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Predicting Post-Operative Side Effects in VIM MRgFUS Based on THalamus Optimized Multi Atlas Segmentation (THOMAS) on White-Matter-Nullled MRI: A Retrospective Study

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ABSTRACT

BACKGROUND AND PURPOSE: Precise and individualized targeting of the ventral intermediate thalamic nucleus for the MR-guided focused ultrasound is crucial for enhancing treatment efficacy and avoiding undesirable side effects. In this study, we tested the hypothesis that the spatial relationships between Thalamus Optimized Multi Atlas Segmentation derived segmentations and the post-focused ultrasound lesion can predict post-operative side effects in patients treated with MR-guided focused ultrasound.

MATERIALS AND METHODS: We retrospectively analyzed 30 patients (essential tremor, $n = 26$; tremor-dominant Parkinson's disease, $n = 4$) who underwent unilateral ventral intermediate thalamic nucleus focused ultrasound treatment. We created ROIs of coordinate-based indirect treatment target, focused ultrasound-induced lesion, and thalamus and ventral intermediate thalamic nucleus segmentations. We extracted imaging features including 1) focused ultrasound-induced lesion volumes, 2) overlap between lesions and thalamus and ventral intermediate thalamic nucleus segmentations, 3) distance between lesions and ventral intermediate thalamic nucleus segmentation and 4) distance between lesions and the indirect standard target. These imaging features were compared between patients with and without post-operative gait/balance side effects using Wilcoxon rank-sum test. Multivariate prediction models of side effects based on the imaging features were evaluated using the receiver operating characteristic analyses.

RESULTS: Patients with self-reported gait/balance side effects had a significantly larger extent of focused ultrasound-induced edema, a smaller fraction of the lesion within the ventral intermediate thalamic nucleus segmentation, a larger fraction of the off-target lesion outside the thalamus segmentation, a more inferior centroid of the lesion from the ventral intermediate thalamic nucleus segmentation, and a larger distance between the centroid of the lesion and ventral intermediate thalamic nucleus segmentation ($p < 0.05$). Similar results were found for exam-based side effects. Multivariate regression models based on the imaging features achieved areas under the curve of 0.99 (95% CI: 0.88 to 1.00) and 0.96 (95% CI: 0.73 to 1.00) for predicting self-reported and exam-based side effects, respectively.

CONCLUSIONS: Thalamus Optimized Multi Atlas Segmentation-based patient-specific segmentation of the ventral intermediate thalamic nucleus can predict post-operative side effects, which has implications for aiding the direct targeting of MR-guided focused ultrasound and reducing side effects.

ABBREVIATIONS: AC-PC = anterior commissure-posterior commissure; AUC = areas under the curve; ET = essential tremor; FGATIR = Fast Gray Matter Acquisition T1 Inversion Recovery; FTM = Fahn-Tolosa-Marin Clinical Rating Scale for Tremor; MRgFUS = MR-guided focused ultrasound; PD = Parkinson's disease; THOMAS = THalamus Optimized Multi Atlas Segmentation; TH = thalamus; VIM = ventral intermediate nucleus

MR-guided focused ultrasound (MRgFUS) provides an incisionless therapeutic option for neurological disorders, utilizing high intensity ultrasound waves to ablate target tissue via thermocoagulation.¹⁻⁴ Clinically validated for its efficacy

and safety,^{2,5,6} MRgFUS has received FDA approval for managing essential tremor (ET) and tremor-dominant Parkinson's disease (PD), two prevalent movement disorders that substantially impact patients' quality of life. For patients with drug resistant tremor, MRgFUS targeting ventral intermediate nucleus (VIM)^{4,7} provides a non-surgical, incisionless solution, particularly benefiting the elderly population with PD and ET.^{1,8}

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SUMMARY

PREVIOUS LITERATURE: VIM-MRgFUS is an effective treatment for tremor in patients with essential tremor or Parkinson's disease. Precise targeting of the VIM is crucial but challenging due to its invisibility on standard MR imaging. While indirect targeting using the AC-PC line is common, it does not account for individual anatomical differences. Recently, the THOMAS method, an automated thalamic nucleus segmentation technique based on white-matter-nulled MRI, was developed. We seek to investigate its utility in predicting post-procedural side effect.

KEY FINDINGS: Spatial relationships between FUS-induced lesions and THOMAS-based thalamic segmentations can predict post-operative gait and balance side effects. Larger off-target lesion fraction and inferior displacement of lesion centroids relative to VIM were associated with increased side effects. Multivariate models using these imaging features achieved high predictive accuracy for side effects.

KNOWLEDGE ADVANCEMENT: This study provides quantitative evidence that THOMAS-based segmentation can be used for more precise VIM targeting in MRgFUS procedures, offering a objective and reliable method for VIM targeting and intra-operative adjustment. This advancement has significant implications for improving surgical outcomes and reducing post-operative side effects.

Accurate targeting of the VIM is essential for maximizing MRgFUS treatment efficacy and minimizing undesirable side effects. However, challenges arise from the insufficient contrast and poor delineation of the nucleus on standard anatomical MR images. The traditional VIM targeting relies on indirect targeting based on coordinates relative to the anterior commissure-posterior commissure (AC-PC) line. This technique, while widely adopted, has the limitation of lacking patient-specific anatomical consideration, such as age-related ventricle enlargement,⁹ which may directly alter the patient-specific VIM coordinates in relationship with the AC-PC line. The VIM targets are often adjusted based on the ventricle size, but the choice remains subjective.^{5,10,11} In addition, there is currently no consensus on the coordinates used. Commonly used coordinates are 10.5–15 mm lateral to the midline or 10–11 mm lateral to the ventricular wall for cases with enlarged ventricles, 6 mm posterior to the mid-commissural point or 25% of AC-PC distance anterior to the PC, and 0–2 mm superior to the AC-PC line.^{5,10-12}

Both the size and the location of the FUS-induced lesion have been associated with the incidence of post-procedural adverse effects.¹³⁻¹⁸ Gait ataxia and unsteadiness has been reported to be the most common neurological side effect, observed in 44–56% patients immediately after treatment (within 48 hours), 22–38% in the short-term (48 hours–3 months), and persisting in 24–38% of the cases beyond 3 months.¹⁹ The high complication rate was postulated to be associated with the small size of VIM and the close proximity of regions responsible for post-operative ataxia with those associated with clinical benefit. The pronounced prevalence of these adverse effects underscores a critical need for the improvement in MRgFUS planning strategies.

