

Original article

Imaging of the centromedian thalamic nucleus using 3D fast gray matter acquisition T1 inversion recovery sequence in 3T MRI in epilepsy

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Abstract

Background: The centromedian thalamic nucleus (CM) is an emerging deep brain stimulation (DBS) target for neurological disorders, including drug-resistant epilepsy. Traditional DBS localization relies on predefined stereotactic coordinates, which may be imprecise. Innovative magnetic resonance imaging (MRI) sequences enhance gray–white matter contrast, potentially allowing direct CM visualization and improving accuracy in DBS planning and targeting.

Objective: This study evaluated the 3D fast gray matter acquisition T1 inversion recovery (FGATIR) MRI sequence for visualizing the CM in patients with epilepsy.

Methods: This prospective IRB-approved descriptive study included adult patients with epilepsy who underwent a 3D FGATIR MRI sequence at 3 Tesla. Two neuroradiologists independently assessed CM visualization using qualitative grading and quantitative measurements of signal-to-noise ratios (SNR) and contrast-to-noise ratios (CNR) of the CM and three neighboring nuclei. These nuclei included the mediodorsal (MD), medial pulvinar (PuM), and ventrolateral (VL) nuclei in each thalamus. Interobserver agreement for quantitative assessment was evaluated with the intraclass correlation coefficient (ICC).

Results: A total of 16 patients with epilepsy (mean age 42.8 ± 21.3 years, 44.0% male) were included. Qualitative assessment revealed good CM visualization in 84.0% and poor CM visualization in 16.0% of cases. Mean signal intensities and SNRs differed significantly between the CM and other neighboring thalamic nuclei ($P < 0.001$). CNRs of the CM relative to the MD, PuM, and VL varied across the thalami. Interobserver agreement was excellent, with $ICC > 0.96$ for all measurements.

Conclusion: The 3D FGATIR MRI sequence is a practical tool to visualize the CM. Its adoption in clinical practice could potentially improve DBS planning.

Keywords: Centromedian thalamic nucleus, epilepsy, fast gray matter acquisition T1 inversion recovery, magnetic resonance imaging, thalamus.

Deep brain stimulation (DBS) is a neurosurgical procedure that involves the implantation of electrodes into specific regions of the brain to modulate neural activity for therapeutic purposes. The centromedian thalamic nucleus (CM) is an emerging DBS target, which has potential as a treatment area for various

neurological and psychiatric disorders, including drug-resistant epilepsy, Tourette syndrome, neuropathic pain, and disorders of consciousness.⁽¹⁾

The CM is a spheroid-shaped structure approximately 10 mm in diameter that is located among the caudal intralaminar thalamic nuclei. It is involved in sensorimotor coordination, cognition, and pain processing.⁽²⁾

Previously, the indirect targeting method based on established stereotactic coordinates was commonly used to localize the CM, as direct visualization via structural neuroimaging was not available.^(3, 4) However, the traditional indirect targeting method

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Received: January 14, 2026

Revised: February 18, 2026

Accepted: March 28, 2026

often failed to account for interpatient anatomical variability, leading to suboptimal outcomes and an increased risk of adverse effects.⁽⁵⁾ With the advent of newer magnetic resonance imaging (MRI) sequences, direct visualization of the CM and several other DBS targets has become possible. Several studies have employed MRI at 3 Tesla and 7 Tesla to delineate and map the intrathalamic nuclei, thereby demonstrating their ability to provide detailed anatomical localization. Some of these studies employed MP2RAGE⁽¹⁾, quantitative susceptibility mapping (QSM)⁽⁶⁾, white matter nulled-MPRAGE⁽⁷⁾, edge-enhancing gradient echo⁽⁸⁾, and diffusion tensor imaging.⁽⁹⁾ However, these advanced MRI sequences are not routinely included in standard clinical protocols and require specialized acquisition techniques along with complex postprocessing.

