Impact of Trajectory Planning With Susceptibility-Weighted Imaging for Intracranial Electrode Implantation

**BACKGROUND:** While T1-weighted gadolinium-enhanced (T1-Gd) magnetic resonance imaging (MRI) is the standard imaging sequence for trajectory planning of stereotactic procedures, including deep brain stimulation, stereoelectroencephalography, and laser interstitial thermal therapy, susceptibility-weighted imaging (SWI) has been reported to demonstrate increased sensitivity for the visualization of microvasculature.

**OBJECTIVE:** To determine the impact of SWI visualization on trajectory planning for electrode implantation and evaluate the relationship between the rate of vessel-electrode intersections and intracerebral hemorrhage (ICH).

**METHODS:** We conducted a retrospective study of 13 patients who underwent stereoelectroencephalography and laser interstitial thermal therapy placement between 2014 and 2015, using their preoperative T1-Gd and SWI scans, and postoperative MRI scans to determine the rate of vessel-electrode intersections seen on the 2 imaging modalities, the mean diameter and depth of the vessels identified, and the rate of ICH after implantation.

**RESULTS:** Among 13 patients, 106 electrodes were implanted. Sixty-three unique vessel-electrode intersections were identified on SWI with a mean of 4.85 intersections per patient. There were 13 intersections seen on T1-Gd with a mean of 1 intersection per patient. The intersected vessels visualized on SWI had a diameter of $1.49 \pm 0.46$ mm and those on T1-Gd were $2.01 \pm 0.52$ mm. There was no clear ICH observed in this series.

**CONCLUSION:** SWI allows for improved visualization of the smaller, deep vessels, whereas T1-Gd adequately detects superficial, larger vessels. Despite the larger number of vessel-electrode intersections seen on SWI, no clear evidence of ICH was identified. Increased detection of deep vasculature does not appear to significantly benefit trajectory planning for stereotactic intracranial procedures and may limit the number of trajectories perceived to be safe.

**KEY WORDS:** Electrodes, Epilepsy, Magnetic resonance imaging, Stereotactic techniques

**ABBREVIATIONS:** CT, computed tomography; DBS, deep brain stimulation; FLAIR, fluid-attenuated inversion recovery; ICH, intracerebral hemorrhage; IRB, institutional review board; LITT, laser interstitial thermal therapy; MRI, magnetic resonance imaging; sEEG, stereoelectroencephalography; STN, subthalamic nucleus; SWI, susceptibility-weighted imaging; T1-Gd, T1-weighted gadolinium-enhanced MRI; TOF, time of flight

Stereotactic intracranial procedures, such as deep brain stimulation (DBS), stereoelectroencephalography (sEEG), and laser interstitial thermal therapy (LITT), are increasingly used in the treatment of neurological disorders. Along with infection and lead malposition, intracerebral hemorrhage (ICH) remains a common surgical complication, occurring at a rate of 1% to 5%, and is the primary cause of mortality and severe morbidity.1 Trajectory planning and entry point selection have emphasized the need for avoidance of vessels, ventricles, and sulci to minimize the risk of hemorrhage and brain shift.2,3 Advanced magnetic resonance imaging (MRI) techniques have emerged in order to more accurately identify these structures.

Susceptibility-weighted imaging (SWI) has recently been introduced alongside traditional T1-weighted gadolinium-enhanced (T1-Gd) MRI for trajectory planning. T1-Gd is the standard imaging modality used for DBS,
sEEG, and LITT planning, but recent studies have highlighted the increased sensitivity of SWI over T1-Gd for the visualization of vessels, particularly the venous microvasculature.4-7

This study was performed to investigate the increased visualization of microvasculature seen in SWI and its effect on hemorrhagic complications in intracranial electrode implantation procedures, as compared to T1-Gd. We aim to clarify the clinical utility of SWI in trajectory planning with regard to the incidence of ICH.

METHODS

We conducted an Institutional Review Board (IRB)-approved retrospective study consisting of a review of hospital charts and MRI of sEEG and LITT patients between 2014 and 2015. Patients were selected to be included in the study based on their procedure type and the availability of required imaging within the study criteria, as demonstrated by Figure 1. Given the retrospective nature of this study and the lack of any direct influence on patient care, it was deemed by our IRB that no patient consent would be required.

Thirteen patients undergoing sEEG or LITT procedures for epilepsy at a large university medical center were implanted with a total of 106 electrodes or probes. Preoperative MRI, including both T1-Gd and SWI, was obtained for all patients. All trajectories were planned based on the preoperative T1-Gd, on Waypoint Navigator stereotactic planning software (FHC, Bowdoin, Maine). In no patient was SWI used to plan the electrode or probe trajectory, but was studied independently of T1-Gd. Each patient also underwent 3-dimensional volumetric MRI postoperatively to document final electrode placement and to evaluate for the presence of postoperative hemorrhage.

