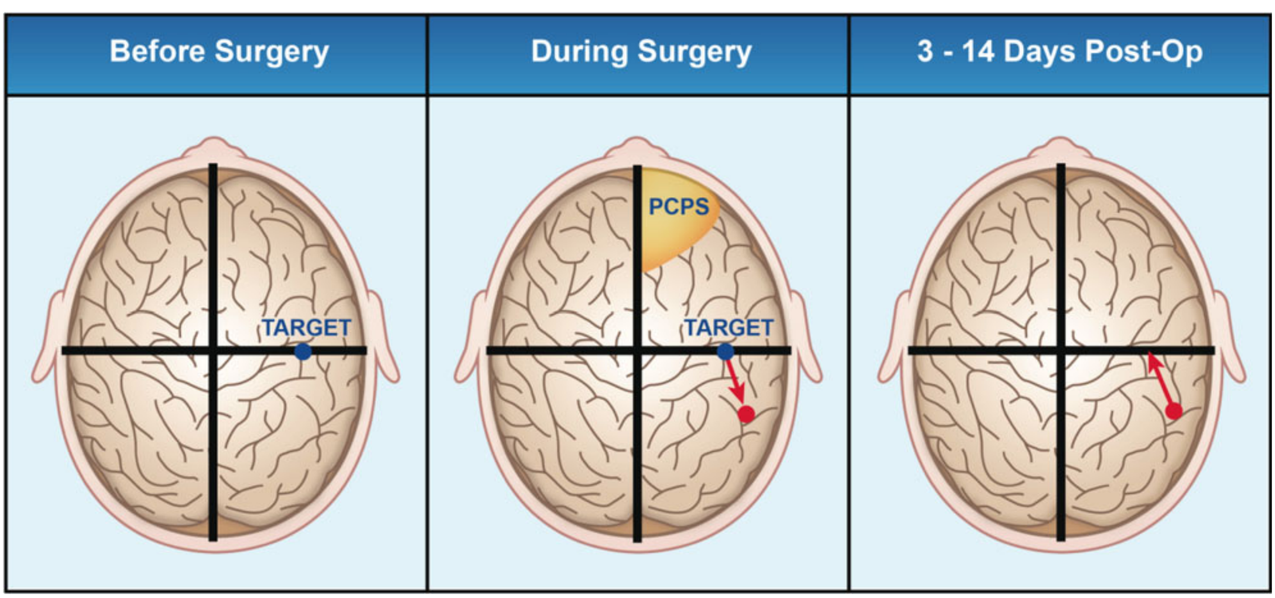

FIGURE 1. Three stage characterization of brain shift Brain shift, and thus, electrode displacement, occurs in three distinct stages. Prior to surgery, a target location is determined based on the brain in its original position (no shift has occurred yet). Then, during surgery, as subdural air (PCPS) rushes into the brain, the brain shifts, as does the target location. Intraoperative electrophysiology or imaging is required to adjust the implant trajectory, and the electrode is implanted into a shifted brain. Finally, on average, 3–14 days following surgery, the PCPS resolves, and the brain is allowed to return to its original position and shifts back. However, this means that the target location and electrode will also shift. It is when the brain shifts back to its original position that electrode tip displacement occurs. The figure above depicts a unilateral surgery, with subdural air on the surgery side. Thus, the middle brain shows an unshifted left-brain and a shifted right-brain.

As brain shift has been a clear factor introducing targeting error, microelectrode recording[7] and computational models have been utilized to correct for and minimize potential electrode misplacement. Recent publications[3,17] have highlighted steps to minimize intraoperative brain shift. Steps such as proper positioning, decreasing surgery time, flooding the burr hole with saline irrigation and the use of sealant at the burr hole may be taken to alleviate the degree of brain shift.

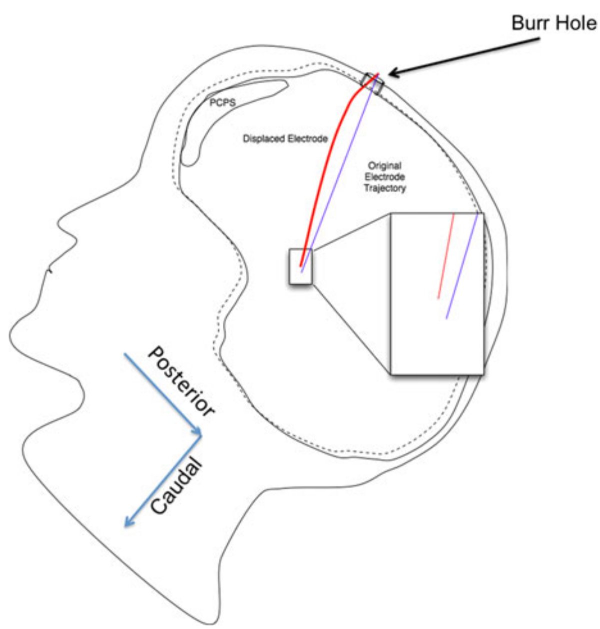

FIGURE 2. Model of pneumocephalus (PCPS) and displacement of electrode from original trajectory following resolution of brain shift. Brain shift with respect to the burr hole can also be seen in the lateral and caudal directions.

However, eliminating all traces of shift proves to be elusive. Other publications[3,17] have focused on understanding the degree to which the location of an implanted electrode differs from the preoperatively targeted location at the time of implantation.

Additionally, if implanted devices have the potential to exhibit several millimeters of shift, applications involving infusion within the brain may be well advised to occur after the resolution of all acute intracranial processes thought to contribute to brain shift.[11] Furthermore, understanding the time course and degree of device retraction and potential influences on chronic rigid delivery devices has been an aim of this retrospective review.

MATERIALS AND METHODS

Patient Selection

A retrospective chart review was performed of all patients who underwent DBS surgery for treatment of movement disorders including: PD, tremor or dystonia at the University of Wisconsin between 8/07/2007 and 8/10/2010. All patients with bilateral DBS electrodes implanted during separate surgeries (staged bilateral implantation) were included with the hypothesis that preoperative imaging for the second stage surgery was available for brain shift comparison after the resolution of the acute surgical process. Patients were excluded from analysis if any of the following studies were absent or of insufficient quality and did not support analysis: (1) preoperative brain MRI; (2) perioperative brain MRI after implantation of the first electrode; (3) preoperative CT prior to the second DBS implantation.

