Utilization of Novel High-Resolution, MRI-Based Vascular Imaging Modality for Preoperative Stereoelectroencephalography Planning in Children: A Technical Note

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Keywords

Stereoelectroencephalography · Vessel imaging · Vascular imaging · Magnetic resonance imaging · Intracranial hemorrhage

Abstract

Introduction: Stereoelectroencephalography (SEEG) is a powerful intracranial diagnostic tool that requires accurate imaging for proper electrode trajectory planning to ensure efficacy and maximize patient safety. Computed tomography (CT) angiography and digital subtraction angiography are commonly used, but recent developments in magnetic resonance angiography allow for high-resolution vascular visualization without added risks of radiation. We report on the accuracy of electrode placement under robotic assistance planning utilizing a novel high-resolution magnetic resonance imaging (MRI)-based imaging modality. **Methods:** Sixteen pediatric patients between February 2014 and October 2017 underwent SEEG exploration for epileptogen-

ic zone localization. A gadolinium-enhanced 3D T1-weighted spoiled gradient recalled echo sequence with minimum echo time and repetition time was applied for background parenchymal suppression and vascular enhancement. Electrode placement accuracy was determined by analyzing postoperative CT scans laid over preoperative virtual electrode trajectory paths. Entry point, target point, and closest vessel intersection were measured. **Results:** For any intersection along the trajectory path, 57 intersected vessels were measured. The mean diameter of an intersected vessel was 1.0343 ± 0.1721 mm, and 21.05% of intersections involved superficial vessels. There were 157 overall intersection + near-miss events. The mean diameter for an involved vessel was 1.0236 ± 0.0928 mm, and superficial vessels were involved in 20.13%. Looking only at final electrode target, 3 intersection events were observed. The mean diameter of an intersected vessel was 1.0125 ± 0.2227 mm. For intersection

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+ near-miss events, 24 were measured. An involved vessel's mean diameter was 1.1028 ± 0.2634 mm. For non-entry point intersections, 45 intersected vessels were measured. The mean diameter for intersected vessels was 0.9526 ± 0.0689 mm. For non-entry point intersections + near misses, 126 events were observed. The mean diameter for involved vessels was 0.9826 ± 0.1008 mm. **Conclusion:** We believe this novel sequence allows better identification of superficial and deeper subcortical vessels compared to conventional T1-weighted gadolinium-enhanced MRI.

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Introduction

Stereoelectroencephalography (SEEG) is an intracranial diagnostic tool that utilizes depth electrodes to identify the epileptogenic zone in drug-resistant focal epilepsies when noninvasive measures are inconclusive [1]. A valuable addition to a neurosurgeon's armamentarium, SEEG is complementary to traditional intracranial subdural grid and strip electrodes due to the ability to record in 3D space from deep cortical structures, investigate both hemispheres, and avoid a craniotomy. Developed in the 1950s by Talairach and Bancaud in France, SEEG originally utilized 2D angiography for planning and was frame based [2, 3]. Though it was initially thought to be overly invasive, initial adopters helped establish SEEG's safety and efficiency [4, 5]. Munari et al. [6] published one of the earliest explorations of SEEG methodology. Olivier et al. [7] demonstrated SEEG's usefulness for cases of bitemporal epileptogenic zones. These pioneers paved the way for acceptance and opened the door for greater innovation.

Current SEEG technologies, including frameless and robotic guidance systems, have also improved the precision of electrode implantation, decreased complications, and reduced operative times [8, 9]. These innovations have led to increased popularity of SEEG, bolstered by its robust safety profile and established clinical efficacy [10, 11]. Minimally invasive intracranial procedures like SEEG, however, still depend heavily on the accuracy of preoperative imaging modalities for planning and image guidance. Even a robot-assisted SEEG platform requires imaging faithful to individual patient anatomy for safe trajectory planning. Intracranial hemorrhage following electrode placement is responsible for significant morbidity and mortality and occurs at a rate of 1–5% [12]. Avoiding this complication is particularly important for pediatric patients due to the risk to neurological development [13–15].

Proper depth electrode trajectory planning is critical to avoid intracranial hemorrhage and generally involves keeping a minimum safe distance from the cerebral vasculature, sulci, ventricles, and other nontargeted neurocritical structures [16]. Thus, utilization of some type of high-fidelity vessel imaging is the standard of care for SEEG trajectory planning [17–20]. However, there is no established consensus regarding the vessel imaging modality of choice for this purpose. Some centers use digital subtraction angiography (DSA) or computed tomography angiography (CTA), although an alternative would be ideal due to the cumulative X-ray exposure in a child. To minimize these risks, other magnetic resonance imaging (MRI) sequences, such as susceptibility-weighted imaging (SWI) [12], 3D [21] and 4D [22] time of flight magnetic resonance angiography, and contrast-enhanced magnetic resonance angiography may have increased vessel visualization sensitivity.