Fast Gray Matter Acquisition T1 Inversion Recovery (FGATIR) is an MRI sequence that is specifically designed to optimize the visualization of DBS targets.⁽¹⁰⁾ It was developed as a modification of the standard Magnetization-Prepared Rapid Gradient Echo sequence by modifying the conventional 90° saturation pulse to a full 180° inversion pulse during the inversion prepulse stage. This allows magnetization to become negative, thereby increasing the possible T1 contrast range and improving differentiation between gray matter, white matter, and cerebrospinal fluid (CSF). The inversion time (TI) is set to nullify the white matter signal, thereby maximizing the contrast between gray and white matter. The use of a short TI results in contrast inversion of some regions relative to conventional T1-weighted images. For instance, CSF, which typically appears dark on conventional T1-weighted images, appears bright in FGATIR images.⁽¹⁰⁾

FGATIR is a commercially available MRI sequence that is compatible with 3 Tesla clinical MRI scanners and does not require advanced postprocessing, which makes it a promising tool for visualizing DBS targets. Moreover, the advantage of 3D FGATIR is its 3D acquisition, which provides thin-slice imaging and enables multiplanar reconstruction, thus allowing for enhanced anatomical visualization from multiple views. A survey of U.S. epilepsy centers reported the use of MP2RAGE and FGATIR sequences to identify thalamic targets in patients with drug-resistant epilepsy.⁽¹¹⁾ At 3 Tesla, FGATIR has demonstrated the ability to delineate the borders of deep brain nuclei, including the subthalamic nucleus⁽¹²⁾,

dentatorubrothalamic tract⁽¹³⁾, thalamus, striatum, globus pallidus, red nucleus, substantia nigra pars reticulata⁽¹⁰⁾, mammillothalamic tract for targeting the anterior nucleus of the thalamus⁽¹⁴⁾, and ventrolateral thalamic nuclei.⁽¹⁵⁾ However, no studies have specifically evaluated the use of 3D FGATIR for identifying the CM, despite its demonstrated ability in determining other deep brain structures. We hypothesized that the 3D FGATIR sequence at 3 Tesla MRI would serve as an optional imaging modality for identifying the CM, thereby providing an additional tool for DBS planning. The objective of this study was to evaluate the 3D FGATIR sequence for visualization of the CM in patients with epilepsy.

Materials and methods

Study design and participants

The study was reviewed and approved by the institutional review board (IRB no. 0718/66), and all participants provided written informed consent prior to enrollment. This was a single-center, prospective descriptive study. Eligible participants were patients with epilepsy who underwent an MRI brain epilepsy protocol or functional MRI as part of preoperative planning between March 2023 and October 2024. The inclusion criteria were consenting adult epilepsy patients aged >18 years who underwent an MRI brain epilepsy protocol or functional MRI for preoperative planning on a GE Signa Premier 3 Tesla clinical scanner, with an additional 3D FGATIR scan. The exclusion criteria were poor image quality, thalamic lesions, evidence of prior thalamic surgery, and congenital brain anomalies. Demographic information regarding the patients' age, gender, and type of epilepsy was collected.

Data acquisition

Imaging was performed using a 3 Tesla GE Signa Premier scanner equipped with a 24-channel head coil. Each patient was positioned supine with the head fixed to minimize motion artifacts and underwent MRI, which included a 3D FGATIR sequence. The field of view of the 3D FGATIR sequence covered the whole thalamus. The acquisition time for the 3D FGATIR sequence was 5 min. Detailed imaging parameters for the 3D FGATIR sequence, including repetition time (TR), echo time (TE), field of view, and acquisition time, are summarized in **Table 1**.

Table 1. Imaging parameters.

Parameters	3DFGATIR
Imaging plane	Axial
Repetition time (TR) (ms)	7.7
Echo time (TE) (ms)	3.2
Flip angle (degrees)	8.0
Inversion time (prep time) (ms)	450
Inversion time (recovery time) (ms)	2500
Field of view (mm)	240 x 90
Matrix	256x280
Slice thickness (mm)	1.2
Spacing (mm)	0.6
NEX	1.0
Bandwidth (Hz/Px)	223
Voxel size	0.9 x 0.9 x 1.2
Parallel acceleration factor	2.0
Acquisition time (minutes)	5.0

FGATIR, fast gray matter acquisition T1 inversion recovery.

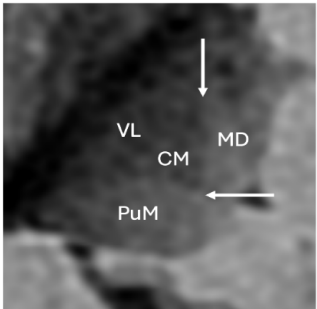
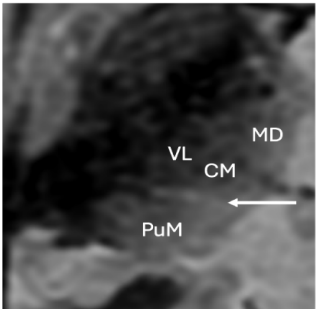
Good visualization	Poor visualization	Non-visualization
≥2 borders identifiable	1 border identifiable	no identifiable borders
		N/A
-Identifiable borders between CM and MD, and CM and PuM (white arrows) -Lateral border between CM and VL not identifiable	-Identifiable border between CM and PuM (white arrow) -Borders between CM and MD, and CM and VL not identifiable.	N/A