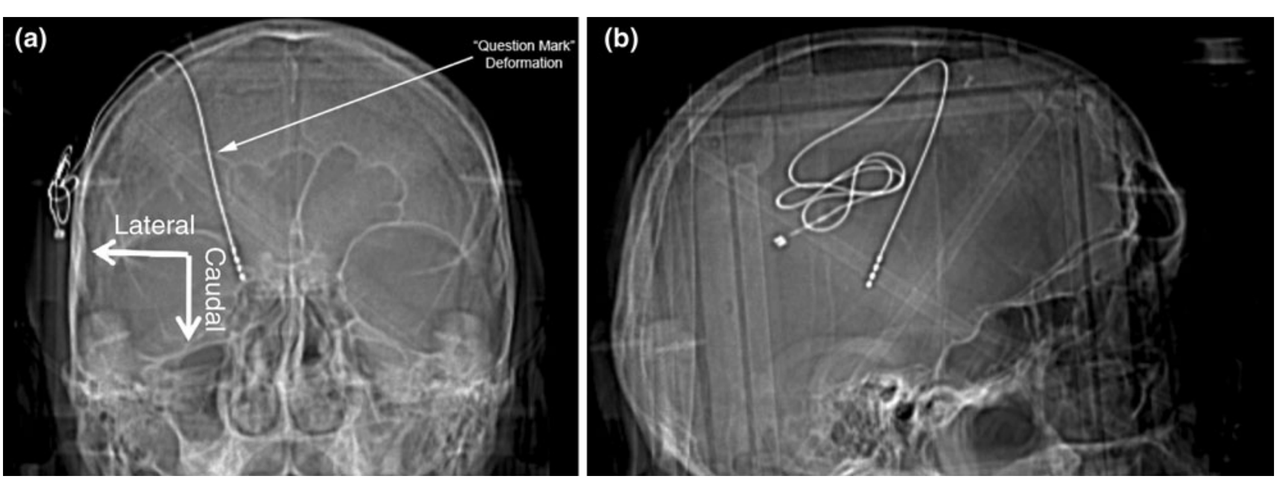

FIGURE 3. CORONAL (a) and SAGGITAL (b) images taken after the resolution of intracranial pneumocephalus showing a nonlinear "question mark" implant appearance. The coronal view also indicates the initial direction of brain shift in the lateral (toward the ear) and caudal (toward the feet) directions.

Description of Stereotactic Surgical Targeting and Implantation

Following current protocol at our institution, patients are taken to the operating suite on the morning of surgery for sedation, stereotactic frame placement, imaging for surgical targeting, and surgical implantation. After the administration of propofol/dexmetatomadine sedation and administration of lidocane/bupivicane local anesthetic, the Cosman-Roberts-Wells (CRW) stereotactic frame (Integra Neuroscience, Plainsboro, NJ) and associated Luminant® stereotactic MRI/CT localizer is applied. The stereotactic computed tomography (CT) scan of the head is performed [kV = 120, mA = 500, slice thickness = 2.5 mm] with the patient in the supine position. Preoperatively obtained stereotactic magnetic resonance imaging (MRI) images are computationally rendered stereotactic through fusion to the stereotactic CT scan using a commercially available neuronavigation system (StealthStation®, Framelink®, Medtonic Inc.). The anterior commissure (AC) and posterior commissure (PC) as well as three midline points are identified on preoperative imaging to define the commissural plane and AC/PC coordinate system for indirect targeting. Indirect targeting coordinates are modified if patient specific anatomy differs significantly from the expected or previously determined. After selecting the target coordinates in AC/PC space, the frame coordinates and trajectory information are extracted computationally from the neuronavigation system. The trajectory is then set with CRW frame coordinates. During surgery, patients are in a semirecumbant position and are kept under only local anesthesia to allow for intraoperative stimulation.

Microelectrode recording (MER) is employed in all cases. Following the completion of intraoperative, MER guided determination of the final implant location, the linear DBS device is deployed and anchored to the skull in a several step process. At our institution, this involves: first, removing the rigid insertion tube; second, securing the electrode with a skull mounted anchoring device designed to apply non-damaging firm pressure perpendicular to the electrode; third, removing the rigid internal stylet from the electrode; and fourth, closing the scalp incision (Fig. 4a). After completion of the initial unilateral DBS implant, patients undergo postoperative MRI scanning to document electrode location in MRI space relative to the midcommissural point.

Patients returning for the second sided implant have a repeat of the aforementioned procedure on the second side (contralateral DBS implant). During this second side of staged bilateral DBS implantation, the stereotactic localization scan for surgical planning of the second implant is available for analysis of the first electrode implantation with the resolution of perioperative processes and associated brain shift.

Computational Techniques for Post Implant DBS Electrode Deformation Analysis

In order to determine deformation and shift of the DBS electrode and measure pneumocephalus, both early post-implant brain scans and time-delayed post-implant brain scans were utilized. The post-operative CT/MRI images (with brain shift) from the initial DBS implantation and the pre-operative CT/MRI images from the second of the staged DBS implantations (showing the initial lead in the brain after brain shift