Recent advances in imaging techniques offer great promise in personalized VIM targeting, including tractography-based identification of the dentatorubrothalamic tract using DTI,^{20,21} proton density imaging²², and susceptibility MRI at ultrahigh field strength.²³⁻²⁶ Additionally, a combination of advanced sequences with the recent development of automated segmentation algorithms may further facilitate treatment planning. Fast Gray Matter Acquisition T1 Inversion Recovery (FGATIR), one of the

white matter-nulled contrast sequences has been developed for better visualization of the deep gray matter and intra-thalamic structures with high-resolution, including VIM.²⁷⁻³⁰ Compared to tractography and susceptibility imaging methods, this method can be acquired without specialized sequences or reconstruction algorithms and can be readily incorporated into the existing clinical protocol. Complementing this imaging technique, the THalamus Optimized Multi Atlas Segmentation (THOMAS) tool has emerged as a novel method for automated delineation of thalamic nuclei.³¹ This combination of advanced imaging and an expert-level segmentation tool potentially allows for more precise and personalized MRgFUS treatment planning for the reduction of procedure-related side effects.

This study aims to integrate FGATIR and THOMAS for patient-specific VIM targeting. We hypothesize that the spatial relationships between post-FUS lesion and THOMAS segmentations will predict the post-operative side effects.

MATERIALS AND METHODS

Patients

We retrospectively analyzed 36 consecutive patients with medication-refractory essential tremor or Parkinson's disease who underwent unilateral VIM MRgFUS at our institution between May 2022 and June 2023. All patients were diagnosed by board-certified neurologists. We excluded six patients with absent or poor-quality pre-operative FGATIR images. Thirty patients were included in the analysis (21 males, age 75.0 ± 8.0 years) (Online Supplemental Data). This research was approved by the Institutional Review Board and informed consent was waived for the retrospective study.

Image Acquisition

We acquired FGATIR, T1-weighted MPRAGE, and 3D or 2D T2-weighted image for pre-operative scan, either a 3D T1-weighted fast spoiled gradient-echo or a 3D fast imaging employing steady-state acquisition during the operation, and T1-weighted MPRAGE and T2-weighted images for post-operative scan, which were

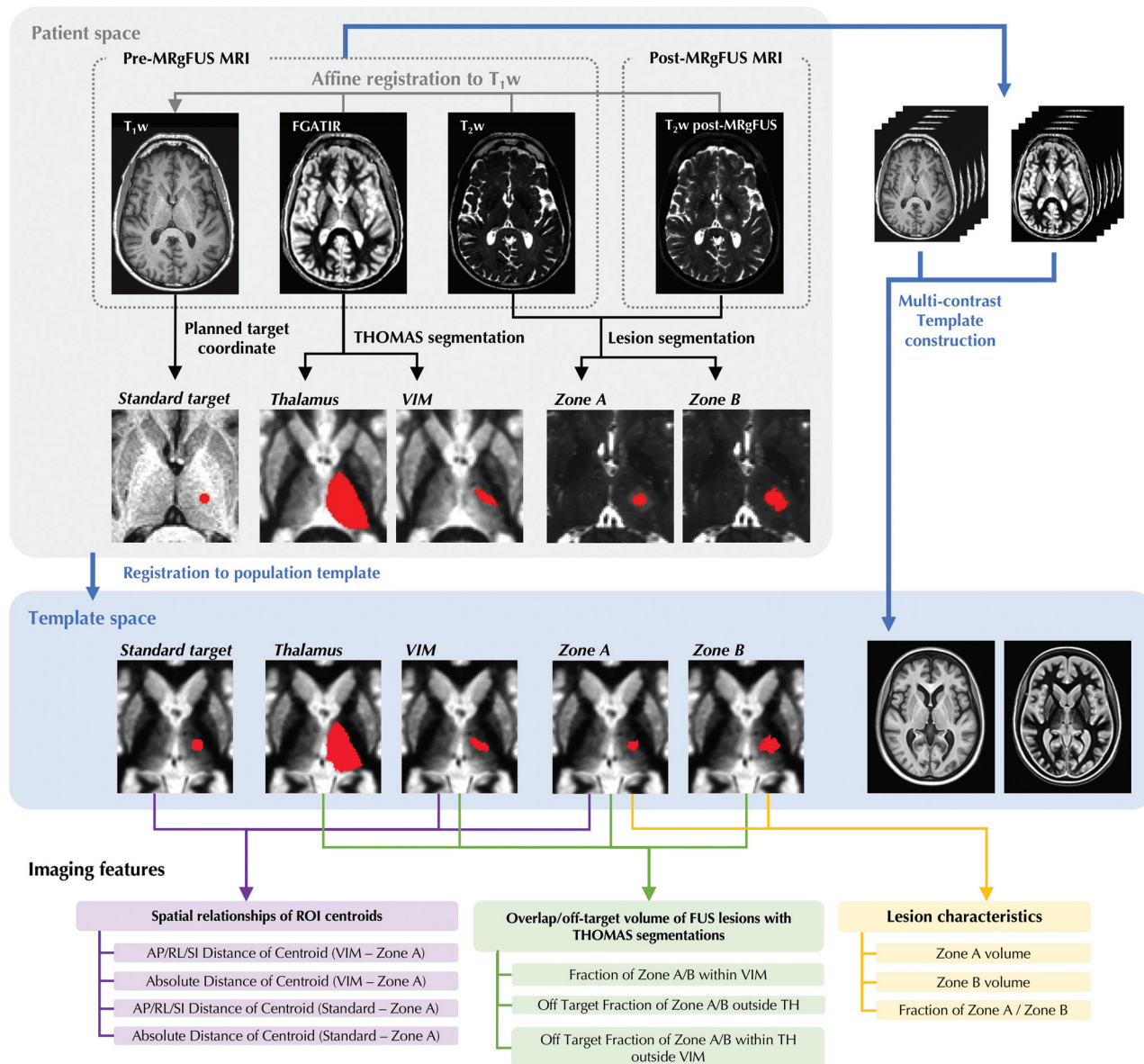


FIG 1. Imaging feature extraction pipeline. ROIs of standard target, FUS lesions and THOMAS segmentations were registered to the population-specific template generated from pre-operative T_1w and FGATIR images. Spatial relationships of ROI centroids, overlap of FUS lesions with segmentations and lesion volume characteristics were assessed. MRgFUS, MR-guided focused ultrasound; FGATIR, Fast Gray Matter Acquisition T_1 Inversion Recovery; THOMAS, Thalamus Optimized Multi Atlas Segmentation; VIM, ventral intermediate nucleus; TH, thalamus; AP, anterior-posterior; RL, right-left, SI, superior-inferior; ROI, region of interest.

acquired the following day of MRgFUS. Detailed sequence parameters are provided in the Online Supplemental Data.

