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# Minimizing Hemorrhage Complications in Deep Brain Stimulation Surgery - The Impact of Imaging Modalities and Trajectory Planning

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**Objective :** This retrospective study aims to analyze hemorrhage complications in patients undergoing deep brain stimulation (DBS) surgery, focusing on the impact of imaging modalities and trajectory planning.

**Methods :** We conducted a retrospective review of patients who underwent DBS at a single institution from September 2018 to February 2023. Surgical planning data were analyzed using a combination of 1.5 Tesla (T) and 3.0 T magnetic resonance image (MRI) for trajectory planning. Trajectories were classified into four types (type 1–4) based on the proximity of vascular structures within 2 mm on preoperative MRI scans, as defined in this study. Hemorrhage presence was evaluated through postoperative computed tomography scans.

**Results :** Out of 200 patients analyzed, type 1 trajectories (no vascular structures within 2 mm on both MRIs) accounted for 72.70% of cases with the lowest hemorrhage rate. Significant differences in hemorrhage rates were observed among the types, with higher risks associated with type 4 trajectories. Additionally, significant variations in vascular structure types were noted across DBS targets, with subthalamic nucleus showing the highest risk.

**Conclusion :** Meticulous trajectory planning using both 1.5 T and 3.0 T MRI is crucial in minimizing hemorrhagic complications in DBS. The study underscores the need for precise imaging and planning to enhance patient safety and surgical outcomes.

**Key Words :** Deep brain stimulation · Postoperative complications · Magnetic resonance imaging · Cerebral hemorrhage.

## INTRODUCTION

Deep brain stimulation (DBS) is an essential therapeutic intervention for patients suffering from various neurological disorders, including Parkinson's disease (PD), essential tremor (ET), and dystonia[13]. Recently, its applications have expanded to psychiatric conditions, further demonstrating its clinical importance[8]. Despite significant advancements, DBS surgery car-

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ries a critical risk of hemorrhagic complications, which can present as intraparenchymal, intraventricular, epidural, subarachnoid hemorrhages, or venous infarction with secondary bleeding. Among these, intraparenchymal hemorrhage is particularly concerning due to its potential to cause severe morbidity and mortality[14].

Cortical hemorrhage occurs in approximately 0.5% to 1% of DBS cases[5], often asymptomatic or presenting as seizures, whereas deep intracerebral hemorrhage (ICH) carries a higher incidence, around 1.4–2.5% per electrode and 2.5–3.6% per patient, with more severe clinical outcomes[15,16]. These include permanent disability or death, making it a major concern in DBS procedures.

Since DBS relies on highly precise procedures, minimizing the risk of complications is essential. Accurate identification and avoidance of vascular structures are critical to prevent intracranial bleeding. This retrospective study focuses on hemorrhagic complications and evaluates the effectiveness of 1.5 Tesla (T) and 3.0 T magnetic resonance image (MRI) for trajectory planning in DBS surgery. By analyzing patient outcomes using these imaging modalities, this study aims to provide insights into improving safety in DBS procedures.

## MATERIALS AND METHODS

The study design was reviewed and approved by the Institutional Review Board (IRB) of Severance hospital (under the approval number : 1-2023-0076), which determined that the requirement for informed consent was waived due to the retrospective nature of the study.

### Patients

After obtaining IRB approval, this retrospective study included patients who underwent DBS at a single institution between September 2018 and February 2023. Patients were excluded if their surgical planning data were incomplete or if their 3.0 T MRI was performed more than 1 year before surgery without an enhancement study. This study was conducted as a retrospective analysis based on previously collected data and, therefore, did not require informed consent from individual participants.

### DBS procedures

The operation involved frame-based stereotactic implantation of a DBS electrode. After applying the Leksell G-frame (Elekta, Stockholm, Sweden), stereotactic 1.5 T MRI was performed with a double dose of contrast medium. The acquired data were then transferred to the Leksell SurgiPlan (Elekta) for trajectory planning. This system allows for detailed mapping of brain structures and blood vessels, enabling precise DBS electrode placement.

Subsequently, the 3.0 T MRI taken before surgery for DBS indication verification was also imported into the SurgiPlan software (Elekta, Stockholm, Sweden) and used as a reference in the planning process. The fusion of both 1.5 T and 3.0 T MRI images provided enhanced visualization of vascular structures along the planned trajectory. By comparing these imaging modalities, we aimed to minimize the risk of passing through or near critical vascular structures.