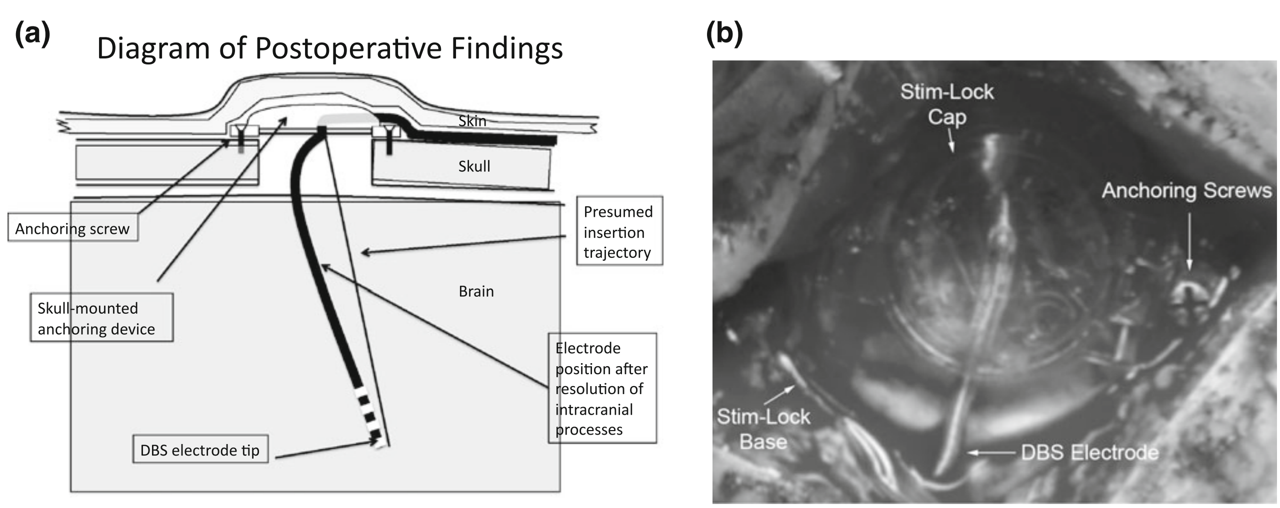

FIGURE 4. Expanded view of skull mounted fixation device interface and operative photograph demonstrating relationship of Stim-lock device and anchoring bone screws Both the DBS electrode an anchoring screws are hyper dense to brain and skull on CT and are easily segmented using iPlan Stereotaxy 2.6 (BrainLab). The DBS electrode is anchored using the Stim-lock device at the skull entry point, which can be seen in the expanded view of the fixation device interface on the left.

resolution) were loaded in a neuronavigation system (iPlan Stereotaxy® 2.6, BrainLab, Heimstetten, Germany) and fused (scan #2 [time delayed] = reference scan, scan #1 = comparison scan) based upon identifiable anatomical landmarks as is done routinely during surgical planning. Coordinates in all three axes, lateral–medial (X), anterior–posterior (Y), and caudal–rostral (Z) were obtained for the midpoint of the anterior commissure (AC) and posterior commissure (PC) in the pre- and post-operative images and for the electrode tip. The difference between pre- and immediate post-operative coordinates was calculated to quantify the difference in tip location with brain shift and following resolution. Pneumocephalus volume and distance were also computationally determined using iPlan Stereotaxy 2.6 (BrainLab). For both volume and distance, images were loaded into BrainLab and referenced with AC/PC coordinates. Pneumocephalus was segmented out of the scan and volume reported. In order to report distance of pneumocephalus, sequential parasagittal images were examined, and the maximum perpendicular distance due to the presence of pneumocephalus was measured and reported.

Electrode Segmentation & Mathematical Models of Electrode Displacement

Each patient's electrode was segmented out of the fused CT and MRI images using iPlan Stereotaxy 2.6 (BrainLab) and OsiriX (Pixmeo SARL, Geneva, Switzerland) (Fig. 5).

Two methods were utilized in an attempt to model the distance that the electrode tip is displaced upward following resolution of brain shift (Fig. 4). Results from both methods are reported.

Calculated Method

Calculated Method (Method 1) uses point 2 (Fig. 6) as the point of electrode entry into the skull, which is located between the two anchoring screws (S1 and S2). Point 1 is the implant depth (assumed tip location) at the time of surgery. A straight trajectory was assumed from point 2 to point 1 using SolidWorks™ (©2012 Dassault Systèmes SolidWorks Corporation, Waltham, MA). Vector measurements were taken along the entire length of the projected straight trajectory and the point at which the electrode deviated the farthest from the trajectory was denoted as the "width at greatest deviation" and can be seen on Fig. 6 as *. This deviation distance was measured and recorded. Distance A is the distance from the point of greatest deviation to the implant depth. Distance B is the recorded implant depth from surgery. Distance C is the distance from the entry point into the skull to the point of greatest deviation.

Using simple geometry, the approximate degree of tip retraction could be modeled and estimated. In looking at Fig. 6, it can be assumed that the dashed trajectory connecting points 1 and 2 is the implant depth following electrode deformation. We hypothesize that the implant depth after electrode deformation is going to be shallower than the initial implant depth

