Turk Neurosurg, 2023

Original Investigation

Received: 07.09.2022
Accepted: 21.03.2023

DOI: 10.5137/1019-5149.JTN.42185-22.2

Published Online: 08.12.2023

Stereotactic Frame-Based Electrode Insertion: The Accuracy of Increasingly Oblique Insertion Angles

Zachary D. GILBERT[1], Austin M. TANG[1], Terrance PENG[1], Li DING[1], Emiliano TABARSI[1], Jonathan CAVALERI[1], Andrea LEONOR[1], Roberto Martin Del CAMPO-VERA[1], Arthur SHAO[1], Ryan CHUNG[1], Shivani SUNDARAM[1], Alexandra KAMMEN[1], Angad S. GOGIA[1], Charles Y. LIU[1,2], Spencer S. KELLIS[1,2], Brian LEE[1,2]

[1]University of Southern California, Keck School of Medicine of USC, Department of Neurological Surgery, Los Angeles, CA, United States
[2]USC Neurorestoration Center, Keck School of Medicine of USC, Los Angeles, CA, United States

Corresponding author: Zachary D. GILBERT ✉ zgilbert@usc.edu

ABSTRACT

AIM: To investigate the relationship between planned drill approach angle and angular deviation of the stereotactically placed intracranial electrode tips.

MATERIAL and METHODS: Stereotactic electrode implantation was performed in 13 patients with drug resistant epilepsy. A total of 136 electrodes were included in our analysis. Stereotactic targets were planned on pre-operative magnetic resonance imaging (MRI) scans and implantation was carried out using a Cosman-Roberts-Wells stereotactic frame with the Ad-Tech drill guide and electrodes. Post implant electrode angles in the axial, coronal, and sagittal planes were determined from post-operative computerized tomography (CT) scans and compared with planned angles using Bland-Altman plots and linear regression.

RESULTS: Qualitative assessment of correlation plots between planned and actual angles demonstrated a linear relationship for axial, coronal, and sagittal planes, with no overt angular deflection for any magnitude of the planned angle.

CONCLUSION: The accuracy of CRW frame-based electrode placement using the Ad-Tech drill guide and electrodes is not significantly affected by the magnitude of the planning angle. Based on our results, oblique electrode insertion is a safe and accurate procedure.

KEYWORDS: Oblique, Orthogonal, Stereotactic, Depth electrode, Cosman-Roberts-Wells

ABBREVIATIONS: SEEG: Stereotactic electroencephalography, **CT:** Computerized tomography, **MRI:** Magnetic resonance imaging, **CRW:** Cosman-Roberts-Wells, **SD:** Standard deviation, **EPLE:** Entry point localization error, **TPLE:** Target point localization error

INTRODUCTION

Stereotactic lead placement for stereotactic electroencephalography (SEEG) is a procedure first described in a 1962 publication by neurosurgeon Jean Talairach and neurologist Jean Bancaud. SEEG allowed for access to subcortical deep brain structures to identify and monitor epileptiform activity (24,29). There are several methods used for stereotactic electrode placement: frame-based (e.g., Leksell, Cosman-Roberts-Wells) (6,32), frameless (e.g., Nexframe) (19), and robotic (e.g., ROSA) (16,26). Stereotactic electrode

Zachary D. GILBERT : 0000-0003-4967-4383
Austin M. TANG : 0000-0002-0472-9005
Terrance PENG : 0000-0003-1661-1730
Li DING : 0000-0001-8565-430X
Emiliano TABARSI : 0000-0003-4221-9177
Jonathan CAVALERI : 0000-0001-6239-4461
Andrea LEONOR : 0000-0002-3216-6932
Roberto M. Del CAMPO-VERA : 0000-0001-9794-2894
Arthur SHAO : 0000-0003-4652-6326
Ryan CHUNG : 0000-0002-4732-9028
Shivani SUNDARAM : 0000-0003-2863-9204
Alexandra KAMMEN : 0000-0001-5490-2171
Angad S. GOGIA : 0000-0001-8193-1824
Charles Y. LIU : 0000-0001-6423-8577
Spencer S. KELLIS : 0000-0002-5158-1058
Brian LEE : 0000-0002-3592-8146