Specifically, recent studies have shown that contrast-enhanced 3D volumetric spoiled gradient recalled echo (SPGR) sequences with minimum repetition times (TR) and echo times (TE) accentuated visualization of vasculature, especially of smaller vessels compared with “standard clinical” SPGR parameters [23, 24]. Here, we report our series of pediatric SEEG with robotic assistance planned utilizing this novel contrast-enhanced, MRI-based vessel imaging modality and describe its vessel visualization and impact on SEEG trajectory planning.

Methods

From February 2016 to October 2017, 16 pediatric patients underwent robotic stereotactic assistance (ROSA) SEEG at our treatment center for localization of epileptogenic zone for treatment of medically refractory epilepsies of varying etiologies (Table 1). All patients were reviewed by a multidisciplinary epilepsy review board for SEEG consideration and approval. This study was approved by the Stanford University Institutional Review Board.

For electrode trajectory planning, all patients' cranial vaults were imaged with volumetric MRI to determine cortical and subcortical anatomy and vasculature. We utilized 3D T1-weighted gadolinium-enhanced (T1-Gd) SPGR sequences with minimum TE and TR. The use of minimum TE and TR accentuates visualization of the vasculature by providing more T1 weighting and sharper appearance of small vessels for vascular enhancement while suppressing the background brain parenchyma [23, 24] (Fig. 1). Image parameters for this sequence were as follows: TR 4 ms, TE 1 ms, slice thickness 1 mm, slice spacing 0.5 mm, matrix $416 \text{ mm} \times 416 \text{ mm}$, field of view 240–260 mm, inversion time (performed for fat suppression) 12.6 ms, and flip angle 15° , with a scan time of approximately 5 min and 45 s. Volumetric CT scans were also obtained to register superficial facial anatomy. Both MRI and CT scans were loaded into native ROSA planning software which facilitates image fusion and electrode trajectory planning. The neu-

Table 1. Vessel intersections

Vessel intersections	Total	Target	Total w/o entry ^a
Vessel intersections, total	57	3	45
Vessel intersections, mean per patient	3.5625	0.1875	2.8125
Vessel intersections, rate per electrode	0.3359	0.0148	0.2686
Intersection depth (superficial/total), %	21.05	0	0
Mean diameter of intersected vessel, mm	1.03±0.17	1.01±0.22	0.95±0.07
Vessel intersections + near miss, total	157	24	126
Vessel intersections + near miss, mean per patient	9.625	1.5	7.875
Vessel intersections + near miss, rate per electrode	0.9104	0.1364	0.7557
Intersection + near miss depth (superficial/total), %	20.13	0	0
Mean diameter of intersections + near misses, mm	1.02±0.09	1.10±0.26	0.98±0.10

^a Vessel intersections at target point and any point along the electrode trajectory.

rosurgical team chose optimal trajectories that maximize deep cortical and subcortical sampling within selected regions of interest. Within the ROSA planning software, virtual electrodes diameters were set to 4 mm in the cross-trajectory view to avoid collision. A set of volumetric noncontrast 3D CT scans were performed post-operatively to ensure electrode placement accuracy and monitor for complications (i.e., intracranial hemorrhage) (Fig. 2).

A postoperative CT scan was retrospectively analyzed to confirm final electrode placement. Actual electrode trajectories were captured by tracking electrodes on the postoperative CT scan from the entry point up to the target point, generating a corresponding virtual electrode. This method allowed accurate representation of the postoperative electrode placement as suggested by Barros et al. [12]. Electrode trajectory analysis utilized the merged preoperative MRI and postoperative CT scan to detect vessel intersections with the overlaid virtual electrodes. Through plane by plane axial slice reconstruction of the brain, the distances between the virtual electrode and the closest cerebral vessels were measured. For every electrode, 3 parameters were assessed: entry point, target point, and closest vessel intersection (Fig. 3). The entry point was defined as the point of entry of electrode at the cortical surface. The target point was defined as the final position of the electrode. The closest intersection was defined by the point along the virtual electrode path where the electrode is closest to or intersects any vessel. Each electrode had at least 1 value for each parameter and may have more if there are multiple vessel intersections. In addition to the distance to the closest vessel at these 3 points, the vessel diameter and depth from the cortical surface were also recorded. “Surface” vessels are categorized as those on the brain surface, and “deep” vessels are those within the parenchyma. A vessel intersection occurred when the virtual electrode directly crossed or touched a cerebral vessel. Additionally, we set a threshold of ≤ 1.5 mm as an intersection “near miss.” The value of 1.5 mm was determined due to the 0.86- to 1.1-mm diameters of the physical electrode utilized (Epilepsy LTM depth electrodes, Adtech®). Akin to Barros et al. [12], we calculated the rates for both “hit” and “hit + near-miss” intersections for total and mean electrodes per patient, rate per electrode, intersection depth, and mean diameter. With the same postprocedure scans, these rates were also calculated exclusively looking at entry and target intersections.