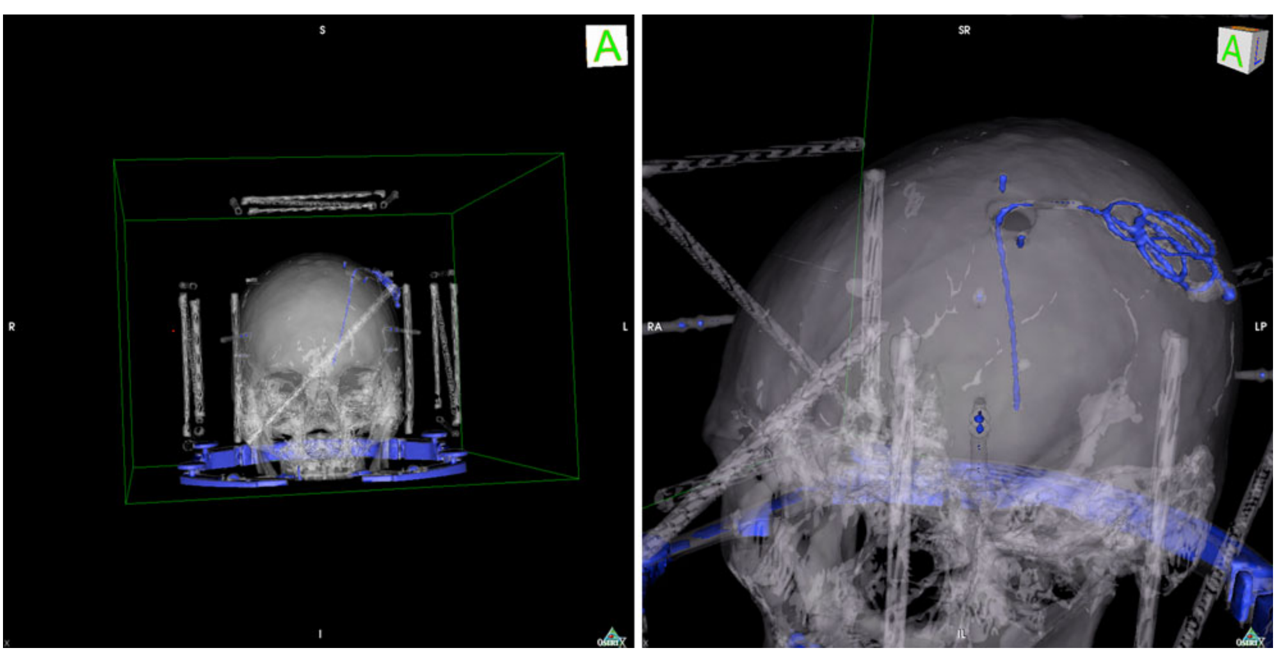

FIGURE 5. Visualization of electrode segmentation of electrode performed from stereotactic CT image following pneumocephalus resolution.

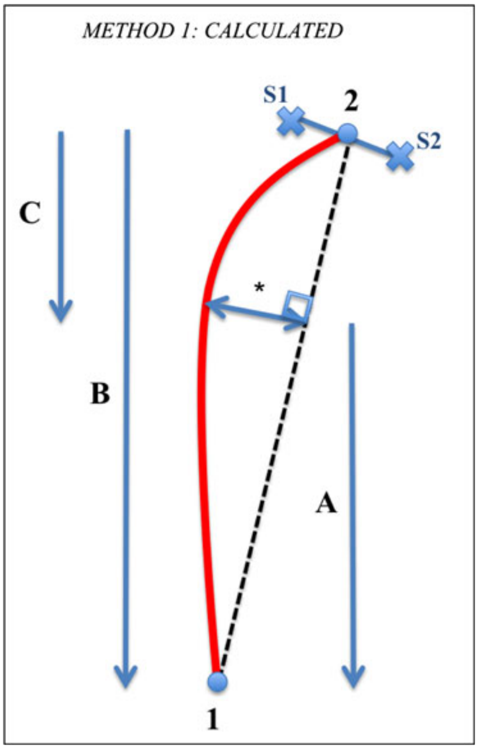

FIGURE 6. **Method 1 used to calculate electrode tip retraction Method 1 was used to mathematically calculate electrode tip retraction for all 12 patients. Distances A, B, and C, along with points 1 and 2, were used to calculate final retraction as a result of brain shift resolution. The dashed black line is the projected straight trajectory for the electrode, as it connects points 1 and 2, the implanted tip location and the entry point into the skull, respectively. The solid red line is the actual shape and curvature of the electrode following brain shift resolution, demonstrating its deviation from the projected straight trajectory. The * represents the point of greatest deviation from the straight trajectory, which was found using SolidWorks.**

when the electrode is straight. In order to determine the distance the electrode was retracted following deformation, one must know the implant depth following deformation (known) and the length of the curved electrode. By subtracting the two, one can estimate how far the electrode was retracted out of its initial implant location. In order to do this, two right triangles can be assumed. The width at greatest deviation, or *, was first determined using Solidworks. As can be seen in Fig. 6, after the determination of the width at greatest deviation, one is left with two approximate right triangles, both utilizing the width at greatest deviation as one of its sides. Next, the distance between the point of greatest deviation and point 1 was measured on the straight dashed trajectory. Using the Pythagorean Theorem with the width at greatest deviation and the aforementioned measurement, the third side (the curved electrode side) is estimated for the bottom right triangle. This step is then repeated but for the triangle above the point of greatest deviation. The two hypotenuses determined from calculations are then added together (to determine the electrode length) and then subtracted from the implant depth following deformation, in order to determine distance of retraction Width at greatest deviation and distance retracted were both calculated and reported for Method 1 (Fig. 6).

Measured Method

Patients' post-operative MRI scans (with brain shift) following their first surgeries were retrospectively reviewed for Measured Method (Method 2). Additionally, a time-elapsed CT scan was performed postoperatively (after resolution of brain shift) and was also retrospectively reviewed. An average of 32 $\pm$ 60 days in between the initial surgery and the time-elapsed CT was observed in this study, with the elapsed time ranging anywhere from 7 to 211 days depending on the patient. It was assumed that the MRI scan would show a straight electrode, and the time-elapsed CT scan would show a curved electrode following the resolution of pneumocephalus and brain shift. AC/PC coordinates of the electrode tip from both scans were recorded and compared in the lateral–medial, anterior–posterior, and rostral–caudal planes, in order to accurately determine displacement in space (Fig. 7). The difference in all directions was determined by subtracting the AC/PC coordinates recorded from the post-operative MRI from those recorded from the time elapsed CT (time-elapsed CT—post-operative MRI). The time elapsed CT scan served as the reference scan, while the post-operative MRI scan was the comparison scan. In contrast to Method 1, which mathematically calculated the electrode tip retraction, Method 2 measured the displacement by the subtraction of coordinates (Fig. 7).

RESULTS

Characteristics of Patient Population

All patients who underwent a staged bilateral DBS surgery for treatment of movement disorders, including PD, tremor or dystonia, were included, and a total of 52 patients were identified. If patients did not receive a post-operative MRI or a pre-operative CT prior to the second DBS implantation or if their images were of poor quality, they were excluded. A total of 12 patients out of 52 who underwent DBS surgery were included in the study, and 8 of those 12 patients were being treated for PD. The patients had a mean age of 66 $\pm$ 5.9 years and 58% were men. All included subjects had pre-operative CT or MRI scans prior to the second staged DBS implantation following resolution of pneumocephalus and post-operative