Figure 1. Three-point scale for qualitative assessment of the visualization of CM. CM centromedian thalamic nucleus; MD, mediodorsal thalamic nucleus; PuM, medial pulvinar thalamic nucleus; VL, ventrolateral thalamic nucleus.

Image inspection and data analysis

Two board-certified neuroradiologists, with 13 and 6 years of experience, independently reviewed the MRI images and performed qualitative and quantitative assessments to evaluate CM visualization. The readers were blinded to the patients' clinical information and trained to identify the CM using the Morel histologic atlas as a reference.⁽¹⁶⁾ First, the anterior commissure-posterior commissure (AC-PC) line was identified. The axial MRI section selected for CM visualization

may not exceed 2.4 mm above the AC-PC line to correspond with the histological references.⁽¹⁶⁾

The qualitative assessment of each thalamus was performed using a 3-point scale to evaluate the visualization quality. The categories included good visualization, defined as good delineation of at least two borders of the CM and neighboring nuclei; poor visualization, defined as only one border identified; and nonvisualization, where no borders were discernible (**Figure 1**). Multiplanar reconstruction techniques were allowed to enhance accuracy.

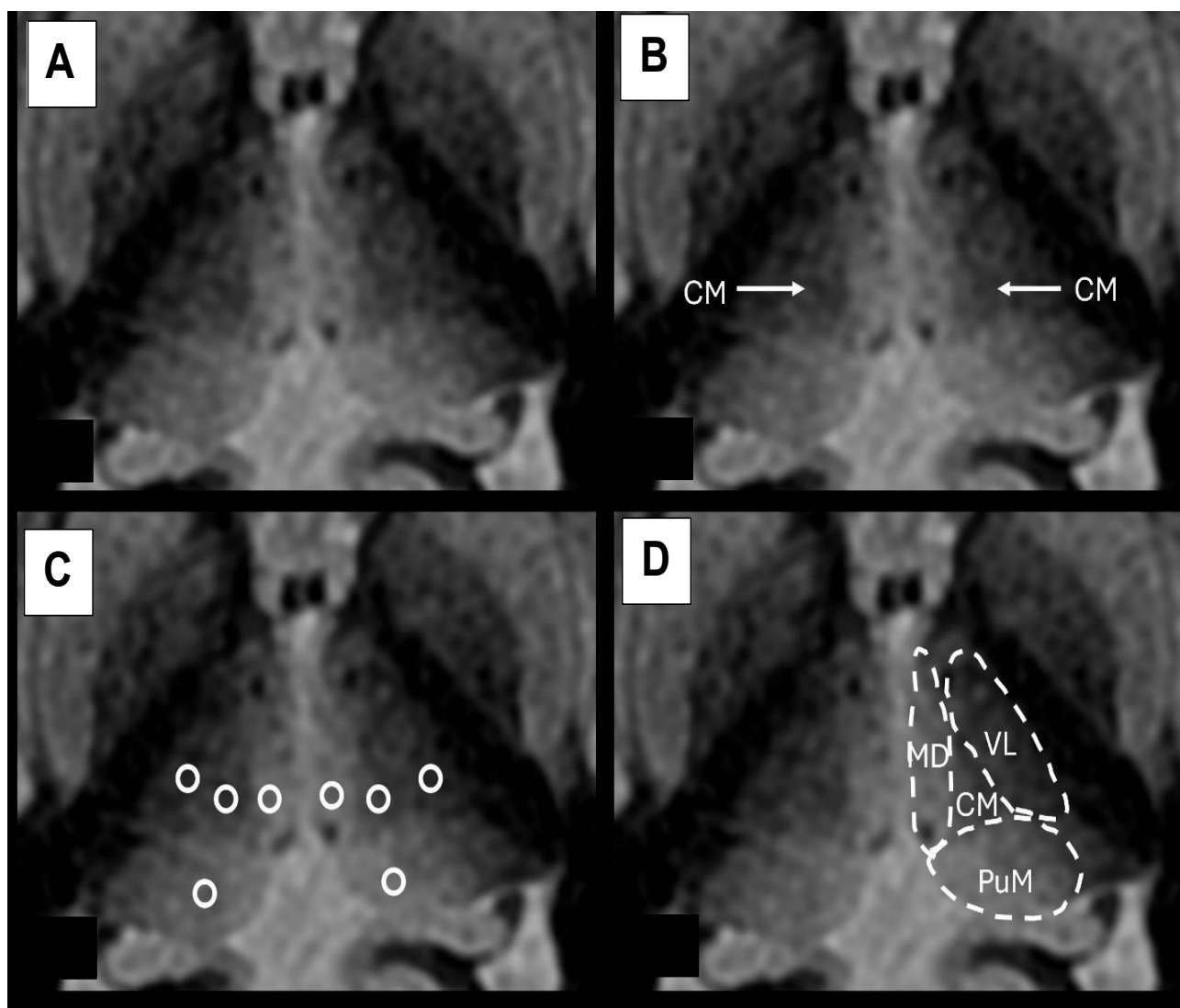


Figure 2. (A) Axial 3D FGATIR image demonstrating the thalamic nuclei without labeling, (B) axial 3D FGATIR image showing the CM thalamic nuclei indicated by arrows, (C) axial 3D FGATIR image illustrating ROI placement in both thalami, (D) axial 3D FGATIR image with dotted lines outlining the borders of the CM, MD, PuM, and VL nuclei in the left thalamus. CM, centromedian; FGATIR, fast gray matter acquisition T1 inversion recovery; ROI, region-of-interest; MD, mediodorsal thalamic nucleus; PuM, medial pulvinar thalamic nucleus; VL, ventrolateral thalamic nucleus.