MRgFUS Procedure

The therapeutic sonication of the targeted VIM was performed in an MRgFUS system (ExAblate Neuro, InSightec, Tirat Carmel, Israel). Details of the MRgFUS procedure have been described in prior studies.^{2,32} The ablation target coordinate was specified pre-operatively as one quarter of the length of the AC-PC line from the PC, 14 mm lateral to the midline or 11 mm lateral to third ventricle, and 3 mm superior to the AC-PC line, and fused to intra-operative MR images. Target localization was adjusted further intraoperatively by clinical monitoring of side effects and the reduction of tremor for each patient.

Image Post-processing

Five ROIs were generated in patient space for analysis, including the standard treatment target, thalamus segmentation, VIM segmentation, and two FUS lesion segmentations (Figure 1). All images were co-registered to the pre-operative T_1 -weighted image using an affine transformation in FSL (FLIRT; FMRIB Software Library, Oxford, England; <http://www.fmrib.ox.ac.uk/fsl/>) prior to subsequent processing.

Standard FUS Target. We generated the spherical ROI of the standard VIM ablation target with a radius of 4 mm centered on the coordinates of the first sonication recorded in the MRgFUS workstation, which was determined by the indirect targeting

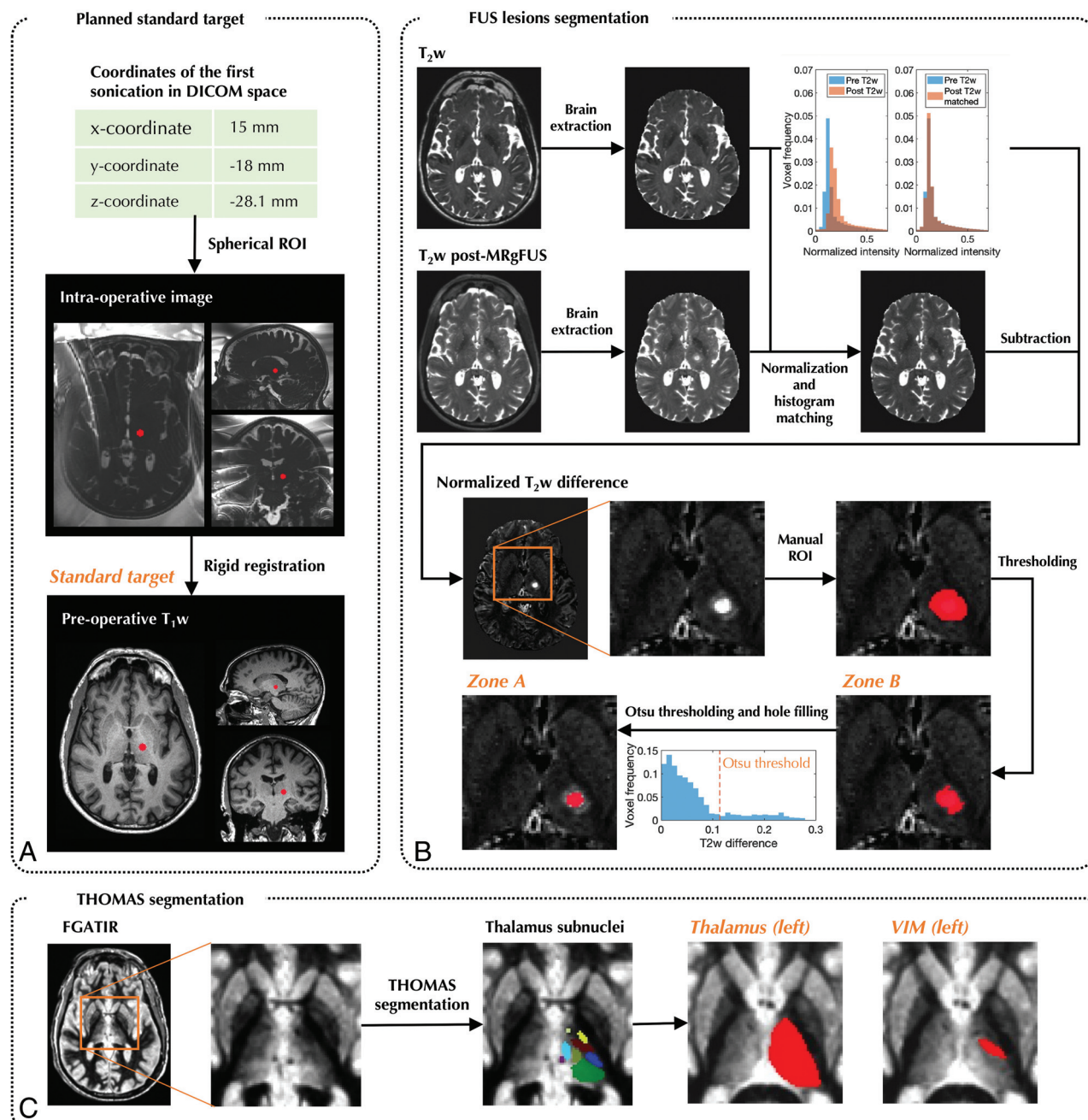


FIG 2. Procedures to create standard target, FUS lesions and THOMAS segmentations of thalamus and VIM. A, Standard target ROIs were created from coordinates of the first sonication. B, FUS lesions were generated by subtracting the pre-operative T₂-weighted image from the post-operative image and applying a thresholding method. C, The thalamus and VIM were segmented by applying THOMAS to pre-operative FGATIR images. The VIM here corresponds to the ventral part (inferior half) of the ventral lateral posterior nucleus in the Morel atlas. MRgFUS, MR-guided focused ultrasound; THOMAS, THalamus Optimized Multi Atlas Segmentation; VIM, ventral intermediate nucleus; FGATIR, Fast Gray Matter Acquisition T1 Inversion Recovery; ROI, region of interest.

method based on the AC-PC line as described in the previous paragraph (Figure 2A).