The retrospective analysis was performed by first coregistering postoperative MR images with preoperatively acquired T1-Gd and SWI sequences within the Waypoint Navigator software package (FHC) as a means of establishing electrode trajectories for analysis. A trajectory was then overlaid upon the center of the hypointense tract seen on postoperative MR image, by carefully tracing its path from the entry point to the target structure. In doing so, we were able to accurately depict the postoperative location of the electrodes as demonstrated by Hyam et al8,9. Each of these trajectories was then analyzed on the coregistered preoperative SWI and T1-Gd image sequences.

The overlaid trajectories were depicted in a manner consistent with the diameter of the probe/electrode used for each given procedure (ie, 0.8 mm sEEG electrodes, 1.27 mm DBS electrodes, or 1.65 mm laser probe) to analyze intersections with vascular anatomy. Trajectories were examined using plane-of-probe reconstructions for the presence of direct intersections with or encounters within 1 mm of cerebral vessels on both T1-Gd and SWI sequences. The initial analysis was performed by the first author (G.B.) and verified by the second and senior authors (M.L. and C.W.).

We identified each point on a trajectory intersecting or within 1 mm (“near miss”) of a blood vessel and recorded the vessel’s diameter and the depth of its occurrence. Intersections or near misses with blood vessels on the cortical surface itself were classified as ‘superficial’, while those located within the brain parenchyma were classified as ‘deep’. The rates of vessel intersection per patient and per electrode, along with the mean diameter of the intersected vessel, were calculated for both SWI and T1-Gd image series. These rates were also calculated for both direct intersections with and near misses within 1 mm of vessels, labeled as ‘intersection plus near miss’. The hemorrhagic complication rate for the subject population was also determined based on the review of postoperatively acquired imaging (G.B., M.L., and N.M.).

Data are presented as mean and standard deviation for continuous variables, and as frequency for dichotomous variables. Analysis was carried out using the unpaired $t$-test, with $P$-values $\leq .05$ considered statistically significant. Cohen’s kappa, a measure of agreement between 2 imperfect tests, was used to investigate the types of vessels identified on T1-Gd and SWI.10 Statistical analysis was carried out with the SPSS Statistics 22.0 software (IBM Corp, Armonk, New York).

RESULTS

There was no clear evidence of procedure-related ICH on postoperative MRI or computed tomography (CT) in any patients. One patient in our study demonstrated a small amount of left temporal fluid-attenuated inversion recovery (FLAIR) signal around a single electrode (0.9%) in the postoperative MR sequence consistent with “possible hemorrhage” as read by a Neuroradiologist after sEEG placement. The number of unique instances of electrodes intersecting cerebral blood vessels varied significantly between SWI and T1-Gd imaging, as shown in Table 1. Sixty-three unique instances of electrodes intersecting cerebral blood vessels were identified on SWI sequences (0.59 intersections per electrode, average 4.85 intersections per patient), of which only 39.7% were superficial. Thirteen intersections were identified on T1-Gd (0.12 intersections per

FIGURE 1. Patient selection criteria and imaging used.
TABLE 1. Results of T1-Gd vs SWI Vessel Intersection Analysis

<table>
<thead>
<tr>
<th></th>
<th>T1-Gd</th>
<th>SWI</th>
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<tbody>
<tr>
<td>Vessel intersections, total</td>
<td>13</td>
<td>63</td>
</tr>
<tr>
<td>Vessel intersections, mean per patient</td>
<td>1.0</td>
<td>4.85</td>
</tr>
<tr>
<td>Vessel intersections, rate per electrode</td>
<td>0.12</td>
<td>0.59</td>
</tr>
<tr>
<td>Intersection depth (superficial/total, %)</td>
<td>10/13 (76.9%)</td>
<td>25/63 (39.7%)</td>
</tr>
<tr>
<td>Mean diameter of intersected vessel, ( P &lt; .001 )</td>
<td>2.01 ± 0.52 mm</td>
<td>1.49 ± 0.46 mm</td>
</tr>
<tr>
<td>Vessel intersections + near miss, total</td>
<td>56</td>
<td>155</td>
</tr>
<tr>
<td>Vessel intersections + near miss, mean per patient</td>
<td>4.31</td>
<td>11.92</td>
</tr>
<tr>
<td>Vessel intersections + near miss, rate per electrode</td>
<td>0.53</td>
<td>1.46</td>
</tr>
<tr>
<td>Intersection + near miss depth (superficial/total, %)</td>
<td>46/56 (82.1%)</td>
<td>61/155 (39.4%)</td>
</tr>
<tr>
<td>Mean diameter of intersections + near misses, ( P &lt; .001 )</td>
<td>2.01 ± 0.48 mm</td>
<td>1.45 ± 0.43 mm</td>
</tr>
</tbody>
</table>