For quantitative assessment, the regions of interest (ROIs) were placed within each thalamus, targeting the four thalamic nuclei: the CM, mediodorsal nucleus (MD), medial pulvinar nucleus (PuM), and ventrolateral nucleus (VL) (**Figure 2**). ROI sizes were constrained to 4–8 mm². Careful ROI placement was ensured to minimize partial-volume averaging from adjacent structures. The mean signal intensity within each ROI was measured. In addition, four ROIs were placed in the air space at the corners of the MRI images to assess noise signal intensity and standard deviation (SD). The SD of noise across these four ROIs was averaged to calculate the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR).

The SNR of each thalamic nucleus was calculated as follows:

$$\text{SNR} = \text{SI}_{\text{thalamic nucleus}} / \eta$$

where $\text{SI}_{\text{thalamic nucleus}}$ represents the mean signal intensity (SI) of each thalamic nucleus, and η represents the average SD of noise derived from two independent readers. Similarly, the CNR of the CM relative to neighboring thalamic nuclei was calculated as follows: $\text{CNR} = (\text{SI}_{\text{CM}} - \text{SI}_{\text{neighboring thalamic nucleus}}) / \eta$. To account for the Rayleigh noise distribution, the calculated SNR and CNR values were multiplied by 0.66 for correction.⁽¹⁷⁾

Table 2. Mean signal intensities and SNRs of each thalamic nucleus in the right thalamus.

		Mean signal intensity		SNR	
		Mean $\pm$ SD	P-value	Mean $\pm$ SD	P-value
CM-MD	CM	728.3 $\pm$ 259.6	<0.001	76.6 $\pm$ 40.8	<0.001
	MD	1050.1 $\pm$ 361.8		112.2 $\pm$ 67.2	
CM-PuM	CM	728.3 $\pm$ 259.6	<0.001	76.6 $\pm$ 40.8	<0.001
	PuM	1049.6 $\pm$ 359.7		110.8 $\pm$ 58.2	
CM-VL	CM	728.3 $\pm$ 259.6	<0.001	76.6 $\pm$ 40.8	<0.001
	VL	556.3 $\pm$ 177.7		60.1 $\pm$ 37.0	

* $P < 0.05$ is considered statistically significant. CM centromedian thalamic nucleus; MD, mediodorsal thalamic nucleus; PuM, medial pulvinar thalamic nucleus; SD, standard deviation; SNR, signal-to-noise ratio; VL, ventrolateral thalamic nucleus.