FUS Lesion Segmentations. Pre- and post-operative T₂-weighted images were used to identify FUS-induced lesions. We created the ROIs of Zone A, which includes a strongly hyperintense cytotoxic edema and a central hypointense coagulation necrosis on T₂-weighted images, and Zone B, which includes the Zone A and the peripheral slightly hyperintense area of vasogenic

edema.³³⁻³⁵ The ROIs were created by subtracting pre-operative T₂-weighted images from post-operative T₂-weighted images after registration, normalization, and histogram matching. Otsu thresholding method was applied to delineate the ROIs. The detailed procedure is described in the Online Supplemental Data and in Figure 2B.

THOMAS Segmentations. Pre-operative FGATIR images were processed with the THOMAS segmentation tool, a pipeline

designed to achieve optimal performance on white matter-nulled imaging contrasts (https://github.com/thalamicseg/thomas_new)³¹ to create segmentations of the thalamus (TH) and VIM of the treated side (Figure 2C).

Cohort Template Construction

We created an MRI template specific for the study population using the Advanced Normalization Tools multivariate template construction algorithm (*antsMultivariateTemplateConstruction*).³⁶ For each subject, the ROIs generated in previous steps were nonlinearly aligned to the population-specific template to enable direct comparisons across the subjects (Figure 1). The details of template creation and the figure of THOMAS segmentations on cohort template images are included in the Online Supplemental Data.

Imaging Features

We calculated the following imaging features: spatial relationships of ROI centroids (anterior-posterior [AP], right-left [RL], superior-inferior [SI] and absolute distances), overlap/off-target volume of FUS lesions with THOMAS segmentations, and lesion volume characteristics (Figure 1). Details are documented in the Online Supplemental Data.

Clinical Assessment

We reviewed the clinical records of self-reported and examination-based gait or balance disturbance on the day after MRgFUS and self-reported gait or balance disturbance at one-month post-procedure. The record of self-reported side effects at one month after surgery was not available for one patient. In order to assess the relationships between imaging features and treatment efficacy, we evaluated post-treatment Fahn-Tolosa-Marín Clinical Rating Scale for Tremor (FTM) scores of the treated side on the day after MRgFUS, and the reduction in drawing test scores from before to after the procedure, both of which were evaluated in the operating room. Details are documented in the Online Supplemental Data.

Statistical Analysis

We compared imaging features between patients with side effects and those without using Wilcoxon rank-sum test. Voxel-wise analysis was performed using a chi-square test to determine if the proportion of subjects with a Zone A lesion in that voxel differed between patients with and without side effects. In addition, we built multivariate prediction models of self-reported/exam-based side effects using three imaging features that showed the largest z-statistics in cross-sectional comparisons. We further evaluated models using features associated solely with THOMAS segmentations and lesion core (Zone A), to assess the potential of THOMAS segmentations for guiding the ablation procedure. The classification performance of the models was evaluated using the receiver operating characteristic curve analyses. Comparison of imaging features was also performed between patients with no side effects or with side effects that resolved within one month and those with persistent side effects after one month. Lastly, we assessed correlations between imaging features and FTM scores using Spearman's rank correlation. Benjamini-Hochberg (BH) correction was performed for multiple comparison and correlation tests. $P < 0.05$ after BH correction was considered statistically significant.

RESULTS

All patients demonstrated marked tremor improvement as suggested by low post-operative tremor scores and patients' self-report. Eighteen patients reported gait or balance disturbance on the day following MRgFUS procedure, with seven exhibiting these disturbances based on physical examination. One of these patients showed lower extremity weakness, while the others displayed gait instability or imbalance. Five out of 18 patients reported symptoms persisting after one month. Detailed clinical evaluations for each patient are provided in the Online Supplemental Data.

Example ROIs from two subjects are illustrated in Figure 3, depicting the FUS lesions and THOMAS segmentations, as well as their spatial relationships. In the patient with the gait and balance side effects, the FUS lesion extended further outside of the thalamus and VIM segmentations, compared to the patient without side effects. Figure 4 illustrates THOMAS-based thalamic nuclei segmentations, Zone A probabilistic maps, and standard targets of all subjects and subjects with or without side effects in the population-specific template space, and the result of voxel-wise analysis. Visually, the lesions in the group of patients with side effects were shifted more laterally and inferiorly relative to the VIM. The voxel-wise analysis indicates that voxels outside the VIM segmentation tend to have a higher proportion of patients with side effects compared to those without. The comparison of imaging features between patients with and without side effects are summarized in the Table and the Online Supplemental Data. Based on FUS lesion analysis, Zone B volume was significantly larger in patients with self-reported side effects (1.67 ± 0.70 ml vs. 1.04 ± 0.34 ml, $p_{\text{uncorrected}} = 0.01$, $p_{\text{BH}} = 0.03$). The fraction of Zone A/Zone B was smaller in both patients with self-reported side effects (0.20 ± 0.07 vs. 0.26 ± 0.07 , $p_{\text{uncorrected}} = 0.01$, $p_{\text{BH}} = 0.03$) and those with physical exam-based side effects compared to patients without (0.18 ± 0.05 vs. 0.24 ± 0.08 , $p_{\text{uncorrected}} = 0.04$), although the difference with physical exam-based side effects was not significant after BH correction.

We found that the volume fraction in Zone A or B overlapping with VIM was significantly smaller in patients with self-reported side effects (Figure 5A; Zone A within VIM: 0.31 ± 0.14 vs. 0.50 ± 0.17 , $p_{\text{uncorrected}} = 0.006$, $p_{\text{BH}} = 0.02$; Zone B within VIM: 0.14 ± 0.07 vs. 0.23 ± 0.07 , $p_{\text{uncorrected}} = 0.001$, $p_{\text{BH}} = 0.005$). Similarly, these measurements also trended smaller in patients with physical exam-based side effects, albeit without statistical significance after BH correction (Figure 5D; Zone A within VIM: 0.27 ± 0.12 vs. 0.43 ± 0.18 , $p_{\text{uncorrected}} = 0.03$; Zone B within VIM: 0.11 ± 0.05 vs. 0.20 ± 0.08 , $p_{\text{uncorrected}} = 0.01$). The off-target lesion volume fractions outside TH positively correlated with the presence of side effects, with higher off-target fractions found in patients with self-reported side effects (Figure 5B; Zone A outside TH: 0.33 ± 0.22 vs. 0.09 ± 0.07 , $p_{\text{uncorrected}} < 0.001$, $p_{\text{BH}} = 0.004$; Zone B outside TH: 0.52 ± 0.13 vs. 0.27 ± 0.08 , $p_{\text{uncorrected}} < 0.001$, $p_{\text{BH}} < 0.001$). The same features were also higher in patients with physical exam-based side effects (Figure 5E; Zone B outside TH: 0.57 ± 0.14 vs. 0.38 ± 0.15 , $p_{\text{uncorrected}} = 0.003$, $p_{\text{BH}} = 0.04$). There was no significant difference in imaging features between patients with and without persistent side effects at one month after BH multiple comparison correction, although our data showed a