FIGURE 2. T1-Gd. Sequence of 2 perpendicular planes of probe images of an electrode trajectory A and B. A probe’s eye view of the trajectory C and a magnified view of the probe’s eye view D demonstrate no vessel intersection on T1-Gd imaging.

electrode, average 1.0 intersection per patient, with 76.9% as superficial). An example of the discrepancy between the 2 modalities is illustrated in Figures 2 and 3, where identical electrode trajectories and imaging planes demonstrate clear vessel intersection with the electrode on SWI, with no such intersection on T1-Gd. The calculated Cohen’s kappa for SWI and T1-Gd testing vessel intersections only is \(-0.066\) (95% confidence interval \(-0.169\) to \(0.037\)), indicating no agreement between the 2 imaging modalities. There was also a statistically significant difference in mean diameter of intersected vessel, measuring \(1.49 ± 0.46\) mm on SWI, and \(2.01 ± 0.52\) mm on T1-Gd images (\(P < .001\)).

The instances of intersection plus near misses were also calculated for the 2 imaging modalities and resulted in 155 total instances on SWI (1.46 per electrode, 11.92 per patient), of which 39.4% were superficial, and 56 such instances on T1-Gd (0.53 per electrode, 4.31 per patient), with 82.1% superficial. The calculated kappa for SWI and T1-Gd as tests for both vessel intersections and near misses is \(-0.22\) (95% confidence interval \(-0.311\) to \(-0.138\)), also indicating no agreement. When
including near misses with intersections, there was also a statistically significant difference in vessel mean diameter, measuring $1.45 \pm 0.43$ mm on SWI, and $2.01 \pm 0.48$ mm on T1-Gd images ($P < .001$).

**DISCUSSION**

Inadequate avoidance of superficial cortical vessels can result in symptomatic hemorrhage and infarction during electrode insertion (Francesco Cardinale, MD, PhD, personal communication, November 2013). While arterial injury may present with acute neurological injury with subarachnoid and intraparenchymal hemorrhage, venous injury may present with subacute neurological deficits, along with characteristic cerebral edema and/or irregularly shaped subcortical hemorrhage surrounding the superficial aspect of the electrode on CT.\(^1\) It is prudent to safely visualize these superficial cortical vessels in surgical planning with high-resolution, contrast-enhanced MRI. Conversely, SWI is particularly sensitive to visualizing the deep venous microvasculature, while missing many of the superficial intersections noted on T1-Gd. Our results support this concept by demonstrating a lower mean diameter of intersected vessels for T1-Gd-planned trajectories visualized on SWI.

The role of SWI is supplementary instead of inclusive, supported by the negative kappa values indicating no agreement between the 2 tests, thereby demonstrating a discordance in the cerebral blood vessels visualized on SWI when compared to T1-Gd. The SWI sequence integrates the magnitude data and high pass filtered phase data of MRI to highlight the local magnetic susceptibility differences between tissues across voxels. Deoxyhemoglobin in veins, along with both calcium and hemosiderin, is paramagnetic relative to surrounding tissue and generates a hypointense signal under SWI. This allows for supplementary heightened differentiation over T1-Gd or CT when imaging the venous microvasculature, at the cost of weaker definition of superficial vessels and parenchymal boundaries. SWI is therefore usually accompanied by additional imaging such as time of flight (TOF) MRI to better visualize arteries and T1-MRI (without contrast) for visualizing the parenchymal anatomy.\(^12,13\)

The SWI sequence has also been used for imaging deep structures such as the DBS targets of the subthalamic nucleus (STN) and the globus pallidus. While some authors found SWI to be advantageous in visualizing such structures,\(^14,15\) a recent study by Chandran et al\(^6\) showed that SWI overestimates the size of STN while Bot et al\(^16\) found SWI to be inaccurate in identifying the lateral aspect of the STN. Additional limitations include its increased acquisition time, which is approximately
10 to 20 min, and elevated sensitivity to air-tissue interface artifact, resulting from unwanted high spatial frequency phase variations and aliasing in the background magnetic field. It is important to carefully recognize the geometric dark shadows around these structures as an artifact, as this issue limits the utility of the study if the structure in question is near the mastoid, sinuses, pituitary, and skull base.