placement is increasingly shifting towards robotic assistance, but many centers still use frame-based techniques (15). These procedures can be performed perpendicular to the tangent plane of the cranial surface (i.e., orthogonal approach) or at a non-perpendicular angle (i.e., oblique approach) (Figure 1). Ideally, stereotactic procedures are performed with orthogonal insertions, as this approach is thought to be less prone to deflections caused by an angle between the drill and the skull surface (3,26). Historically, Talairach used the term "orthogonal" to refer to the relationship between the drill and the sagittal plane of the frame, and therefore the brain midline (25). However, in this study we use orthogonal to describe the angle between the drill and the cranial surface.

This study analyzes drill angular deflection in the axial, sagittal, and coronal planes after electrode insertion (Figure 2). While placement errors have the potential to cause complications, stereotactic procedures are well tolerated and demonstrate low morbidity rates, with vascular injury being of primary concern (9,10,22). Symptomatic intracerebral hemorrhage occurs in less than 1% of patients who undergo stereotactic electrode implantation (8,13,17,21,28). To maintain procedural safety, it is important to maximize the distance from cortical and intracortical vasculature while targeting the brain structures of interest. Not only is accuracy important in terms of safety, but precise electrode placement is critical to identifying epileptogenic activity through SEEG.

The insular cortex and surrounding structures are commonly involved in epilepsy. Insulo-opercular epilepsy is best targeted using an orthogonal approach as this allows sampling of both cortices with one lead (2). However, if the epileptic activity is primarily of insular origin, an oblique approach will provide a larger sample of the insula (2,5). Afif et al. originally demonstrated the safety of oblique approaches for sampling the insular cortex in 2008 (1). Oblique trajectories with the Leksell frame have since been used to access the insular cortex in several centers using frontal (12) and/or parietal (14,27) approaches. There is still concern as to whether deviations from an orthogonal approach significantly affects electrode angle placement. This study aims to further classify the relationship between oblique approaches and angular deflection of the electrode, specifically determining whether greater divergences from the orthogonal approach (e.g., more than 30 degrees) are associated with larger deflections in electrode insertion angle.

MATERIAL and METHODS

This study was approved by the University of Southern California IRB (ID: HS-22-00195) and was conducted in accordance with the principles embodied in the Declaration of Helsinki and local statutory requirements. All patients gave written informed consent prior to participation.

Study Design

To assess electrode angular deflection, the planned electrode implant angle was compared with the final operative implant angle. The planned and final implant angles of the electrode insertion in the axial, coronal, and sagittal planes were compared to evaluate for drill deflection at the point of cranial entry. Specifically, these angles were defined as the divergence of the planned and final electrode paths from the normal line, which is the line perpendicular to the tangent line at the point of tangency (i.e., the electrode insertion point). This concept is illustrated in Figure 3, in which θ and ϕ represent the planned and final lead angles, respectively. For any given electrode, both planned and operative lead angles could be effectively visualized and measured in only two planes. As an example, an electrode path may be easily visualized on an "X and Y" axis in the axial and coronal plane but appear in the "Z" axis in the sagittal plane. The Medtronic StealthStation S7 Neuronavigation workstation (Medtronic, Minneapolis, MN) was used to view all relevant images and collect stereotactic coordinates.

Participants

A total of 13 consecutive patients underwent stereotactic electrode implantation for SEEG epilepsy monitoring in 2019, for a total of 136 electrode target coordinates. All patients gave informed consent prior to participation (IRB ID: HS-22-00195), and received preoperative magnetic resonance imaging (MRI) within 2 weeks before surgery which was used to plan the placement of each electrode. Computerized tomography (CT) imaging was performed after placement of the stereotactic frame and used for frame registration. Intraoperative 3D fluoroscopy was used after lead implantation to confirm final electrode locations. All patients were recruited from the hospital where the procedures were performed.