For all DBS surgeries, including those performed under general anesthesia, single-tract micro-electrode recording was used to verify the target area before electrode insertion. This involved recording electrical signals from the brain to ensure accurate placement of the DBS electrodes. Once the desired position was confirmed, the electrodes were inserted into the brain tissue according to the pre-planned trajectory.

Postoperative computed tomography (CT) scans were conducted immediately before removing the stereotactic frame. The CT scans were merged with the preoperative MRI images to confirm the final position of the electrodes and to check for the presence of hemorrhage or other complications. After this assessment, an implantable pulse generator was placed subcutaneously in the chest under general anesthesia, concluding the DBS surgery.

### Evaluation and categorization of vascular structures along the trajectory

To assess the proximity of vascular structures (both arteries and veins) to the planned DBS electrode trajectory, we classified the trajectories into four distinct types (type 1, 2, 3, and 4), based on MRI findings (Table 1). These types were defined by whether any vascular structures were visible within a 2 mm range of the trajectory on 1.5 T and/or 3.0 T MRI scans, a commonly used threshold in stereotactic neurosurgery to minimize hemorrhagic risk[11,12]. The definitions are as follows : type 1 : no vascular structures were visible within 2 mm on either the 1.5

T or the 3.0 T MRI; type 2 : vascular structures were visible within 2 mm only on the 3.0 T MRI; type 3 : vascular structures were visible within 2 mm only on the 1.5 T MRI; and type 4 : vascular structures were visible within 2 mm on both MRI scans (1.5 T and 3.0 T).

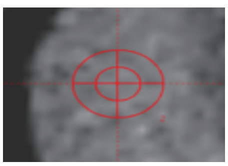
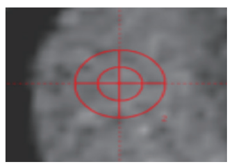
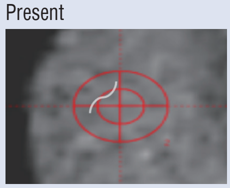
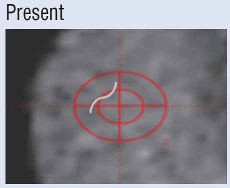
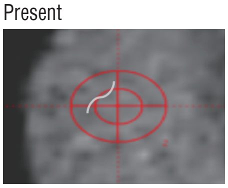
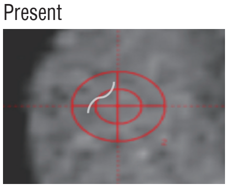
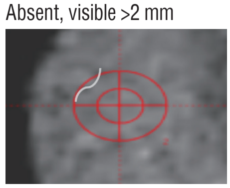
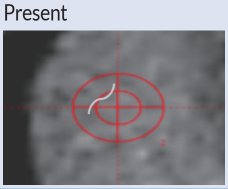
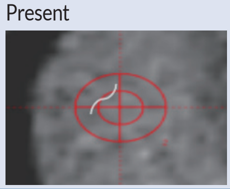
Additionally, for type 2 and type 3 cases, we further classified them into two subtypes, 2A and 2B (and 3A and 3B), based on whether the vascular structure was visible on one MRI but not the other (A), or if the vascular structure was visible in both but outside the 2 mm range on the second MRI (B).

For better understanding of the hemorrhage patterns, the trajectory was divided into two distinct levels (Fig. 1) : superficial level : this ranged from the dura to the point where the frontal horn of the ventricle first becomes visible and deep level : this ranged from the ventricle to 5 mm beyond the target, covering deep brain nuclei areas.

Different hemorrhagic risks are associated with each level, depending on the presence of cortical vessels in the superficial section and deep structures in the deep section. If any of the planned trajectories showed two or more occurrences of type 2 or higher, the trajectory was revised by altering the entry point or adjusting the target to avoid vascular structures. The presence of hemorrhage was determined using CT scans conducted immediately post-surgery or within the next day.