Given some of the early literature suggesting that using SWI in trajectory planning could reduce the risk of ICH, we began obtaining preoperative SWI images in our sEEG and LITT patients with the intent of first evaluating its utility for planning purposes. Given our already low rate of ICH with T1-Gd, the utility of an additional imaging sequence was unclear. The analysis presented here represents our initial evaluation of this imaging technique. Even though all trajectories were planned in order to avoid blood vessels visible on T1-Gd, 13 vessel intersections were observed. Despite this finding, there were still no clear hemorrhages in this series of patients. As such, our concern is that detecting a higher number of vessels with SWI during trajectory planning may lead surgeons to be overly conservative and consequently limit therapeutic options for their patients.

Contrast-enhanced MRI markedly facilitates the stereotactic trajectory planning principle of avoiding vessels, sulci, and ventricles in order to minimize ICH occurrence. The current literature estimates the overall incidence of ICH for DBS procedures to be 5.0%, with asymptomatic ICH occurring in 1.9% of patients, symptomatic ICH in 2.1%, and ICH resulting in permanent deficit or death in 1.1%. Selecting the entry point at the crest of the gyrus is an important first step towards reducing the incidence of ICH; however, each individual trajectory must be precisely tailored to each patient’s anatomic complexities and vasculature. If it is impossible to reach a particular target without intersecting the aforementioned structures, priority should be given to first avoid vessels, followed by sulci, and lastly ventricles to minimize the risk of bleeding. Given the presence of vessel intersections even on T1-Gd images, our study also raises the question of whether or not this modality is necessary for trajectory planning; however, since T1-Gd is so commonly used and regarded as the standard preoperative modality for trajectory planning, we do not feel that we can analyze this modality in the manner that we have done for SWI.

Accurate coregistration of preoperative MR images and frame-based CT must also be confirmed in order to realize the value of precision trajectory planning, regardless of the image set used. Furthermore, even with frame-based methodologies, deviation from the intended trajectory can occur intraoperatively. In order to eliminate any potential error introduced by such deviations, we used postoperative images to directly extract the position of the implanted electrodes or probes.

For the 1 instance of “possible hemorrhage” (0.9%), there were 0.9 intersections and 2.1 intersections plus near misses per electrode on SWI, and 0.2 intersections and 0.9 intersections plus near misses per electrode on T1-Gd for this particular patient. Of note, these values fall within 1 standard deviation above the study’s corresponding mean per electrode rates of intersections and intersections plus near misses; however, there were still 2 other patients with higher respective intersection rates than this patient, who demonstrated no clinical or radiographic evidence of hemorrhage. This supports our proposition that the increased detection of intersections seen on SWI does not necessarily correlate with a higher incidence of ICH.

Furthermore, we conducted a power analysis with 95% confidence to further understand the potential for decreasing hemorrhagic complications with additional imaging such as SWI. A recent sEEG series of 500 patients and 6496 electrodes demonstrated an ICH rate of 0.2% per electrode using standard MRI protocols. Using this as the hemorrhage rate per electrode, the number of electrodes needed to be analyzed to demonstrate a decrease in ICH by half would be 23,508. This calculation points to the impracticality of demonstrating any true benefit of additional imaging, such as SWI, in reducing the rate of ICH given the extremely low risk already demonstrated by standard practice.

CONCLUSION

Our findings suggest SWI may be unnecessary for preoperative imaging when treating patients with stereotactic methods. T1-Gd appears to adequately visualize the superficial, larger diameter vessels that are more prone to rupture and cause symptomatic bleeding when compared to microvasculature. The absence of any clinically significant ICH in this series is an obvious limitation. However, given the high rate of direct vessel intersection on coregistered SWI images of 106 independent trajectories, it can be concluded that such events are likely to be clinically irrelevant. Even with the single instance of a questionable radiographic hemorrhagic complication within our study population, the number needed to treat with SWI would be significantly high and thus its clinical utility still questionable at best. The utility of SWI is likely limited by the identification of smaller veins, unnecessarily complicating trajectory planning with little impact on ICH frequency.

Our results demonstrate SWI vessel identification is likely oversensitive for the purpose of intracranial electrode trajectory planning. There was no incidence of clear ICH, despite the high rate of electrode intersection and close proximity to cerebral vessels seen on SWI compared to T1-Gd imaging. Using SWI for vessel avoidance is most likely unwarranted because SWI may overestimate the consequence of small vessel intersection by electrodes and is unlikely to result in clinically significant ICH. Moreover, SWI may limit the number of trajectories perceived to be safe, which in turn may lead surgeons to be overly conservative and limit therapeutic options for their patients.

Disclosure

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.
REFERENCES