Stereotactic Surgical Planning

All patients underwent preoperative thin-slice MRI (T1 with contrast, T2 and T2 fluid-attenuated inversion recovery without contrast, 1 mm slice thickness) as well as CT imaging without

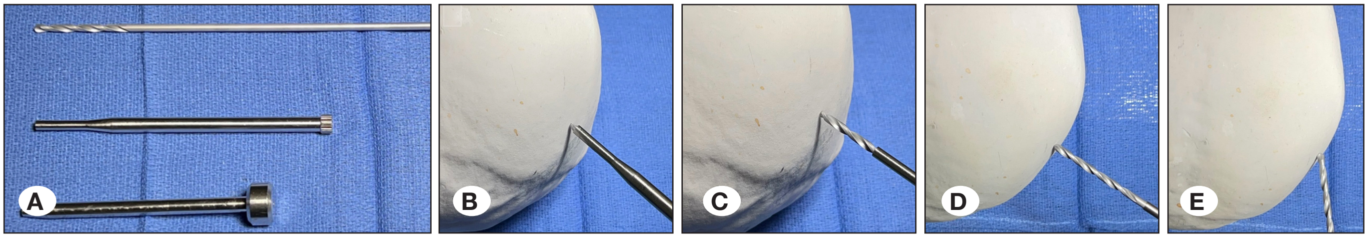

Figure 1: A) Commonly used drill (top), Cosman-Roberts-Wells (CRW) drill guide tube (middle), and Ad-tech drill sleeve guide (bottom) for insertion of Stereotactic electroencephalography (SEEG) electrodes. **B)** Drill minimally protruding beyond guide tube resulting in little drill flex. **C)** Drill protroding beyond the guide tube resulting in more drill flex. **D)** Ideal orthogonal approach angle. **E)** Oblique drill approach angle.

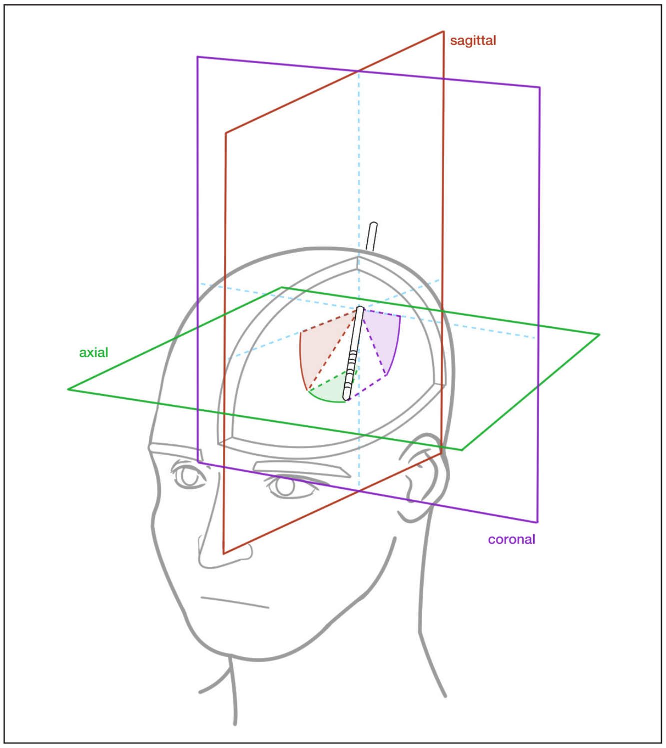

Figure 2: Depiction of a depth electrode with its corresponding angular measurements in the sagittal, axial, and coronal planes.