Fig. 1. 3D visualization of planning MRI and electrodes. 3D visualization of planning MRI with vessel imaging and superimposed electrode placement from postoperative CT scan. **a** Lateral view of the skull and electrode placement from CT scan. **b** Axial view of intracranial vasculature (red) and cerebrospinal fluid spaces (blue) from MRI with superimposed electrode position from postoperative CT scan. **c** Sagittal view of intracranial vasculature only (red) with superimposed electrodes (green). **d** Oblique view of intracranial vasculature (white) with superimposed electrodes (green).

Fig. 2. MRI vessel imaging with trajectory planning. Specific 3D T1-weighted, contrast-enhanced SPGR images with minimum TE and TR images with superimposed trajectory plans and final electrode positions. **a** Axial slice of vessel imaging with superimposed trajectory plans. **b** Axial slice of vessel imaging with superimposed trajectory plans and final electrode positions from postoperative CT. **c, d** Coronal and sagittal slices, respectively, of vessel imaging with superimposed trajectory plans.

Results

Electrode vessel intersection or near-miss events are reported in Table 1. In terms of overall intersections (i.e., intersections at entry, target, and any point along the electrode trajectory), a total of 57 events were observed (3.5625 events/10.875 electrodes per patient). For this category, 21.05% of intersections were with superficial vessels. The mean diameter of the intersected vessels was 1.03 ± 0.17 mm. For overall intersection + near miss, 157 events were observed (9.625 per patient). 20.13% of intersections and near misses were with superficial vessels. The mean diameter of an involved vessel was 1.02 ± 0.09 mm.

At the final electrode target points, a total of 3 intersection events were noted (0.1875 per patient). The mean diameter of intersected vessels was 1.01 ± 0.22 mm. For intersection + near-miss events at target point, there were a total of 24 events (1.5 per patient). The mean diameter for intersected or near-missed vessel was 1.10 ± 0.26 mm.

Fig. 3. MRI vessel imaging with measurements. Demonstrative figures of specific vascular measurements of superimposed final electrode positions. **a** Axial slice of entry point position of electrode at the cortical surface and distance to the nearest vessel. **b** Axial slice of electrode-vessel intersection with direct crossing of the vessel along the electrode trajectory. **c** Axial slice of electrode-vessel intersection with touching of the vessel along the electrode trajectory. **d** Axial slice of electrode position at target depth and distance to the nearest electrode. **e** Axial slice of electrode position at target depth with “near miss” of vessel with distance to the nearest electrode of <1.5 mm.

In non-entry point observations (target + closest), a total of 45 intersections were found (2.81 per patient). Since entry point data were excluded, these were all intersections with deep vessels. The mean diameter of intersected vessels was 0.95 ± 0.07 mm. A total of 126 intersection and near-miss events was observed (7.875 per patient). The mean diameter for intersected or near-missed vessels was 0.98 ± 0.10 mm. No intracranial hemorrhage was detected on postoperative CT scans obtained in all 16 patients.

Discussion

Achieving optimal 3D electrophysiological characterization of epileptogenic zones via SEEG to enable surgical resection or treatment relies heavily on the accuracy and density of electrode trajectory planning. However, direct trajectories to deeper structures sampled in SEEG are often surrounded by extensive vasculature. Avoidance of these vessels during electrode placement is critical for minimizing intracranial hemorrhage. While overall SEEG complication rates for intracranial hemorrhage are 1%, the sequelae can be wide-ranging from asymptomatic to permanent neurologic damage [15, 25, 26].