The classification and review of vascular structures were conducted by two independent researchers (S.W.H., D.D.P.), ensuring objectivity. Vascular structures were defined by their continuity across consecutive image slices, with gadolinium

**Table 1.** Classification of trajectories by proximity of vascular structures

| | Framed 1.5 T MRI | Preoperative 3.0 T MRI |
|---|---|---|
| Type 1 | Absent  | Absent  |
| Type 2 | | |
| 2A | Absent  | Present  |
| 2B | Absent, visible >2 mm  | Present  |
| Type 3 | | |
| 3A | Present  | Absent  |
| 3B | Present  | Absent, visible >2 mm  |
| Type 4 | Present  | Present  |

T : Tesla, MRI : magnetic resonance image

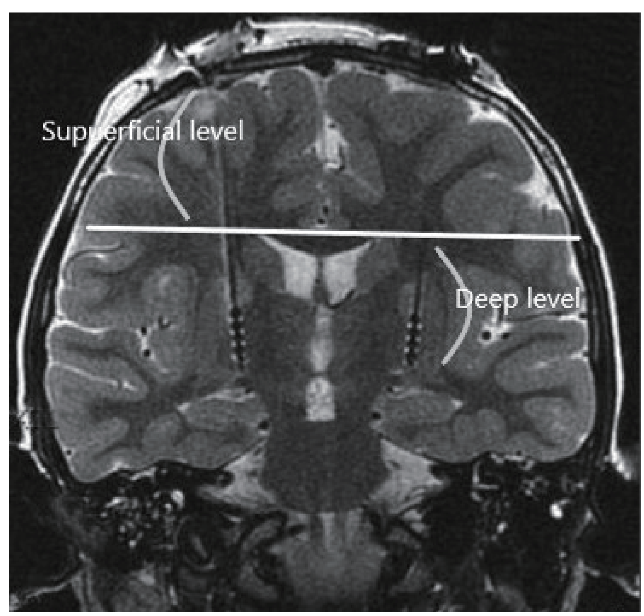



**Fig. 1.** Trajectory levels for hemorrhage pattern analysis in deep brain stimulation (DBS). Schematic representation of DBS trajectory levels, divided into superficial and deep sections, to assess hemorrhage patterns. The superficial level extends from the dura to the frontal horn of the ventricle, while the deep level includes structures from the ventricle to 5 mm beyond the target nuclei.

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enhancement used to further verify the presence of blood vessels. In addition, we evaluated the statistical distribution of trajectory types for each target (e.g., subthalamic nucleus [STN], globus pallidus internus [GPi], and ventral intermediate nucleus [VIM]) to assess whether certain DBS targets were associated with higher risks of hemorrhage due to their anatomical proximity to vascular structures.

### Statistical analysis

SPSS Statistics for Windows, version 26.0 (SPSS Inc., Chicago, IL, USA), was used for all statistical analyses. A chi-square test was used to evaluate the difference in hemorrhage rates across trajectory types, and a pairwise Z-test was performed for *post-hoc* comparisons. Additional chi-square tests were used to assess the distribution of trajectory types by target, with the Mantel-Haenszel test confirming trends. Fisher's exact test and a linear-by-linear association test were used to analyze vascular structure types, with significance set at $p<0.05$.

## RESULTS

Of the 256 patients reviewed, 56 were excluded due to incomplete surgical planning data, leaving a total of 200 patients for analysis. Table 2 summarizes the demographic details. The cohort had 101 male and 99 female patients, with an average age of 58.61 years (standard deviation, 14.57). Among the patients, 60 had PD, 96 had ET, 23 had dystonia, and 21 had Tourette's syndrome. Across all patients, 315 electrodes were implanted, targeting 120 in the STN, 106 in the VIM, 59 in the GPi, and 30 in other regions.

Table 3 presents the proximity of vascular structures by trajectory type and level, as well as the incidence of hemorrhage based on these classifications, as previously outlined (Table 1 and Fig. 1). Among the 315 plans, 72.7% (229 cases) were classified as type 1, where no vascular structures were within 2 mm on either MRI. Type 2, where vascular structures were visible on the 1.5 T MRI but not on the 3.0 T MRI, accounted for 13.33% (42 cases). Specifically, 12 cases (3.81%) were classified as type 2A, where no vascular structures were visible on the 1.5 T MRI, and 30 cases (9.52%) as type 2B, where vascular structures deviated from the 2 mm trajectory. Type 3 accounted for 8.25% (26 cases), with 2.54% (eight cases) classified as type 3A and 5.71% (18 cases) as type 3B. Finally, type 4 comprised 5.71% (18 cases), where vascular structures were visible on both MRI scans.