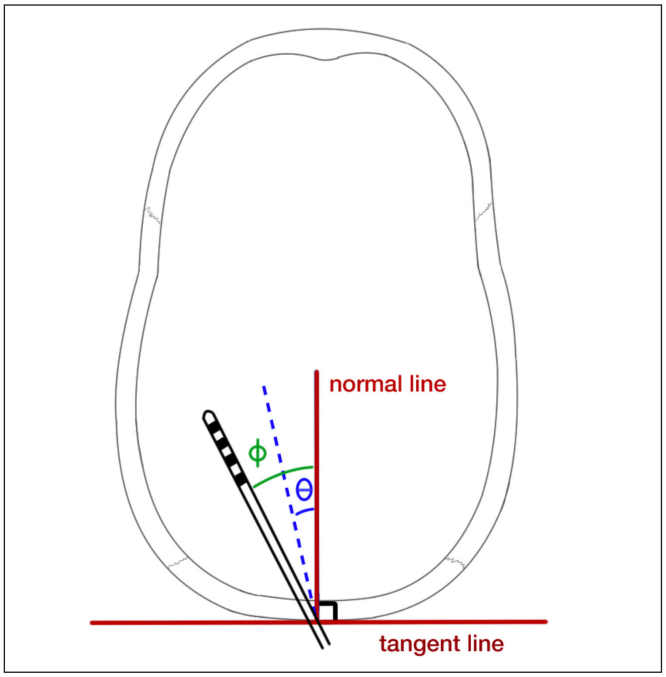

Figure 3: Oblique electrode implantation viewed from the axial plane of the skull. An orthogonal electrode would ideally be inserted directly along the normal line, while the oblique electrode (blue dashed line) is implanted at an angle from the normal line. θ and ϕ represent the hypothetical planned and operative lead angles, respectively. In this example, the electrode deviated laterally from its planned angle of trajectory.

contrast following anesthesia induction and stereotactic frame placement. The Cosman-Roberts-Wells (CRW) frame (Integra LifeSciences Corp., Burlington, Massachusetts) was used for all the patients. CT imaging was performed with the appropriate localizer device for each frame. The Medtronic StealthStation S7 Neuronavigation workstation with Cranial 3.0 software (Medtronic, Fridley, MN) was used to create merged scans of preoperative MRI and postop CT images, which allowed us to identify stereotactic coordinates for each electrode. All targets were reviewed for consistency in all MRI sequences.

Electrode Placement and Intraoperative Imaging

2.4 mm holes in the skull were made by a powered drill and Ad-Tech (Ad-Tech Medical Instrumentation Corp, Oak Creek, WI USA) anchor bolts were used for SEEG lead implantation. Using the included stiffening stylet, each electrode was introduced through the anchor bolt until reaching target depth. Approach of the surgical target was facilitated with 2D visualization of the lead using C-Arm fluoroscopy. After all leads were implanted, intraoperative 3D fluoroscopy with the Medtronic (Medtronic, Dublin, Ireland) O2 O-arm was performed for 3D assessment of electrode placement accuracy.

Data Collection

Pre-operative planned angles were determined for each electrode in the axial, coronal, and sagittal planes. Post implant electrode angles in the axial, coronal, and sagittal planes were determined from post-operative CT scans.

Analysis

Mean and standard deviation were reported for continuous variables. Linear regression was used for association between planned angle and actual angle in each plane. Mixed effects modeling was used to account for electrodes collected from the same patient. Bland-Altman plots were generated to explore the agreement between planned and actual angle within each plane. All analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, North Carolina).

RESULTS

Data was collected from a total of 13 patients and 136 electrodes. A total of 92 electrode angles were measured in the axial plane, yielding a mean planned angle of 9.80 degrees with a standard deviation (SD) of 8.69 degrees, and a mean actual angle of 10.95 degrees (SD=9.88). 134 electrode angles were measured in the coronal plane, with a mean planned angle of 13.18 (SD=9.07) and a mean actual angle of 13.63 degrees (SD=10.34). 47 electrode angles were measured in the sagittal plane, with a mean planned angle of 11.21 degrees (SD=8.50) and a mean actual angle of 11.48 degrees (SD=9.35).