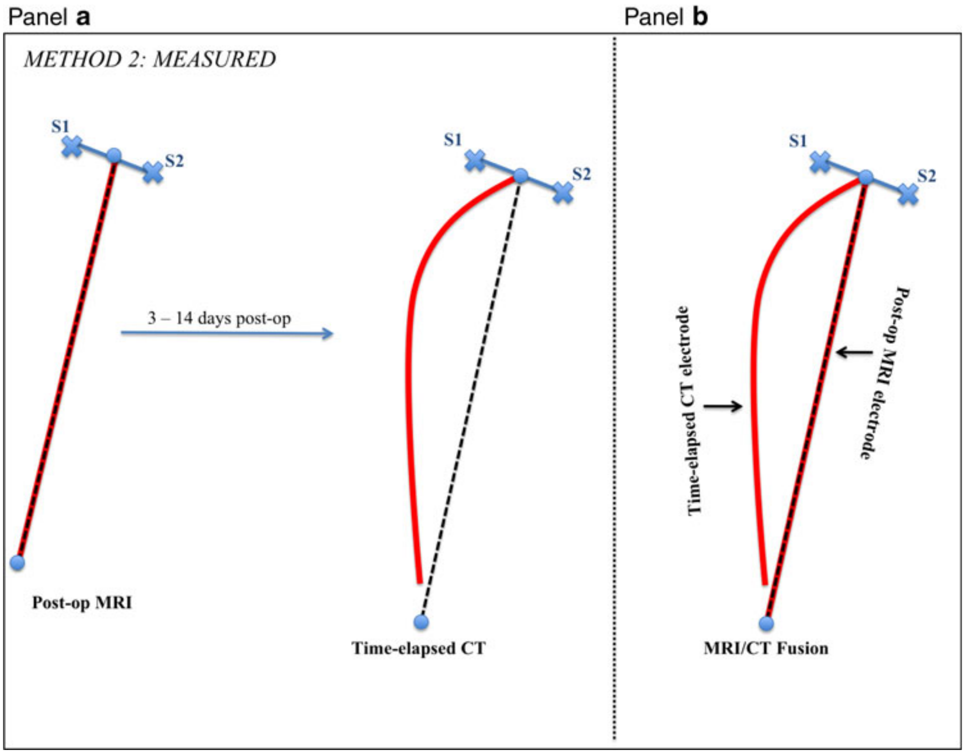

FIGURE 7. Method 2 used to visualize and measure electrode tip displacement from time elapsed CT and post-op MRI Method 2 was used to visualize and measure electrode displacement in all directions by fusing the patient's post-op MRI from his/her first surgery and the time-elapsed CT, taken anywhere from 3 to 14 days following surgery. The post-op MRI, taken immediately after implantation (with brain shift), shows an electrode (red) that is in line with the projected straight trajectory (dashed black), connecting the implant location in the brain to the entry point in the skull. The leftmost diagram in panel (a) depicts this. The time-elapsed CT, taken after brain shift has resolved, shows an electrode (red) that deviates and curves away from the straight trajectory (dashed black). The rightmost diagram in panel (a) depicts this. Panel (b) Demonstrates the fusion of these two scans, based off of AC/PC coordinates in the brain. By fusing the post-op MRI and the time-elapsed CT, the difference in electrode tip location could be seen and measured.

MRI images following the initial surgery of staged bilateral DBS implantation prior to the resolution of pneumocephalus. Of these patients, the electrode (Medtronic 3387, quadrapolar, diameter 1.27 mm, contact spacing 1.5 mm, contact length 1.5 mm) was implanted in the STN (7), VIM (3), GPi (2) (Table 1).

Visualization of Electrode Segmentation

Analysis with the BrainLab planning station and segmentation of the intracranial electrode was performed in all 12 cases. Scout images taken from CT documenting the implant trajectory and angular deviation matched the projections of the three-dimensional segmented object rotated to simulate anterior–posterior and lateral views by visual inspection (Fig. 5).

Distance Retracted According to Calculated Method (Method 1)

According to Method 1 calculations, the 12 patients had a mean implant depth of 80.57 ± 2.70 mm. The

TABLE 1. Characteristics of patient population who underwent DBS surgery for treatment of movement disorders.

Variable	Value
Total no. of DBS procedures	52
No. of staged bilateral procedures selected for this review	12
Mean ± SD age (years)	66 ± 5.9
Male sex	58%
Diagnosis	
Parkinson's disease	2/3
Essential Tremor	1/3
DBS target (no. of patients)	
STN	7 (58%)
VIM	3 (25%)
GPi	2 (17%)

Each patient's file was viewed in the DBS surgery database and statistics compiled. A total number of 52 DBS surgeries were reviewed when compiling data, and 12 patients who underwent the staged bilateral procedure were selected for this publication. Of these 12 patients, 2/3 of them were previously diagnosed with Parkinson's disease, and 1/3 of them were previously diagnosed with essential tremor. 58% of DBS surgeries reviewed for this publication targeted the STN, 25% targeted the VIM, and 17% of them targeted the GPi. The average age of patients selected was 66 ± 5.9 years, and 58% (7 patients of 12) were male.

TABLE 2. Calculation of distance retracted according to Method 1.

Subject	Implant depth (mm)	Width at greatest deviation (mm)	Distance retracted (mm)	PCPS volume (cm^3)	PCPS distance (mm)
4363	75.55	4.67	2.08	19.24	11.50
4365	77.73	5.09	0.99	7.89	8.10
4370	82.90	7.11	1.99	3.44	7.40
4364	84.38	3.89	0.99	14.55	10.60
4366	78.46	6.15	1.33	3.28	4.60
4367	81.01	5.51	1.15	4.46	10.50
4266	80.55	4.79	0.87	2.85	15.90
4376	79.35	6.04	1.45	6.28	10.60
4369	82.53	4.34	0.85	13.44	9.40
4220	78.27	5.56	1.46	9.83	11.30
4221	82.49	6.82	2.68	8.64	6.60
4222	83.58	4.46	1.12	3.90	10.20
Mean	80.57	5.37	1.41	8.38	9.73
SD	2.70	1.01	0.56	5.94	2.90

Each patient's electrode curvature was analyzed using a mathematical prediction, and implant depth, width at greatest deviation, distance retracted, and PCPS volume and distances were calculated. Patients had a mean implant depth of 80.51 ± 2.70 mm, a mean width at greatest deviation of 5.37 ± 1.01 mm, a mean distance retracted of 1.41 ± 0.56 mm, a mean PCPS volume of 8.38 ± 5.94 cm^3, and a mean PCPS distance of 9.73 ± 2.90 mm.