The number of hemorrhages varied across trajectory types. In type 1, one hemorrhage was reported in the superficial layer. For type 2A and 2B, trajectories were distributed across the superficial and deep layers with ratios of 7 : 5 and 18 : 12, respectively, but no hemorrhages were detected at either level. In type 3A, four cases each were observed in the superficial and deep

**Table 2.** Basic demographics of the patient cohort

| | Value |
|---|---|
| Sex, male : female | 101 : 99 |
| Age (years) | 58.61±14.57 |
| Awake : asleep | 154 : 46 |
| Disease | 200 |
| PD | 60 |
| ET | 96 |
| Dystonia | 23 |
| Tourettes syndrome | 21 |
| Target | 315 |
| STN | 120 |
| VIM/PSA | 106 |
| GPi | 59 |
| Others | 30 |

Values are presented as mean±standard deviation or number (%) unless otherwise indicated. PD : Parkinson's disease, ET : essential tremor, STN : subthalamic nucleus, VIM : ventralis intermedius, PSA : posterior subthalamic area, GPi : globus pallidus interna

**Table 3.** Proximity to vascular structures by trajectory type and level and incidence of hemorrhage

| Type | Trajectory | | | Hemorrhage | |
|---|---|---|---|---|---|
| | Total | Superficial | Deep | Superficial | Deep |
| 1 | 229 | | | 1 | 0 |
| 2 | | | | | |
| 2A | 12 | 7 | 5 | 0 | 0 |
| 2B | 30 | 18 | 12 | 0 | 0 |
| Total | 42 | 25 | 17 | 0 | 0 |
| 3 | | | | | |
| 3A | 8 | 4 | 4 | 0 | 0 |
| 3B | 18 | 11 | 7 | 2 | 0 |
| Total | 26 | 15 | 11 | 2 | 0 |
| 4 | 18 | 9 | 9 | 2 | 1 |

layers, and none resulted in hemorrhage. However, in type 3B, 11 cases were in the superficial layer and seven in the deep layer, with two hemorrhages occurring in the superficial layer : one subcortical and one cortical surface hemorrhage. In type 4, nine cases each were found in both the superficial and deep layers. Two subcortical hemorrhages occurred in the superficial layer, and one case of deep-seated ICH with intraventricular hemorrhage was recorded in the deep layer. While all superficial hemorrhages were asymptomatic, the deep-seated ICH led to the patient's death after complications from cerebral edema, despite an ICH catheter insertion and surgical recommendations.

Fig. 2 shows the hemorrhage incidence rate for each trajectory type, specifically at the superficial level. A chi-square test was conducted to determine whether differences in hemorrhage rates existed among the trajectory types, yielding a significant result ($X^2$=19.27, $p$=0.00024, degree of freedom [df]=3). Pairwise Z-tests were then applied to identify significant differences between trajectory types. Statistically significant differences were found between type 1 and type 3, type 1 and type 4, and type 2 and type 4 ($p$=0.00115, $p=6.86\times10^{-5}$, and $p$=0.028, respectively). These results indicate that hemorrhage rates were significantly higher in type 3 and type 4 compared to type 1, and type 4 showed a higher incidence of hemorrhage than type 2.

Table 4 categorizes trajectory types across various DBS targets. For type 1, 72 cases (60.0%) were found in the STN, 42 cases (71.2%) in GPi, 95 cases (89.6%) in VIM, and 20 cases (66.7%) in other targets. Type 2 included 20 cases (16.7%) in STN, nine cases (15.3%) in GPi, seven cases (6.6%) in VIM, and six cases (20.0%) in other targets. Type 3 was observed in 17 cases (14.2%) in STN, five cases (8.5%) in GPi, two cases (1.9%) in VIM, and two cases (6.7%) in other targets, while type 4 accounted for 11 cases (9.2%) in STN, three cases (5.1%) in GPi, two cases (1.9%) in VIM, and two cases (6.7%) in other targets. A chi-square test showed that the differences in trajectory type distributions across these targets were statistically significant ($X^2$=56.214, $p$<0.0001, df=9).

Fig. 3 illustrates the distribution of trajectory types for the STN, GPi, and VIM targets. The Mantel-Haenszel chi-square test ($X^2$=29.72, $p$=0.0044) confirmed a linear trend, showing that the proportion of type 1 trajectories decreased and the

**Table 4.** Distribution of targets by type

| Type | Target | | | |
|---|---|---|---|---|
| | STN | GPi | VIM | Other |
| 1 | 72 (60.0) | 42 (71.2) | 95 (89.6) | 20 (66.7) |
| 2 | 20 (16.7) | 9 (15.3) | 7 (6.6) | 6 (20.0) |
| 3 | 17 (14.2) | 5 (8.5) | 2 (1.9) | 2 (6.7) |
| 4 | 11 (9.2) | 3 (5.1) | 2 (1.9) | 2 (6.7) |