Statistical analysis

The data were analyzed using IBM SPSS Statistics software version 28 (SPSS Inc., Chicago, IL, USA). Parametric continuous data were expressed as the mean $\pm$ SD, whereas binary and nominal data were reported as proportions. Differences in the mean SI and SNR between the two readers across the four thalamic nuclei, including CM, MD, PuM, and VL, in each thalamus were analyzed using a paired Student's *t*-test. $P < 0.05$ was considered statistically significant. Statistical comparisons were performed separately for each thalamus to ensure independent analysis of both sides within the same patient. Discrepancies in the qualitative assessment between the two readers were resolved by consensus. Interobserver agreement for qualitative visual rating was reported using percentage concordance. Interobserver agreement for quantitative measurements was evaluated using the intraclass correlation coefficient (ICC), which was interpreted as follows: <0.5 (poor), 0.5–0.75 (moderate), 0.75–0.9 (good), and >0.9 (excellent).⁽¹⁸⁾

Results

A total of 16 patients were included in the study, with none meeting the exclusion criteria. In total, 16 cases (32 thalami) were analyzed, and the mean age $\pm$ SD of the patients was 42.8 $\pm$ 21.3 years. There were seven males (44.0%) and nine females (56.0%). Half of the participants (eight patients, 50.0%) were diagnosed with focal epilepsy, whereas the remaining eight had generalized epilepsy.

A total of 32 thalami were evaluated. In the qualitative assessment of the CM, 27 CM (84.0%) were classified as having good visualization, whereas 5 CM (16.0%) had poor visualization. None of the cases showed nonvisualization. For the right thalamus ($n = 16$), 13 CM (81.0%) were categorized as having good visualization and 3 CM (19.0%) as having poor visualization. Similarly, for the left thalamus ($n = 16$),

14 CM (88.0%) were classified as well visualized, whereas the remaining 2 CM (12.0%) were poorly visualized.

For the interobserver reliability of the qualitative visual assessment, both readers rated CM as visualized in all cases, resulting in 100.0% concordance. Both readers agreed that CM showed good visualization in 25 out of 32 thalami with a percentage concordance of 78.1%.

The mean SI of the right thalamic nuclei, expressed as the mean $\pm$ SD, was as follows: MD (1,050.1 $\pm$ 361.8), PuM (1,049.6 $\pm$ 359.7), CM (728.3 $\pm$ 259.6), and VL (556.3 $\pm$ 177.7) (**Table 2**). The mean SI of the left thalamic nuclei, expressed as the mean $\pm$ SD, was as follows: MD (1,043.6 $\pm$ 356.5), PuM (1,087.1 $\pm$ 345.9), CM (730.9 $\pm$ 238.3), and VL (570.3 $\pm$ 176.5) (**Table 3**).

The SNRs of the right thalamic nuclei, expressed as the mean $\pm$ SD, were as follows: MD (112.2 $\pm$ 67.2), PuM (110.8 $\pm$ 58.2), CM (76.6 $\pm$ 40.8), and VL (60.1 $\pm$ 37.0) (**Table 2**). The SNRs of the left thalamic nuclei, expressed as the mean $\pm$ SD, were as follows: MD (111.4 $\pm$ 65.7), PuM (115.6 $\pm$ 61.5), CM (76.9 $\pm$ 37.6), and VL (61.6 $\pm$ 36.3) (**Table 3**).

A paired-sample *t*-test revealed significant differences in the mean SI and SNR between the CM and the three neighboring nuclei (MD, PuM, and VL) in both thalami ($P < 0.001$) (**Tables 2 and 3**).

The CNRs of the CM nucleus relative to the MD, PuM, and VL nuclei of the right thalamus were –35.6, –34.2, and 16.5, respectively (**Table 4**). In the left thalamus, the CNRs of the CM nucleus relative to the MD, PuM, and VL nuclei were –34.5, –38.7, and 15.3, respectively (**Table 4**).

The mean SI and SNRs of each thalamic nucleus on both sides exhibited excellent interobserver agreement between the two readers, with ICC values exceeding 0.96 for all nuclei (**Tables 5 and 6**). Similarly, the CNRs of the CM nucleus relative to the three neighboring nuclei in both thalami also exhibited excellent interobserver agreement (>0.97) (**Table 4**).

Table 3. Mean signal intensities and SNRs of each thalamic nucleus in the left thalamus.