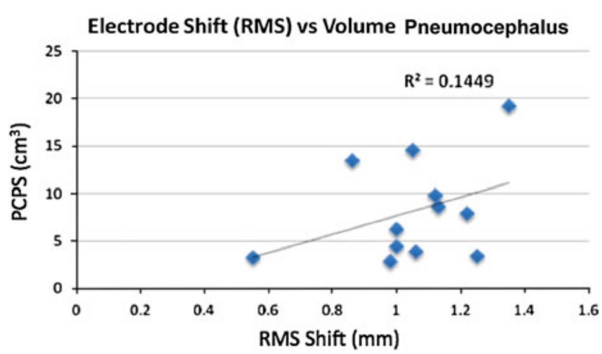

FIGURE 8. Electrode shift (RMS) vs. volume pneumocephalus according to measured method (Method 2) Electrode shift (RMS) was plotted against volume PCPS. The R^2 value was found to be approximately 0.15, which means that 15% of the variation can be explained by this linear relationship.

average width at greatest deviation was 5.37 ± 1.01 mm, and the average distance retracted was 1.41 ± 0.56 mm (Table 2).

Electrode Tip Displacement According to Measured Method (Method 2)

According to Method 2 calculations, the 12 patients had an average electrode tip shift in the lateral–medial direction of −0.10 ± 0.82 mm, 1.23 ± 0.55 mm in the anterior–posterior direction, and 0.76 ± 0.66 mm in the rostral–caudal direction. The average RMS value for electrode tip shift was 1.05 ± 2.10 mm. Each patient's individual RMS shift was plotted against volume pneumocephalus, resulting in an R^2 value of 0.1449 (Fig. 8). Our results demonstrated an intraoperative shift in the lateral–medial, anterior–posterior, and rostral–caudal planes, with individual variability on the degree of shift (Table 3). Nine out of 12 patients showed shift in the medial direction, and three out of 12 patients showed shift in the lateral direction. 12 out of 12 patients showed shift in the anterior direction, and 12 out of 12 patients showed shift in the rostral direction.

Vector Plot of Electrode Displacement

A corresponding vector plot for Method 2 calculations is also shown (Fig. 9), and patients' electrode shift in the medial–lateral and anterior–posterior planes was plotted. The net average shift for the 12 patients was in the lateral and rostral direction, as can be seen by the net vector, indicating both direction and magnitude.

DISCUSSION

In the current study, we analyze and report both electrode deformation and electrode tip movement in a series of patients undergoing DBS with frame-based stereotaxy. We report the relationship of pneumocephalus volume to degree and vector of brain shift. Although our study was retrospective and inadequately powered to significantly correlate these metrics, our results support two previous publications.[3,17]

Three dimensional measurements, maximum electrode deformation (Method 1) and electrode tip retraction (Method 2) provided insight into the hypothesized postero-lateral postoperative brain shift leading to postoperative electrode deformation and electrode retraction, although establishing significance was not possible with this dataset.

TABLE 3. Calculation of electrode tip displacement according to Method 2.

			Electrode Tip Shift (AC/PC space, mm)—measured as (time delayed CT − post operative MRI)				
Subject	PCPS vol (cm^3)	PCPS dist (mm)	*X*	M/L (+ = lateral, − = medial) − (Pre Op 2 → Post Op 1)	*Y*	*Z*	RMS
4363	19.24	11.50	−0.19	0.19	0.53	2.27	1.35
4365	7.89	8.10	0.33	0.33	0.82	1.91	1.22
4370	3.44	7.40	−1.12	−1.12	1.75	0.59	1.25
4364	14.55	10.60	−0.93	−0.93	1.40	0.70	1.05
4366	3.28	4.60	−0.35	−0.35	0.62	0.63	0.55
4367	4.46	10.50	−0.46	−0.46	1.50	0.75	1.00
4266	2.85	15.90	1.57	1.57	0.29	0.59	0.98
4376	6.28	10.60	−1.20	−1.20	1.07	0.66	1.00
4369	13.44	9.40	0.18	−0.18	1.46	0.20	0.86
4220	9.83	11.30	0.72	−0.72	1.80	0.13	1.12
4221	8.64	6.60	0.63	−0.63	1.78	0.51	1.13
4222	3.90	10.20	−0.32	−0.32	1.79	0.21	1.06
Mean	8.38	9.73	−0.1	−0.32	1.23	0.76	1.05
SD	5.94	2.90	0.82	0.76	0.55	0.66	0.21

Each patient's electrode was analyzed in BrainLAB® using retrospective review of pre-op and post-op CT's and MRI's. The *x*, *y*, and *z* coordinates shown, represent electrode tip shift in each direction between the patient's post operative MRI image from his/her first surgery and the time delayed CT image from his/her second surgery (time delayed CT − post operative MRI 1). The average PCPS volume recorded was 8.15 ± 5.26 cm^3, and the PCPS distance recorded was 9.73 ± 2.90. The average electrode shift in the *x* direction was measured to be −0.10 ± 0.82 mm, 1.24 ± 0.55 mm in the *y* direction, and 0.76 ± 0.66 mm in the *z* direction. The average root mean square was calculated to be 1.05 ± 0.21 mm.