Values are presented as number (%). STN : subthalamic nucleus, GPi : globus pallidus interna, VIM : ventralis intermedius

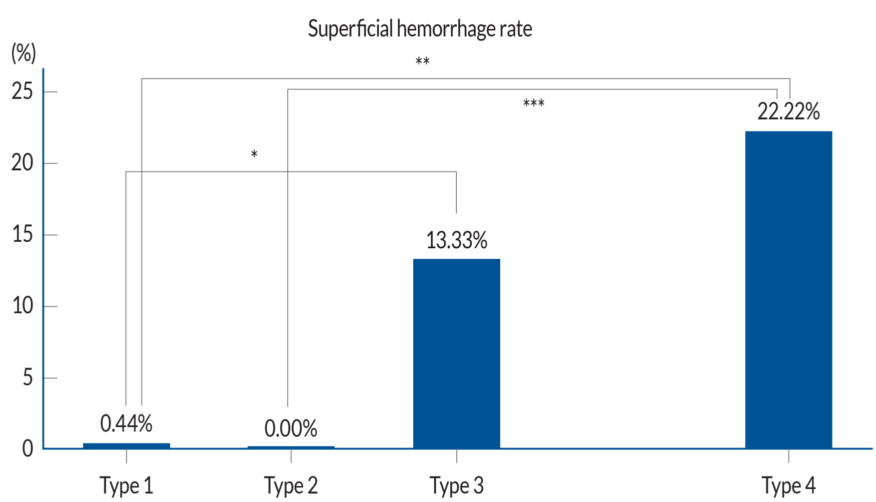


**Fig. 2.** Hemorrhage incidence rate by trajectory type at the superficial level. Hemorrhage incidence across different trajectory types (type 1–4) at the superficial level, based on chi-square analysis. Type 3 and type 4 pathways showed statistically significantly higher bleeding rates than type 1. *Statistically significant difference between type 1 and type 3, with a $p$-value of 0.00115. **Statistically significant difference between type 1 and type 4, with a $p$-value of $6.86\times10^{-5}$. ***Statistically significant difference between type 2 and type 4, with a $p$-value of 0.028.

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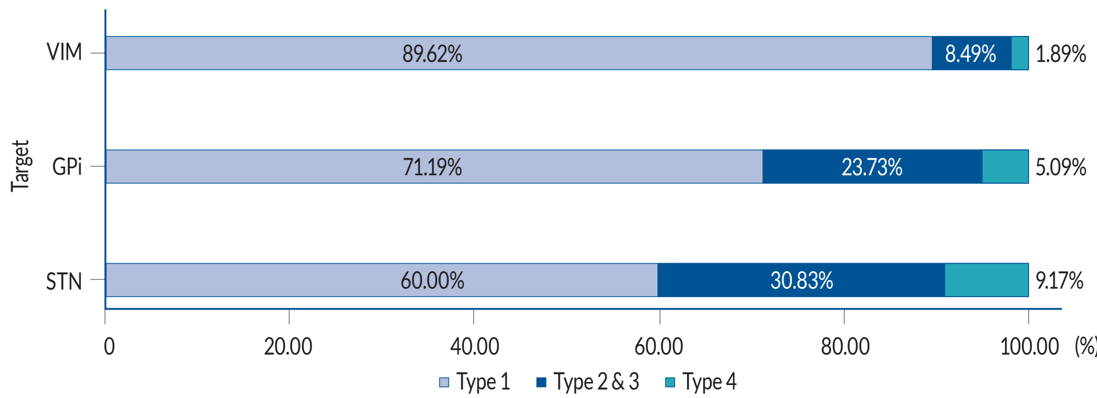


**Fig. 3.** Distribution of trajectory types by deep brain stimulation (DBS) target region. Analysis of trajectory types across DBS target sites, including the STN, GPi, and VIM regions. The STN region exhibits a higher proportion of high-risk type 4 trajectories, suggesting greater vascular density and hemorrhagic risk compared to other targets. A Mantel-Haenszel test ($p$<0.01) confirms a linear trend of increasing hemorrhagic risk from VIM to STN. VIM : ventral intermediate nucleus, GPi : globus pallidus internus, STN : subthalamic nucleus.

proportion of type 4 trajectories increased in the order of VIM, GPi, and STN.