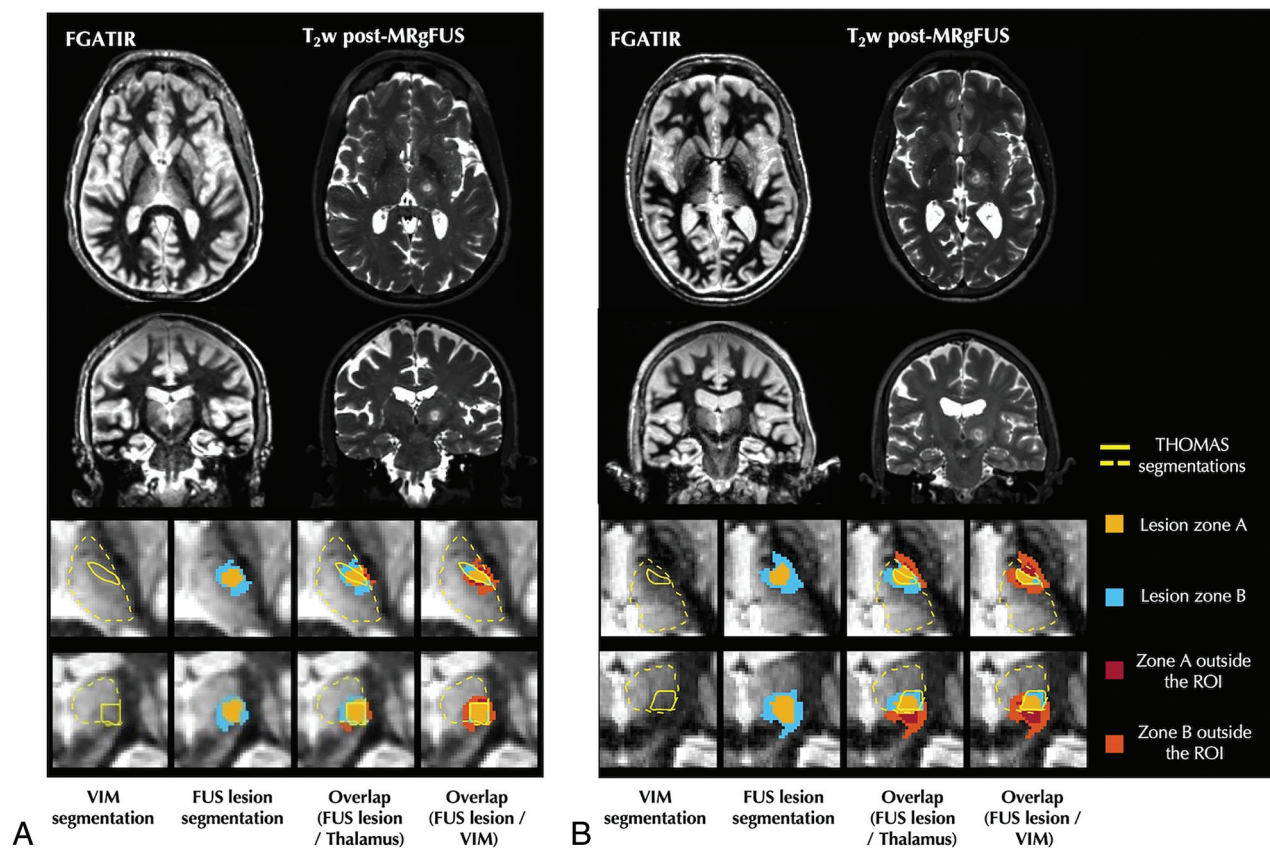


FIG 3. Example THOMAS segmentations (yellow line: thalamus; white line: VIM nucleus) and MRgFUS treated lesions (magenta: Zone A; cyan: Zone B) are shown in axial and coronal views. In the patient with side effects A, lesions extend farther out of the thalamus and segmented VIM, compared to the patient without side effects (B). FGATIR, Fast Gray Matter Acquisition T1 Inversion Recovery; MRgFUS, MR-guided focused ultrasound; THOMAS, Thalamus Optimized Multi Atlas Segmentation; VIM, ventral intermediate nucleus; ROI, region of interest.

trend where patients with persistent side effects showed a smaller fraction of Zone B overlapping with VIM and larger off-target fraction of Zone A or B outside TH compared to those without or with side effects that resolved at one month ($p_{uncorrected} < 0.05$).

As for the spatial relationships between FUS lesions and THOMAS segmentations, the centroid of Zone A tended to be more posterior, lateral and inferior in patients with self-reported side effects compared to those without, although only superior-inferior direction showed statistical significance (SI distance -2.77 ± 1.43 mm vs. -1.14 ± 0.96 mm, $p_{uncorrected} < 0.001$, $p_{BH} = 0.007$). Absolute distance between the centroids of Zone A and the VIM was significantly larger in patients with self-reported side effects (3.79 ± 1.33 mm vs. 2.55 ± 0.83 mm, $p_{uncorrected} < 0.001$, $p_{BH} = 0.02$). Absolute distance between the centroids of Zone A and the VIM was also higher in patients with exam-based side effect, although not significant after BH correction (4.20 ± 1.35 mm vs. 3.01 ± 1.17 mm, $p_{uncorrected} = 0.04$). As for the distance between FUS lesions and the standard planned FUS target, patients with physical exam-based side effects showed Zone A in a more posterior position relative to standard FUS target compared to those without side effects (-0.39 ± 0.69 mm vs. 0.63 ± 0.71 mm, $p_{uncorrected} = 0.005$). Plots of VIM and lesion centroids for patients with and without side effects in the population-specific template space are depicted in the Online Supplemental Data.