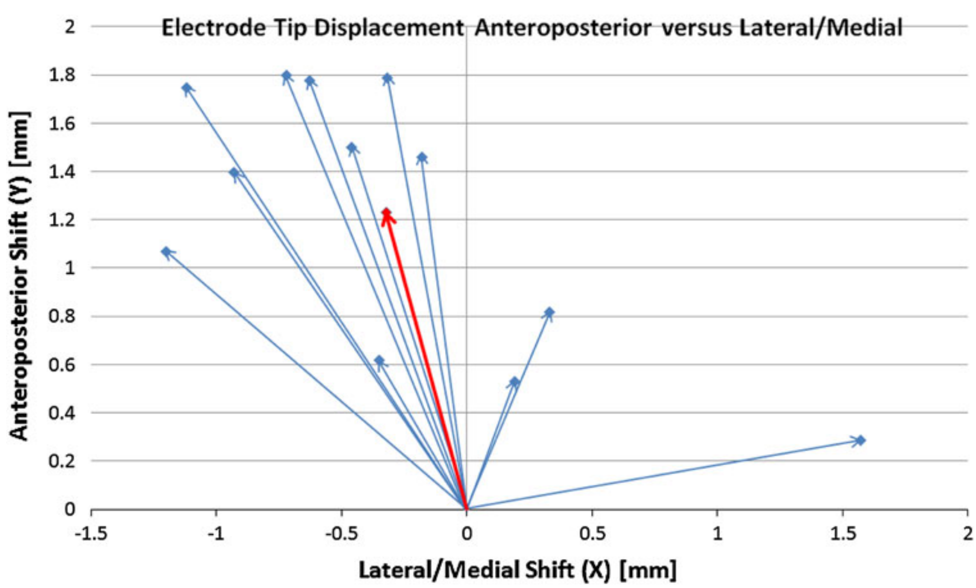

FIGURE 9. Vector plot of electrode tip displacement medial/lateral (*x*) vs. anteroposterior (*y*) in mm for all patients.

Both methods produced results demonstrating substantial rostral deviation. In comparing calculated upward displacement (Method 1) to measured rostral displacement (Method 2), no statistical significance was found between the calculated and measured value for upward tip displacement, with a value of $p < 0.2$. Therefore, Method 1 demonstrates promise as a reasonable substitute for the more time consuming retrospective MRI/CT review utilized in Method 2. Using Method 1 may be a good way to predict a patient's electrode displacement and as a result, program them more effectively, as programming is based upon final electrode location and brain structures being stimulated. Instead of needing to repeat the time-consuming process of both obtaining and viewing CT and MRI scans, as well as fusing them, neurologists may consider deformation calculations to guide adaptation of intraoperative test stimulation data in order to compensate post-operatively.

Initial Shape of Electrode

Some may argue that electrode shift and thus, electrode tip displacement does not occur as a result of brain shift and resolution of pneumocephalus, but is instead a result of removing the rigid stylet around the electrode during surgery. However, the electrode is linear upon implantation with the rigid stylet, and immediately after the removal of the stylet, it is clear that the electrode is not yet curved (Fig. 10). The lateral radiographs shown provide evidence that the electrode is without significant antero-posterior deformation immediately following implantation and the removal of the rigid stylet. Upon implantation, neither brain shift nor pneumocephalus has yet resolved, and the electrode is linear. Ultimately, delayed imaging of the electrode shows deformation due to the resolution of pneumocephalus and the return of the brain to its preoperative condition. Unlike the relative rapid intraoperative brain shift, return of the brain to its preoperative position is unlikely to occur fully until days to weeks following surgery.

Direction of Shift

The ultimate goal of the study was not only to confirm that brain shift does exist in patients undergoing DBS surgery but also to evaluate more efficient methods of objectively documenting brain shift. It was extremely important to quantify brain anatomy in the most accurate and thorough way possible. In an effort to confirm and expand upon results presented in previously published results, patients' electrodes were analyzed in the medial–lateral, anterior–posterior, and rostral–caudal planes. Nine out of 12 patients' electrodes showed shift in the medial direction, and three out of 12 patients' electrodes showed shift in the lateral direction. This was statistically significant, with $p < 0.05$. 12 out of 12 patients' electrodes had shift in the anterior direction, which was statistically significant with $p < 0.01$. Similarly, 12 out of 12 patients' electrodes showed shift in the rostral direction and were, as a result, retracted. This was statistically significant ($p < 0.01$). The vector shift that is depicted in Fig. 9 occurs after the resolution of pneumocephalus and brain shift (Fig. 1). The shift being discussed in the medial–lateral, anterior–posterior, and rostral–caudal planes occurs when the brain returns to its initial preoperative position.

Patient Positioning

It is important to note that shift in all three directions occurred, and patients were operated on in the sitting position (approximately 45° off the horizontal) rather than in the completely supine position. It is highly probable that shift in at least two directions (anterior and rostral) would be greatly exaggerated in procedures where the patient is lying down, as was seen in patients from the two previous papers.[3,17] Because of this observation, we have recently begun to focus on the exact degree of patient positioning in the sitting position and now measure it with an accelerometer during each surgery. We are planning to perform a retrospective review of degree of brain shift and its relation to degree of position during surgery in order to better inform the proposed relationship.

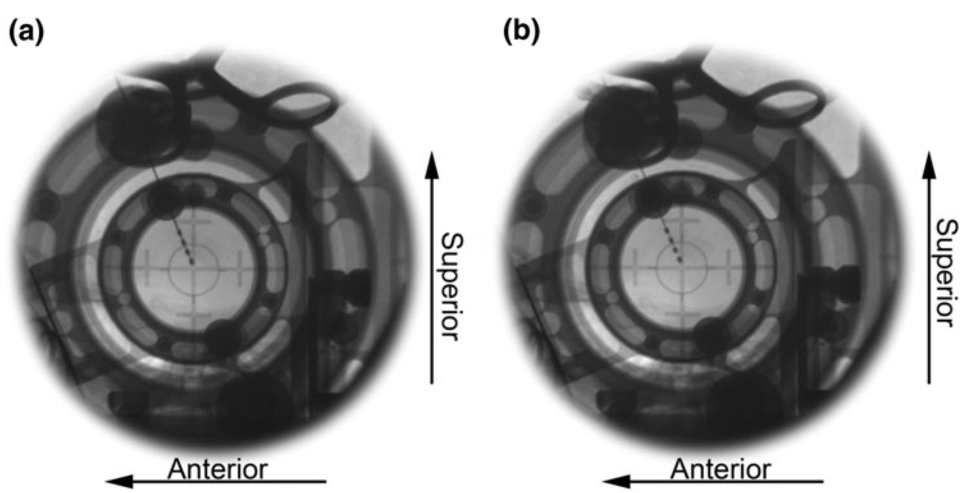

FIGURE 10. Intraoperative lateral radiographs Lateral radiographs through the CRW frame before (a) and after (b) removal of the rigid internal stylet are shown. Targeting cross hairs on one side of the frame are aligned with concentric circles on the other to indicate a true lateral projection. No obvious brain shift is apparent after the removal of the outer rigid insertion cannula and internal rigid stylet.