## DISCUSSION

The declining use of 1.5 T MRI machines limits the generalizability of the trajectory-planning methods described in this study. However, this study uniquely focuses solely on trajectory-making, excluding other variables that are often considered in previous research. By concentrating only on the trajectory, this study provides a clearer and more systematic analysis of how trajectory design impacts hemorrhagic risk. The findings of this study emphasize the crucial importance of meticulous trajectory planning to minimize the risk of hemorrhagic complications during DBS procedures. Furthermore, the hemorrhagic points have been thoroughly reviewed. Except for one case of type 1 hemorrhage, all occurrences were localized to areas with vascular structures identified during preoperative imaging and classified according to the study criteria. This observation reinforces the importance of accurate preoperative vascular assessment in determining hemorrhagic risks.

Errors in DBS surgery are often attributed to various factors inherent to image-guided procedures. These include MRI distortions, inaccuracies during image merging, and errors in trajectory setup, whether using a frame or robotic system. Additional risks include cerebrospinal fluid leakage during electrode insertion, which can exacerbate these challenges[2]. Despite technological advancements, especially in image fusion, errors persist. A study using FrameLink software (Medtronic, Minneapolis, MN, USA) reported an average error margin of 1.25 mm[1]. This highlights the necessity of keeping a 2 mm margin around blood vessels in the planned trajectory to account for potential inaccuracies. Our study underscores the critical role of precise trajectory planning in minimizing hemorrhagic risks during DBS.

Debate continues regarding the most effective imaging modality for DBS planning. Susceptibility weighted imaging (SWI) has been proposed as a superior method for visualizing blood vessels, with higher sensitivity than T1 contrast-enhanced imaging. One study identified adjacent blood vessels in six out of 33 patients using SWI[9]. However, its exaggerated depiction of blood vessels limits its utility in trajectory planning, as avoiding all vessels beyond 2 mm becomes impractical. CT, though often considered the "gold standard," introduces its own set of errors, particularly during image fusion. CT also has limitations, such as radiation exposure, contrast agent risks, and reduced soft tissue contrast. A study utilizing CT angiography found that additional blood vessels were detected in 17.1% of cases, with an average positional discrepancy of 1.24 mm between MRI and CT images[7].

### Variability in MRI enhancement

The consistency of cerebrovascular images in dynamic contrast-enhanced MRI can be influenced by hemodynamic changes, contrast agent distribution, and variations in MRI sequences. The lack of standardization in devices and protocols for 3.0 T MRI across different institutions and clinicians may contribute to these inconsistencies. Studies show no statistically significant difference in the effectiveness of double-dose contrast-enhanced MRI in reducing ICH risk[17]. Interestingly, 1.5 T MRI exhibits less distortion in peripheral areas, which can be advantageous. As illustrated in Fig. 2, type 2 trajectories (vascular structures seen at 3.0 T but not at 1.5 T) were not associated with any hemorrhage events. While no direct statistical difference was found between type 2 and type 3, the observed incidence difference (0% vs. 13.33%) suggests that 1.5 T MRI may provide more reliable imaging in peripheral regions.

## Hemorrhagic complications of DBS

Previous studies have analyzed hemorrhagic complications in DBS surgery, focusing on ICH. For example, Fenoy and Simpson[4] reported that out of 1333 electrodes placed in 728 patients (with 728 electrodes targeting the STN), symptomatic ICH occurred in 0.5% (four patients) and asymptomatic ICH in 1.1% (eight patients). Similarly, Patel et al.[10] found a symptomatic ICH rate of 0.78% (four patients) in 510 DBS cases (270 of which targeted the STN). Tonge et al.[17] analyzed 220 patients and found that the ICH risk was 1.81% per patient, 0.3% per recording electrode, and 0.23% per brain insertion. Our prior study of 426 patients (315 STN implants) observed asymptomatic ICH in 0.9% (four patients) and symptomatic ICH in 1.4% (six patients)[6]. These findings allow for indirect comparisons, as only the planning method differed between these studies. Notably, our study observed just one case of deep-seated ICH, highlighting the relatively low hemorrhagic complication rate in this cohort.

The primary cause of ICH is damage to blood vessels along the surgical trajectory, with several risk factors influencing this. Preoperative risk factors include patient characteristics such as hypertension, age, and the use of anticoagulants[15,19]. Intraoperatively, high blood pressure is a significant concern[14,18]. Unfortunately, our study lacked a control group for a detailed risk factor analysis. Nevertheless, it is worth noting that bleeding was observed even in type 1 trajectories, underscoring the need for caution in all trajectory types.