While advancements in SEEG, such as robot assistance, have aided in technical precision, electrode trajectory planning still relies on clear imaging to determine the most avascular trajectories. An older but still utilized technique for visualizing vessels in SEEG is cerebral angiography for DSA [18]. However, it carries a variety of risks from arterial catheter threading to the administration of contrast media to the utilization of bi-plane X-ray fluoroscopy. An analysis of 2,899 cerebral angiograms found a 1.3% overall neurological complication rate, indicating a low but additional risk [17]. CTA is a less invasive option, but it may lack the accuracy of cerebral angiogram when used in isolation [18, 27]. A number of centers use CTA in conjunction to MR angiography to generate superior images. Cardinale et al. [20] report the use of cone beam CT-generated 3D DSA with 3D fast-field echo T1-weighted MRI for SEEG planning. Out of 191 3D DSA images, only 4 were judged insufficient for SEEG. Mirzayan et al. [28] report the use of intraoperative cerebral C-arm CT angiogram to supplement contrast-enhanced MRI. In their prospective analysis, none of the 146 electrode trajectories placed in this fashion led to intracranial hemorrhage.

T1-Gd MRI is the more popular vessel visualization alternative that also avoids the need for X-ray radiation, which is of particular concern in the pediatric population [29]. The radiation exposure to a child from CTA compared to a stereo CT at our institution is about 80–100 mGy-cm versus 200 mGy-cm, respectively. Still, recent studies demonstrate that T1-Gd MRI may lack high anatomic vascular resolution when used in isolation. Mirzayan et al. [28] report an 18% change in MRI-based trajectory plans when CTA images were taken into account. Gilard et al. [30] also report significantly more vessels visualized with multidetector row CTA compared to T1-Gd MRI (62.3 vs. 9.4%). This has led to integration of other MRI sequences, such as time of flight or SWI, to

improve visualization. Here, we present a novel MRI sequence which achieves effective vessel resolution by utilizing a SPGR sequence with minimum TR and TE and background fat suppression to enhance vascular delineation.

Compared to the T1-Gd and SWI data from Barros et al. [12], we were able to visualize much smaller intersected vessels with our imaging modality compared to both T1-Gd and SWI (diameters 1.03 ± 0.17 vs. 2.01 ± 0.52 mm [T1-Gd] or 1.49 ± 0.46 mm [SWI]). Though our visualized intersected vessels were smaller, we still observed fewer intersections per patient compared to SWI (3.56 vs. 4.85 [SWI]). We were also able to observe a lower rate of entry point vessel interactions (i.e., dural and cortical vessels) (21.05 vs. 76.9% [T1-Gd] and 39.7% [SWI]) which are more dangerous for hemorrhage [12].

Though there were 57 total vessel intersections, our patient cohort presented with no postoperative hemorrhages or other complications. Given the discrepancy between vessel intersections and lack of hemorrhagic complications, some may question the utility and necessity of such high-resolution vessel imaging for SEEG planning. Barros et al. [12] explored similar issues for SWI, concluding that SWI could be oversensitive and, thus, may detrimentally limit sampling trajectories. This also suggests that intraparenchymal vessels may be somewhat mobile and/or not prone to injury with passage of electrodes. While there may be a vessel size tolerance for electrode intersection, we believe utilization of the most sensitive imaging modalities is still preferred. Though arterial bleeds usually follow with rapid-onset neurological sequelae, venous bleeds may present more subacutely with insidious edema and subcortical hemorrhage [23]. Greater awareness of possible vessel intersection may be advantageous in the face of delayed complications. We tolerate a registration error of 2 mm or less prior to proceeding with electrode placement, and the mean error achieved with robotic-assisted placement of depth electrodes at our institution is generally less than 2 mm [31]. We generally strive to avoid all cortical vessel intersections and aim to avoid any deeper vessels with diameters >1 mm. Each of the electrode trajectories are planned by the attending physician and double and triple checked by the resident and fellow physician prior to the surgery. It has also been theorized that the vessels move away from the depth electrodes upon insertion, which may also contribute to the low incidence of postoperative hemorrhage.

Conclusion

This case series reports the use of a novel, high-resolution, contrast-enhanced, vascular MRI sequence for SEEG electrode trajectory planning. Our data highlights the noninferior ability of this unique imaging modality to identify and avoid superficial and deep vessels compared to conventional MRI vascular imaging techniques. This novel technique also contributes significantly to our low (0%) intracranial hemorrhage rate in this cohort. This novel vessel imaging modality, which foregoes the need for radiation, may be a valuable addition to SEEG trajectory planning, especially in the pediatric population.

Statement of Ethics

This study was approved by the Stanford University Institutional Review Board.

Disclosure Statement

The authors of this article have no financial interest in the subject under discussion. No funding was provided for this study.

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