Multivariate regression models using the three most differentiating imaging features were established to predict side effects. The selected imaging features for predicting self-reported side effects include off-target fractions of Zone A/B outside TH, and off-target fraction of Zone B outside VIM and within TH. The multivariate model achieved the area under the curve (AUC) of 0.99 (95% CI: 0.88–1.00) with sensitivity of 100% and specificity of 92% (Figure 5C). For predicting physical exam-based side effects, the selected features include off-target fractions of Zone B outside TH, fractions of Zone B within VIM, and AP distance between the centroids of Zone A and standard coordinate. Similarly, the multivariate model achieved high AUC of 0.96 (95% CI: 0.73–1.00) with sensitivity of 86% and specificity of 100% (Figure 5F). Multivariate models using only the imaging features based on the spatial relationships between THOMAS segmentations and Zone A achieved AUC of 0.91 (95% CI: 0.71–0.99, sensitivity 72%, specificity 100%) for identifying patients with self-reported side effects and AUC of 0.78 (95% CI: 0.59–0.93, sensitivity 100%, specificity 65%) for identifying patients with physical exam-based side effects.

The results of the correlation between imaging features and tremor control, using post-operative tremor score and the reduction in drawing scores after MRgFUS, are shown in the Online Supplemental Data. Although no significant correlation between imaging features and FTM scores was found after BH multiple

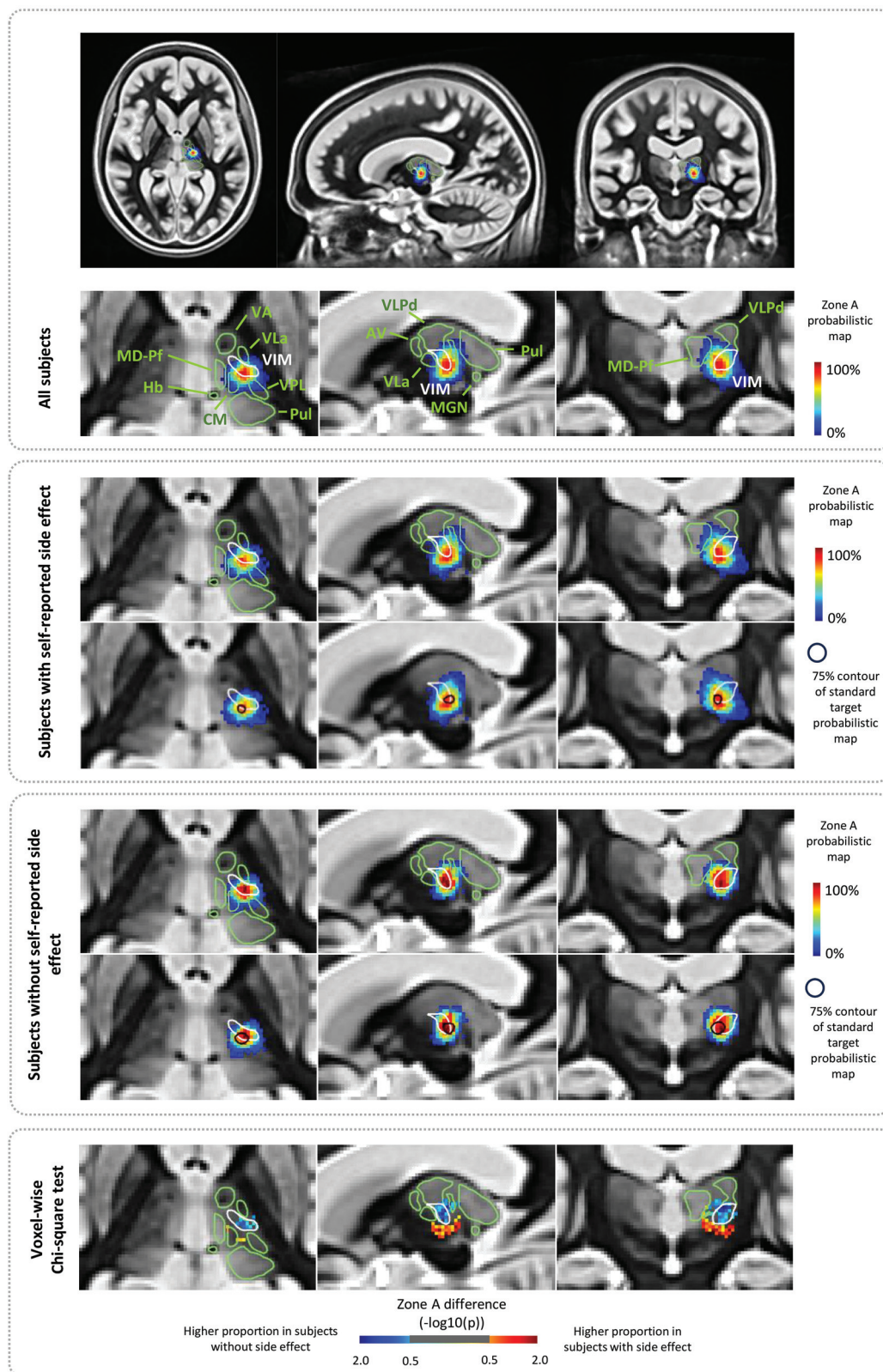


FIG 4. Probabilistic maps of Zone A in the population-specific template space. The spatial relationship between THOMAS-based thalamic nuclei segmentations, Zone A probabilistic maps, and standard targets are illustrated in different cohorts. The Zone A probabilistic map represents the voxel-wise percentage of FUS lesions across the subjects, and the standard target contour represents 75th percentile of standard coordinate ROI across the subjects. THOMAS, THalamus Optimized Multi Atlas Segmentation; FUS, focused ultrasound; VA, ventral anterior nucleus; VLa, ventral lateral anterior nucleus; VLP, ventral lateral posterior nucleus; VPL, ventral posterior lateral nucleus; VPLd, dorsal part of ventral posterior lateral nucleus; Pul, pulvinar nucleus; CM, centromedian nucleus; MD-Pf, mediodorsal-parafascicular nucleus; Hb, habenula; MGN, medial geniculate nucleus; ROI, region of interest.