Qualitative assessment of correlation plots between the planned and actual angles demonstrated a linear relationship for axial, coronal, and sagittal planes (Figure 4). No deflection point was found wherein increased angular difference between planned and final electrode placement was noted.

DISCUSSION

In this study, we compared planned stereotactic electrode insertion angle with final operative insertion angle. We found that greater electrode insertion angles are not associated with greater angular deflection from the planned operative path. When the drill is oriented directly orthogonal to the skull, the tip of the drill will engage into the bone and center the spinning drill as it goes through the bone. However, if the drill approaches the bone at an angle, the center of the drill no longer engages the bone first, instead, the outer edges of the drill may "skive" along the bone and deflect and flex the drill bit. To counteract this, the drill bit is guided by a drill guide tube that resists the flexing of the drill bit as it is deflected on the surface of the skull (Figure 1). Depending upon the position of the frame and arc on the head and the region of the brain to be implanted, the amount of the drill protruding from the guide tube may vary. This is a limitation to using a stereotactic frame with a fixed arc center radius for placement of electrodes in the brain. Robotic approaches allow for approximation of the drill guide tube right up to the scalp to minimize the amount of exposed drill and reduce drill flexion.

Electrode placement errors can be defined as deviation from the desired insertion point on the skull (entry point localization error, EPLE) and departure from the intended final intracortical location (target point localization error, TPLE) (4,7,30). Cardinale et al. first analyzed the effect of a variety of explanatory variables on electrode placement in 2013 and determined that factors such as drill bending and wider drill angles increased EPLE and TPLE (7). Oblique electrode trajectories were found to be less accurate than orthogonal trajectories using a stereotactic robot in a human cadaver study (18). Iordanou et al. found that robotically inserting electrodes at higher oblique angles led to increases in TPLE, and recommended that greater oblique angles, particularly over 30 degrees, should be avoided if possible (16). However, in 2020 Rollo et al. challenged the view that oblique angles should be avoided. Using robotically inserted electrodes, they found that greater oblique angles did not cause clinically significant increases in TPLE, as the vast majority were within 3 mm of their planned destination (26). Ollivier et al. found no significant difference in EPLE and TPLE between orthogonal and oblique approaches with frameless robot assisted SEEG placement (23). Overall in the literature of insular cortex SEEG placement, TPLE differences between orthogonal and oblique approaches range from 0.5 to 1.5 mm (11).

Unlike manual CRW frame insertion, robotic electrode insertion brings the drill sleeve guide directly into contact with the patient's skull. This reduction in distance between the skull and drill sleeve should lead to less variability in insertion angle. Considering our extensive use of CRW frame insertion, we expected to observe a rise in angular deflection with increasing electrode approach angles in a pattern even greater than would be predicted from Iordanou's robotic procedure study (16). However, while there appeared to be more outliers in final operative angle at higher approach angles, qualitative assessment of measured versus planned angles did not show overt angular deflection for any magnitude of oblique insertion (Figure 4). Our results are therefore more in line with those of the robotic frameless studies by Ollivier et al. (23), and Rollo et al. (26), as outlined above. The lack of an increase in angular deflection calls into question the practice of favoring orthogonal over oblique electrode insertion.

Orthogonal electrode insertion is effective, but in certain circumstances oblique angles provide the opportunity to reduce the total number of electrodes used. This feat is accomplished by aligning multiple neural target zones along the electrode trajectory in a manner that could not be accomplished via an orthogonal approach (3). These novel trajectories provide more diverse tissue sampling in epilepsy and offer additional routes to avoid vasculature. Implanting fewer electrodes via the oblique approach would reduce surgically related complications such as hemorrhage and infection (13,31). Therefore, proving the safety of oblique electrode insertions has the potential to improve both treatment efficacy and safety across various stereotactic neurosurgical procedures.