## Hemorrhage analysis by levels

This study is the first to categorize DBS hemorrhages by superficial and deep levels. Differentiating between deep-seated hemorrhages and juxtacortical hemorrhages is important due to their distinct morbidity profiles. Major DBS complications, including fatalities, often stem from deep-level vascular injuries, while juxtacortical hemorrhages present risks such as seizures[3]. Both 1.5 T and 3.0 T MRI demonstrate comparable accuracy in deep brain regions, emphasizing the importance of cross-referencing both modalities to minimize the risk of ICH.

## Hemorrhage analysis by target

The STN target is well known to have the highest risk of hemorrhage, which is supported by the findings of this study. As shown in Table 4, STN trajectories include a higher proportion of type 3 and type 4 pathways compared to other targets, indicating a denser vascular environment. This is consistent with the results in Table 3, where type 3B and type 4 trajectories are associated with significantly higher hemorrhage rates. Despite meticulous trajectory planning, the increased vascular density and longer trajectory required for STN DBS surgery pose a greater risk of vascular injury. These findings underscore the importance of integrating precise imaging and trajectory planning to minimize the risk of intracranial hemorrhage, particularly for high-risk targets like the STN.

## Type 4

Out of the 315 electrode implantations, 18 cases required proceeding with surgery despite vascular structures being visible within 2.5 mm on both MRIs (type 4). This decision followed the surgical principle that the coronal angle of the electrode should fall within 10 to 15 degrees and the sagittal angle between 50 to 60 degrees. This technique ensures that the electrode contacts achieve maximum penetration of the target nucleus.

Precise electrode placement within target structures is critical for optimal efficacy and to minimize side effects of electrical stimulation. As a result, even when type 4 was assigned, surgery proceeded when the trajectory adhered to the specified angles. Importantly, not all type 4 leads penetrated blood vessels directly. With careful planning, surgery can still proceed safely. In cases involving bilateral surgery, none of the patients had type 4 on both sides. Additionally, when type 4 was identified, surgery was prioritized on that side first.

## Limitations

This study has several limitations, including a small sample size and potential recall bias due to its retrospective nature. The exclusion of many patients due to incomplete surgical planning data may have introduced selection bias. Furthermore, the study's focus on trajectory planning overlooks other potential contributors to hemorrhage, such as manual errors or patient-specific factors like hypertension and anticoagulant use. The decreasing use of 1.5 T MRI and the adoption of newer imaging techniques, such as Fast Gray Matter Acquisition T1 Inversion Recovery, also limit the generalizability of these results. Despite these limitations, the study highlights the importance of precise trajectory planning in reducing hemorrhagic risks.

While the incidence of hemorrhagic events in this study was low, limiting statistical significance, the findings still provide practical insights for surgical planning. Specifically, the results emphasize the importance of maintaining a 2 mm margin from vascular structures, which, despite the rarity of complications, serves as a reliable safety measure in DBS procedures. Future studies involving larger cohorts or multi-center collaborations will be essential to validate these findings and further refine risk mitigation strategies.

## CONCLUSION

This study emphasizes the crucial role of precise trajectory planning in minimizing hemorrhagic complications during DBS. Our analysis of 200 patients revealed significant variations in hemorrhage rates depending on vascular structure types, with the highest risks associated with type 4 trajectories. While the study has certain limitations, including its retrospective design and limited generalizability due to evolving imaging technologies, the results underscore the necessity for advanced imaging techniques and careful surgical planning to enhance DBS safety and outcomes.

## AUTHORS' DECLARATION

### Conflicts of interest

Hyun Ho Jung has been editorial board of JKNS since May 2017. He was not involved in the review process of this original article. No potential conflict of interest relevant to this article was reported.

### Informed consent

This type of study does not require informed consent.

### Author contributions

Conceptualization : SWH, JWC; Data curation : SWH; Formal analysis : SWH; Funding acquisition : JWC; Methodology : SWH, HHJ; Project administration : SWH, JWC; Visualization : SWH; Writing - original draft : SWH; Writing - review & editing : SWH, PDD; KWC, JWC