Comparisons of imaging features between patients with and without side effect

		Self-Reported Side Effect		Physical Exam-Based Side Effect
		Gait/Balance	Gait/balance > 1 Month	Gait/Balance
MRI Features		<i>p</i> -Value	<i>p</i> -Value	<i>p</i> -Value
FUS lesion volume	Volume of Zone A	0.21	0.31	0.96
	Volume of Zone B	0.01	0.15	0.14
	Fraction of Zone A/Zone B	0.01	0.45	0.04
Overlap between FUS lesions and THOMAS segmentations	Fraction of Zone A within VIM ^a	0.006	0.09	0.03
	Fraction of Zone B within VIM ^a	0.001	0.01	0.01
	Off Target Fraction of Zone A outside TH ^b	< 0.001	0.02	0.02
	Off Target Fraction of Zone B outside TH ^b	< 0.001	0.008	0.003
	Off Target Fraction of Zone A within TH ^c	0.57	0.22	1
	Off Target Fraction of Zone B within TH ^c	< 0.001	0.07	0.05
Distance between FUS core lesion and THOMAS segmentations	AP Distance of Centroid (VIM - Zone A)	0.57	0.45	0.52
	RL Distance of Centroid (VIM - Zone A)	0.49	0.52	0.34
	SI Distance of Centroid (VIM - Zone A)	< 0.001	0.27	0.1
	Absolute Distance of Centroid (VIM - Zone A)	< 0.001	0.19	0.04
Distance between FUS core lesion and standard coordinate	AP Distance of Centroid (Standard - Zone A)	0.64	0.32	0.005
	RL Distance of Centroid (Standard - Zone A)	0.17	0.94	0.74
	SI Distance of Centroid (Standard - Zone A)	0.43	0.69	0.7
	Absolute Distance of Centroid (Standard - Zone A)	0.23	0.65	0.7

^a Volume of overlap between Zone A (or B) and VIM divided by that of Zone A (or B).

^b Volume of Zone A (or B) outside TH divided by that of Zone A (or B).

^c Volume of Zone A within TH but outside VIM divided by that of Zone A (or B).

P-values in the table represent uncorrected *p*-values. The bolded items represent statistical tests with Benjamini–Hochberg corrected *p*-values < 0.05.

Abbreviations: FUS, focused ultrasound; THOMAS, THalamus Optimized Multi Atlas Segmentation; VIM, ventral intermediate nucleus; TH, thalamus; AP, anterior-posterior; RL, right-left, SI, superior-inferior.

statistics correction, lower positioning of Zone A relative to the VIM showed a tendency to correlate with a lower post-operative tremor score and a greater reduction in drawing score.

DISCUSSION

To examine the usefulness of FGATIR in combination with the thalamus segmentation algorithm, THOMAS, on improving VIM MRgFUS precision, we retrospectively assessed the relationships between FUS lesions and THOMAS segmentations derived from pre-FUS images, and the conventional target adopted during FUS procedures in 30 ET and tremor-dominant PD patients. Two main results emerged from our study: (1) patients with post-FUS gait and balance side effect exhibit significantly different spatial relationships between FUS lesions and THOMAS-based segmentations compared to those without; (2) multivariate models based on imaging characteristics of FUS lesions and THOMAS segmentations demonstrated high predictive accuracy for post-procedural side effects.

Our findings align with previous research,^{6,13,37} indicating that a larger volume of Zone B and a smaller fraction of Zone A/Zone B – indicative of a greater extent of vasogenic edema – are associated with gait and balance side effects. One potential explanation is that the larger area of vasogenic edema may lead to the disruption of the corticospinal and/or cerebellothalamic tracts. In addition to the adjustments to the duration and temperature of sonication during the procedure, hardware improvement to reduce the size of lesions could be an effective approach to minimizing side effects, while it is necessary to consider that excessively small lesions may lead to insufficient therapeutic efficacy.³⁸

Our results also showed that patients with acute gait and balance side effects exhibited a significantly smaller fraction of Zone

A or Zone B within VIM and a larger off-target lesion fraction outside TH, alongside a greater distance between Zone A and VIM. Although only superior-inferior direction showed statistical significance, there was a trend for the centroid of Zone A to be more posterior, lateral and inferior relative to the VIM, supporting previous evidence that lesions inferolateral to the thalamus were associated with an increased risk of acute adverse effects on gait and dysmetria.^{13,37,39} These results are associated with the finding that gait difficulties occur due to lesions impacting the corticospinal tract, which is located just lateral to the VIM.^{13,21} Our results add to the existing literature reporting lesion location as a significant factor impacting post-FUS side effect, and provides evidence that such off-target effects can be quantitatively evaluated using imaging features retrieved with a semi-automated processing procedure. These findings also highlight the utility of THOMAS-based segmentations in refining targets to reduce the acute side effects of MRgFUS. As demonstrated in previous literature, the dentatorubrothalamic tract, which is relayed by the VIM nucleus, also contributes to gait side effects. Therefore, even if the VIM is precisely targeted, side effects are still considered to occur with suboptimal size and temperature of the lesion.¹³ This explains the overlap in the locations of FUS lesions between patients with and without gait side effects in our study, as shown in Figure 5 and Supplementary Figure 2.

Among the 18 patients experiencing acute side effects post-MRgFUS, five reported persistent side effects one month later, a slightly lower incidence rate than previously reported.¹⁹ No significant differences were found in imaging features between patients with and without persistent side effects after BH correction. However, trends toward significance were observed in the overlap of Zone A/B with the VIM and the off-target Zone A/B