While certain centers are transitioning to frameless robotic electrode implantation, many groups continue to employ the frame-based approach due to the lower cost of the procedure (15). This study supports the safety of the oblique approach for SEEG implantation with the CRW frame. Centers currently using the CRW frame may use the oblique approach to reduce the number of electrodes used, achieve more diverse tissue sampling, and decrease surgical complications.

One drawback of oblique trajectories compared to orthogonal is the greater distance the electrode must travel to reach its destination. Traversing a larger amount of neural tissue causes more damage. It is also possible that, in certain scenarios, greater insertion depth with oblique trajectories could lead to a higher TPLE when compared with an orthogonal approach that reaches the target at a shorter distance (18). A recent study of 220 SEEG electrodes implanted in the insular cortex of 27 patients with both frame-based and robotic procedures found that there was no decrease in the accuracy of electrode placement when comparing the orthogonal approach to oblique approaches that required longer trajectories (20). However, as the difference in trajectory distance between oblique and orthogonal approaches will vary based on the target, further studies may be required.

A limitation of this study is the amount of the drill protruding beyond the end of the guide tube or drill sleeve guide is variable for each electrode location. The CRW frame has a fixed arc center radius of 160 mm and depending on how the patient is positioned in the frame, the location of the head that is being accessed, and the length of the guide tube, the amount of drill extending beyond the guide tube will vary for each electrode. In our patients, we consistently used the Ad-tech drill sleeve guide which features a fixed length as per standard protocol. While the amount of exposed drill beyond the drill sleeve guide varied, it was not a variable that we were able to measure during postoperative data collection and analysis. The effects of the amount of exposed drill beyond the guide tube would be the subject of a potential future study.