Delayed Programming

The final step in a DBS procedure is the electrode programming that takes place post-operatively. The electrode is implanted into a particular brain structure (STN, VIM, or GPi), and programming the electrode's leads will result in stimulation of that brain structure. The electrode has four leads and careful programming of these leads results in proper stimulation and the intended therapeutic effect. However, this programming relies on where the electrode is believed to be, which can be altered by brain shift and its resolution. Previous studies have mainly focused on the effects of brain shift upon accurate targeting and electrode placement.[3,17] However, once intracranial pneumocephalus has resolved, little is known about how the movement alters the final resting location of the electrode and thus, how it affects programming. Due to the size of the electrode in DBS, the shift may not be therapeutically relevant. As has been previously reported,[3,17] we confirm that in patients who underwent a DBS surgery, the device moves in the postoperative days following surgery. In a period of three to 14 days following the surgery, after pneumocephalus has resolved, we found that the patient's electrode had shifted and its tip had been retracted out of the initial implant location. As a result, the neurostimulation locations along the axis of implant may vary, and for this reason, it may be reasonable to delay programming the patient. Because the electrode consists of four leads, if the electrode tip is pulled out of its original location, different leads can be stimulated, and the patient's electrode and leads will still be programmed effectively. The detrimental effects of brain shift and electrode retraction can be minimized if the patient's programming takes place after the electrode is in its final position, even if it is not in the exact implant location. However, in therapeutic applications where precision is of ultimate importance, divergence from the desired location may be detrimental. For example, gene therapy administered with rigid catheters may be more greatly affected.[3]

RMS Shift vs. Volume Pneumocephalus

Though the two most recent publications[3,17] discussed a correlation between volume pneumocephalus and electrode shift. While the general trend of brain shift in the current report agrees with recent publications,[3,17] our results did not show a significant correlation between the two. This is most likely due to the fact that our pneumocephalus volumes were smaller than previously reported.[3,17] In viewing a graph plotting electrode shift (RMS) against volume pneumocephalus (Fig. 8), it can be seen that R^2 is only equal to 0.1449. However, it can also be seen that the patient with the least amount of subdural air also has the lowest RMS shift, and the patient with the greatest amount of subdural air has the greatest amount of RMS shift. Additionally, both papers presented a much larger range of pneumocephalus, with much higher values. If one were to view their data, only incorporating data obtained from patients having less than 20 cm^3 of pneumocephalus, it is no longer significant. Both papers[3,17] also suggest changes that may be employed in order to minimize pneumocephalus all of which are already incorporated into DBS surgeries performed for this paper, perhaps explaining the smaller values of pneumocephalus we present.[3,17]

Rigid vs. Non-rigid

Another aspect of procedures utilizing electrodes (DBS) or catheters (convection-enhanced delivery) needing further attention is the question of rigid vs. non-rigid delivery devices. Lengthy procedures that use a rigid delivery device, such as CED, may present unique challenges in regard to the effects of shifting. In this paper, brain shift is discussed in the context of a DBS surgery, in which a rigid electrode is in place for a few minutes before the rigid stylet is removed and implantation is complete. However, in convection-enhanced delivery, a rigid infusion catheter may be in the brain for hours during acute infusions.[11] Infusion through chronic or semi-chronic flexible catheters has been reported over a period of days.[12,13]

As was discussed in the Starr *et al.* paper, intraoperative brain shift also occurs, and it occurs quickly.[7] While the resolution of brain shift occurs slowly over a post-operative period, intraoperative brain shift occurs quickly and may pose greater challenges for a catheter in place for prolonged infusions. Figure 10 details the progression of brain shift and can be informative in this case. The time course between the first and second picture is ultimately what is unknown and has the potential to affect a rigid catheter in the brain for an extended period of time. Using a non-rigid device, such as the electrode utilized in DBS procedures,[14] would allow for better adaptation and movement with respect to the shifting of the brain and structures. However, it may be harder to initially implant and position a non-rigid device in the brain.

Conversely, a rigid device has more potential to damage the brain, as it does not allow for liberal brain movement caused by imminent shift. The brain tissue may be forced to move around the rigid device rather than with it, possibly causing lacerations or bruising. It may be pertinent to investigate materials that combine the positive aspects of both the rigid and the non-rigid catheter, such as materials that have the capabilities to transition from rigid to non-rigid as the result of a temperature change.[8] More research is needed to determine an appropriate delivery device: one that will improve efficacy while also ensuring patient safety. The measurements made in this study are also important, because they begin to elucidate the modes of electrode bending, which are important for dissecting the underlying mechanisms that cause electrode shift.

While it may be possible to minimize brain shift, it may not be plausible to completely eliminate it. Therefore, it would be advantageous to model the electrode–brain interactions so that the electrode movement could be predicted and accommodated for in terms of programming. A number of studies have attempted to address similar issues with microscale electrodes,[15,16] and similar approaches could be used to model the mechanical effects of electrode properties and brain shift on the eventual placement of the device within its intended target.

CONCLUSION

The most significant finding of the current study is the confirmation of previously published reports of rostral DBS electrode shift when measured at delayed follow-up. In the current report we expand upon this concept by presenting and comparing two methods of quantification of electrode deformation and electrode tip retraction.

Method 1 (calculated method) utilizes a three-dimensional reconstruction obtained from a single delayed CT scan. Method 2 (measured method) is performed via fusion of immediate and delayed post-operative images. Both methods predicted significant rostral device shift. To the extent postoperative brain shift can be derived from a single, postoperative scan, workload in determining electrode rostral migration may be mitigated.

Given the asymmetric hysteresis of relatively rapid brain shift and prolonged return from the shifted position, further study is warranted to understand the time course of both arms of this dynamic process. Understanding the relationship of head position and implications of the proposed implementation of lengthy procedures utilizing rigid infusion devices in the setting of convection-enhanced delivery is crucial. Future work with real-time imaging, stress/strain, or impedance monitoring may give insight into the applied forces upon the brain during the perioperative and post-implant periods.

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