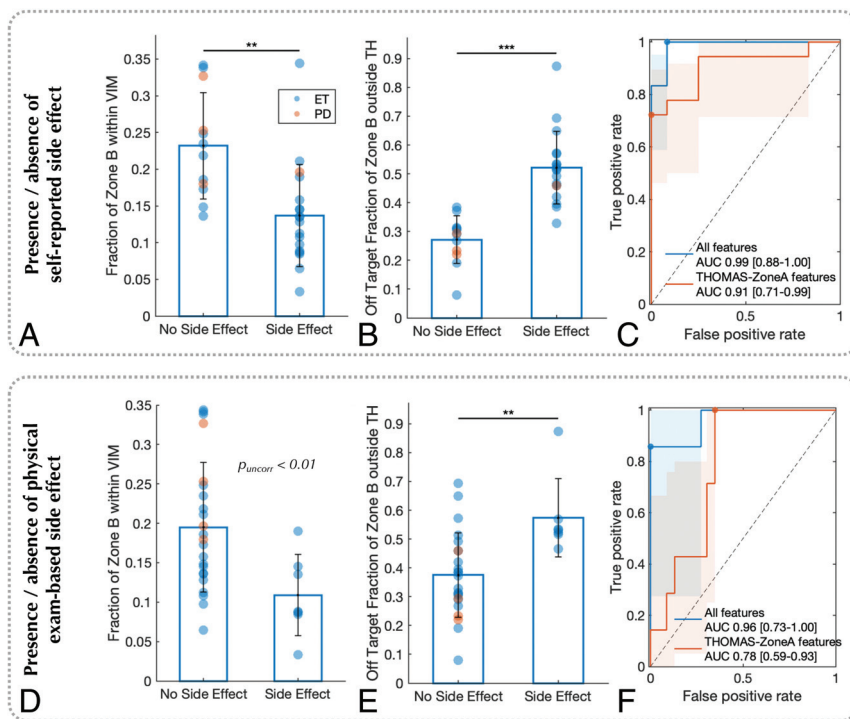


FIG 5. Results of imaging feature comparisons between patients with self-reported or physical exam-based gait/balance side effects and those without. In patients with side effects, Zone B shows less overlap with VIM segmentation and the off-target fraction of Zone B outside TH segmentation is greater (Graphs A–B and D–E). Graphs C and F show receiver operating characteristic curves of multivariate prediction models of side effects using imaging features. ET, essential tremor; PD, Parkinson's disease; VIM, ventral intermediate nucleus; TH, thalamus; AUC, area under the curve.

fraction outside the thalamic segmentation. Given that post-FUS lesion decreases over time and lesion shrinkage varies among individuals, future studies incorporating long-term follow-up MR imaging may assist the identification of specific imaging characteristics associated with persistent side effects.

THOMAS was developed using manual segmentations of 7T white matter-nulled MPRAGE data guided by the Morel atlas.^{31,40} Similar to white matter-nulled MPRAGE, FGATIR provides improved intra-thalamic contrast by highlighting grey matter structures that are surrounded by highly myelinated areas using preferential nullification of white matter signal.³⁰ Such unique contrast is thought to contribute to the reliability of THOMAS segmentation, as validated by high Dice coefficient scores when compared to the ground truth segmentation by expert neuroradiologist.³¹ The VIM segmentation obtained using THOMAS on pre-operative images can effectively guide target selection for pre-operative planning and assist with intra-operative adjustments. Despite its great potential, the clinical application of THOMAS in direct VIM targeting for neuromodulatory treatments like deep brain stimulation or MRgFUS has been scarcely evaluated. Notably, a recent study using THOMAS on 7T MRI found no correlations between overlap/spatial relationships of ablation lesions with VIM and 1-month post-treatment clinical outcome,¹⁷ which is consistent with our results. Expanding upon existing research, our study explores the link between FUS-induced imaging characteristics and side effects using THOMAS

with 3T MR images. While it is an expected finding that post-procedural side effects are associated with off-target ablation, our study provides rigorous quantitative evidence supporting this hypothesis. Additionally, the integration of FGATIR and THOMAS in our methodology can serve as a practical tool for objective and reproducible localization of VIM, for both pre-operative planning and intra-operative adjustments, reducing the reliance on neurosurgeons' experience and expertise.

There have been increasing efforts to improve the targeting of VIM for neuromodulation using various advanced imaging methods.^{1,21,41} VIM targets based on patient-specific dentatorubrothalamic tracts demonstrated by DTI were more anterior and medial than the indirect methods, which may help avoid regions at risk for motor and sensory adverse effects, and VIM targeting by DTI showed reduced post-procedure acute ataxia as compared to indirect targeting.^{19,42} Compared to tractography-based methods, segmenting FGATIR images using THOMAS offers several advantages. First, FGATIR has a higher resolution (about 1-mm isotropic) than DTI (about 2-mm isotropic).

Second, FGATIR is less susceptible to image distortion compared to DTI.⁴³ Tractography based on DTI data may also suffer from inadequate representation of the underlying anatomy in areas with crossing fibers and within gray matter structures such as the thalamus.^{44,45} As such, its usefulness as the primary method of VIM targeting are still being debated.⁴⁶ Other direct VIM imaging methods include susceptibility weighted imaging^{23,25,26} and quantitative susceptibility mapping,²⁴ which have only been evaluated at ultrahigh field of 7T, but not at the more clinically-accessible field strength of 3T or lower. On the other hand, the THOMAS segmentation method we evaluated provides reliable high-resolution targeting of VIM using clinically available FGATIR images acquired by 3T MRI.

MRgFUS is influenced by various factors beyond targeting, such as low skull density ratios, which require higher energy to reach therapeutic temperatures.⁴⁷ Additionally, thermal ablation lesions in the focal zone form a prolate ellipsoid shape.⁴⁸ Techniques like CT-based aberration correction and echo focusing have been developed to stabilize lesion formation, but further research is needed to confirm their full effectiveness.⁴⁷

Our study has several limitations. First, a systematic pre-operative and long-term follow up tremor and side effect evaluations were not available. More rigorously controlled studies with adequate pre- and long-term tremor scores are necessary to evaluate the impact of VIM segmentation by THOMAS on tremor improvement and persistent side effects. Furthermore,

although we performed the additional analysis using physical exam-based gait and balance assessment to overcome the subjective bias of self-reported side effects, prospective studies of MRgFUS-associated side effect using quantitative measures such as Berg Balance Scale and standardized pre- and post-procedure neurologic exam protocols will provide a more comprehensive and robust evaluation of gait and balance impairment. Such methods are particularly crucial for ET and PD, which are prone to causing gait disturbances. Second, due to the limited number of patients, we did not assess other side effects including sensory and speech symptoms. While less common than gait disturbance, these side effects are critical for patients' quality of life.^{13,42} Lastly, the relatively small difference of distance observed between the two groups compared to MRI resolutions indicates that the precise targeting of VIM would benefit from techniques with improved imaging resolution. Future developments to enhance MRI resolution, including ultrahigh field MRI and super-resolution deep learning approaches may further increase the accuracy of THOMAS for direct targeting.

CONCLUSIONS

In conclusion, THOMAS segmentation derived imaging features predict post-operative gait/balance side effect in patients treated with VIM MRgFUS, and may provide a potential tool for aiding the direct targeting of VIM and reducing side effects in patients undergoing MRgFUS.

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