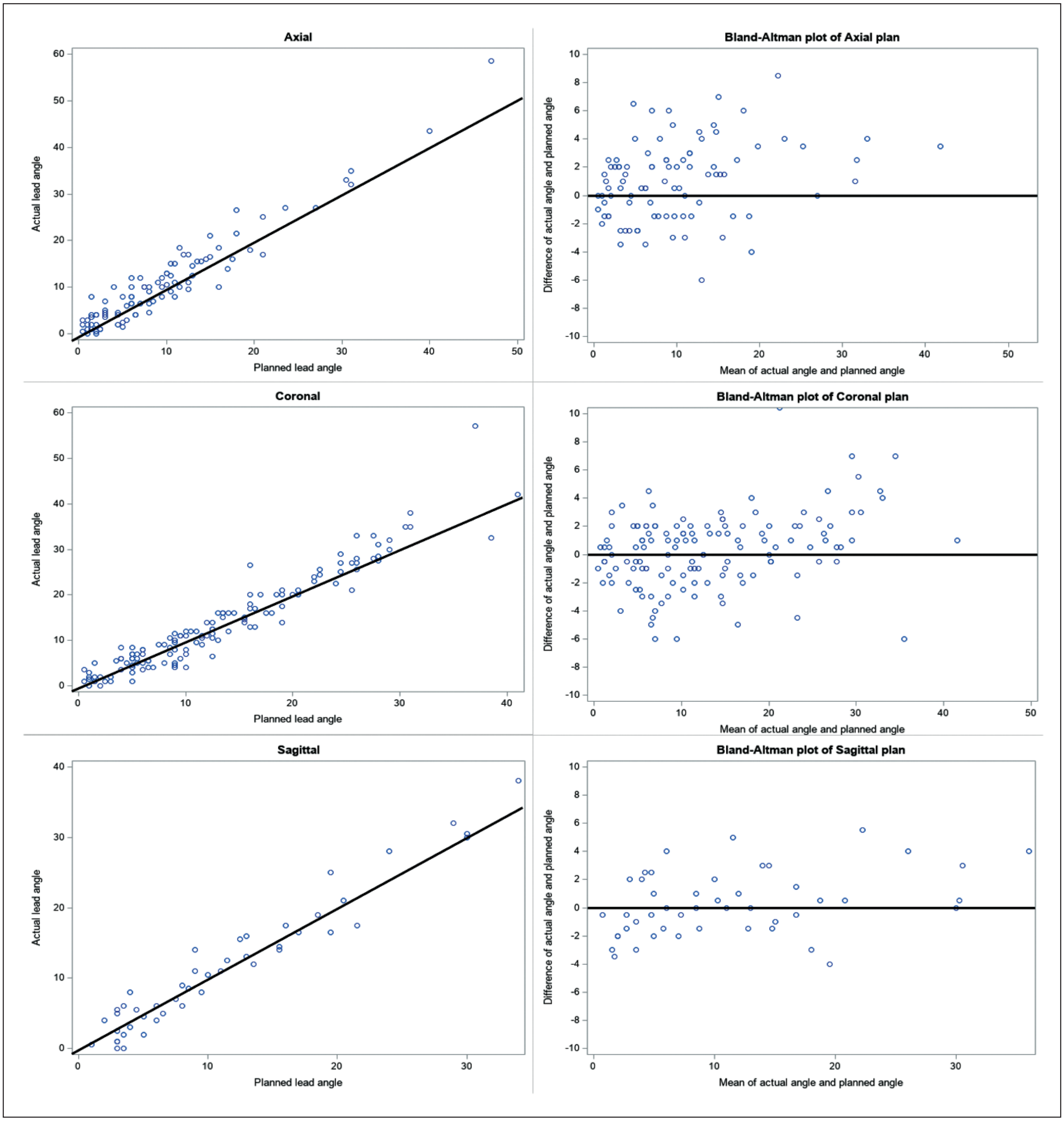

Figure 4: The left column graphs display the relationship between the actual lead angle (y-axis) and the planned lead angle (x-axis) in the axial, coronal, and sagittal planes. The linear relationship between the planned and actual lead angles can clearly be seen in these graphs (black line y = x), and this relationship was maintained even at greater angles (e.g., more than 30 degrees) aside from a few outliers. The Bland-Altman plots (right column) further illustrate this point, as the data points are fairly evenly spread (black line y = 0) around an angle difference of zero between the planned and actual lead angles.

CONCLUSION

We aimed to determine if oblique approaches to electrode insertion are associated with greater deflections in electrode insertion angle, and if this association is magnified with increasing approach angles. The results indicate that wider oblique angles are not associated with greater deflections in electrode insertion angle. However, most neurosurgeons will still likely try to plan their trajectories as orthogonal to the skull as possible. One variable which could have increased the error of the electrode trajectory but was not examined in this paper is the amount of exposed drill from the drill guide tube. As more centers move towards implanting SEEG electrodes using robotic systems which allow for close placement of the drill guide tube near the scalp, this issue is likely to be even less prominent. Even without correcting for this factor, our findings demonstrate the safety and accuracy of oblique electrode insertion at increasing angles and validate its use in clinical practice.

ACKNOWLEDGEMENTS / FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

AUTHORSHIP CONTRIBUTION

Study conception and design: BL, TP
Data collection: TP
Analysis and interpretation of results: LD, ZDG
Draft manuscript preparation: ZDG, AMT, LD
Critical revision of the article: BL, SSK, CYL, ASG, AK, SS, RC, AS, RMDCV, AL, JC, ET
Other (study supervision, fundings, materials, etc...): BL, CYL, SSK
All authors (ZDG, AMT, TP, LD, ET, JC, AL, RMDCV, AS, RC, SS, AK, ASG, CYL, SSK, BL) reviewed the results and approved the final version of the manuscript.

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