### Data sharing

None

### Preprint

None

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## References

1. Burke JF, Tanzillo D, Starr PA, Lim DA, Larson PS : CT and MRI image fusion error: an analysis of co-registration error using commercially available deep brain stimulation surgical planning software. **Stereotact Funct Neurosurg 99 :** 196-202, 2021
2. Chen SY, Tsai ST, Li SH : Controversial issues in deep brain stimulation in Parkinson's disease in David IF (ed) : **Towards New Therapies for Parkinson's Disease.** Rijeka : IntechOpen, 2011, Ch. 1
3. Cheyuo C, Vetkas A, Sarica C, Kalia SK, Hodaie M, Lozano AM : Comprehensive characterization of intracranial hemorrhage in deep brain stimulation: a systematic review of literature from 1987 to 2023. **J Neurosurg 141 :** 381-393, 2024
4. Fenoy AJ, Simpson RK Jr : Risks of common complications in deep brain stimu-

lation surgery: management and avoidance. **J Neurosurg 120 :** 132-139, 2014
5. Goodman RR, Kim B, McClelland S 3rd, Senatus PB, Winfield LM, Pullman SL, et al. : Operative techniques and morbidity with subthalamic nucleus deep brain stimulation in 100 consecutive patients with advanced Parkinson's disease. **J Neurol Neurosurg Psychiatry 77 :** 12-17, 2006
6. Jung IH, Chang KW, Park SH, Chang WS, Jung HH, Chang JW : Complications after deep brain stimulation: a 21-year experience in 426 patients. **Front Aging Neurosci 14 :** 819730, 2022
7. Krüger MT, Coenen VA, Jenkner C, Urbach H, Egger K, Reinacher PC : Combination of CT angiography and MRI in surgical planning of deep brain stimulation. **Neuroradiology 60 :** 1151-1158, 2018
8. Lee DJ, Lozano CS, Dallapiazza RF, Lozano AM : Current and future directions of deep brain stimulation for neurological and psychiatric disorders. **J Neurosurg 131 :** 333-342, 2019
9. Mahvash M, Pechlivanis I, Charalampaki P, Jansen O, Mehdorn HM : Visualization of small veins with susceptibility-weighted imaging for stereotactic trajectory planning in deep brain stimulation. **Clin Neurol Neurosurg 124 :** 151-155, 2014
10. Patel DM, Walker HC, Brooks R, Omar N, Ditty B, Guthrie BL : Adverse events associated with deep brain stimulation for movement disorders: analysis of 510 consecutive cases. **Neurosurgery 11 Suppl 2 :** 190-199, 2015
11. Pivazyan G, Sandhu FA, Beaufort AR, Cunningham BW : Basis for error in stereotactic and computer-assisted surgery in neurosurgical applications: literature review. **Neurosurg Rev 46 :** 20, 2022
12. Rajabian A, Vinke S, Candelario-Mckeown J, Milabo C, Salazar M, Nizam AK, et al. : Accuracy, precision, and safety of stereotactic, frame-based, intraoperative MRI-guided and MRI-verified deep brain stimulation in 650 consecutive procedures. **J Neurosurg 138 :** 1702-1711, 2023
13. Sandoval-Pistorius SS, Hacker ML, Waters AC, Wang J, Provenza NR, de Hemptinne C, et al. : Advances in deep brain stimulation: from mechanisms to applications. **J Neurosci 43 :** 7575-7586, 2023
14. Shin HK, Kim MS, Yoon HH, Chung SJ, Jeon SR : The risk factors of intracerebral hemorrhage in deep brain stimulation: does target matter? **Acta Neurochir (Wien) 164 :** 587-598, 2022
15. Sobstyl M, Aleksandrowicz M, Ząbek M, Pasterski T : Hemorrhagic complications seen on immediate intraprocedural stereotactic computed tomography imaging during deep brain stimulation implantation. **J Neurol Sci 400 :** 97-103, 2019
16. Tiefenbach J, Favi Bocca L, Hogue O, Nero N, Baker KB, Machado AG : Intracranial bleeding in deep brain stimulation surgery: a systematic review and meta-analysis. **Stereotact Funct Neurosurg 101 :** 207-216, 2023
17. Tonge M, Ackermans L, Kocabicak E, van Kranen-Mastenbroek V, Kuijf M, Oosterloo M, et al. : A detailed analysis of intracerebral hemorrhages in DBS surgeries. **Clin Neurol Neurosurg 139 :** 183-187, 2015
18. Wang X, Wang J, Zhao H, Li N, Ge S, Chen L, et al. : Clinical analysis and treatment of symptomatic intracranial hemorrhage after deep brain stimulation surgery. **Br J Neurosurg 31 :** 217-222, 2017
19. Yang C, Qiu Y, Wang J, Wu Y, Hu X, Wu X : Intracranial hemorrhage risk factors of deep brain stimulation for Parkinson's disease: a 2-year follow-up study. **J Int Med Res 48 :** 300060519856747, 2020