		Mean signal intensity		SNR	
		Mean $\pm$ SD	P-value	Mean $\pm$ SD	P-value
CM-MD	CM	730.9 $\pm$ 238.3	< 0.001	76.9 $\pm$ 37.6	< 0.001
	MD	1043.6 $\pm$ 356.5		111.4 $\pm$ 65.7	
CM-PuM	CM	730.9 $\pm$ 238.3	< 0.001	76.9 $\pm$ 37.6	< 0.001
	PuM	1087.1 $\pm$ 345.9		115.6 $\pm$ 61.5	
CM-VL	CM	730.9 $\pm$ 238.3	< 0.001	76.9 $\pm$ 37.6	< 0.001
	VL	570.3 $\pm$ 176.5		61.6 $\pm$ 36.3	

* $P < 0.05$ is considered statistically significant. CM centromedian thalamic nucleus; MD, mediodorsal thalamic nucleus; PuM, medial pulvinar thalamic nucleus; SD, standard deviation; SNR, signal-to-noise ratio; VL, ventrolateral thalamic nucleus.

Table 4. CNR of the CM compared to each neighboring thalamic nucleus in both thalami, and intraclass correlation of the two readers.

		Contrast-to-noise ratio			ICC
		Mean $\pm$ SD of Reader 1	Mean $\pm$ SD of Reader 2	Mean $\pm$ SD of 2 readers	
Right side	CM-MD	-32.6 $\pm$ 22.0	-38.7 $\pm$ 33.1	-35.6 $\pm$ 27.1	0.99
	CM-PuM	-30.1 $\pm$ 12.1	-38.3 $\pm$ 26.8	-34.2 $\pm$ 18.3	0.99
	CM-VL	19.3 $\pm$ 11.2	13.7 $\pm$ 7.4	16.5 $\pm$ 7.0	0.99
Left side	CM-MD	-33.9 $\pm$ 24.7	-35.2 $\pm$ 34.4	-34.5 $\pm$ 29.3	0.97
	CM-PuM	-38.6 $\pm$ 20.4	-38.7 $\pm$ 30.6	-38.7 $\pm$ 25.0	0.99
	CM-VL	16.2 $\pm$ 8.7	14.4 $\pm$ 10.7	15.3 $\pm$ 8.6	0.99

* ICC < 0.5 (poor); 0.5 - 0.75 (moderate); 0.75-0.9 (good); > 0.9 (excellent). CM, centromedian thalamic nucleus; CNR, contrast-to-noise ratio; ICC, intraclass correlation coefficient; MD, mediodorsal thalamic nucleus; PuM, medial pulvinar thalamic nucleus; VL, ventrolateral thalamic nucleus.

Table 5. Intraclass correlation coefficient of the mean signal intensity for each thalamic nucleus in both thalami assessed by two readers.

		Mean signal intensity			ICC
		Mean $\pm$ SD of Reader 1	Mean $\pm$ SD of Reader 2	Mean $\pm$ SD of 2 readers	
Right side	MD	1036.4 $\pm$ 372.2	1063.0 $\pm$ 355.2	1050.1 $\pm$ 361.8	0.99
	PuM	1028.5 $\pm$ 349.8	1070.0 $\pm$ 374.5	1049.6 $\pm$ 359.7	0.98
	CM	732.8 $\pm$ 268.0	723.3 $\pm$ 256.3	728.3 $\pm$ 259.6	0.98
	VL	544.7 $\pm$ 188.3	567.4 $\pm$ 174.4	556.3 $\pm$ 177.7	0.96
Left side	MD	1030.4 $\pm$ 360.5	1056.4 $\pm$ 355.1	1043.6 $\pm$ 356.5	0.99
	PuM	1080.8 $\pm$ 360.6	1092.8 $\pm$ 335.0	1087.1 $\pm$ 345.9	0.99
	CM	716.6 $\pm$ 247.7	744.7 $\pm$ 233.2	730.9 $\pm$ 238.3	0.98
	VL	546.9 $\pm$ 176.1	593.4 $\pm$ 180.5	570.3 $\pm$ 176.5	0.97

* ICC < 0.5 (poor); 0.5 - 0.75 (moderate); 0.75-0.9 (good); > 0.9 (excellent). CM, centromedian thalamic nucleus; ICC, intraclass correlation coefficient; MD, mediodorsal thalamic nucleus; PuM, medial pulvinar thalamic nucleus; VL, ventrolateral thalamic nucleus.

Table 6. The intraclass correlation coefficient of the SNR for each thalamic nucleus in both thalami was assessed by two readers.

		SNR			ICC
		Mean $\pm$ SD of reader 1	Mean $\pm$ SD of reader 2	Mean $\pm$ SD of 2 readers	
Right side	MD	109.6 $\pm$ 62.5	114.9 $\pm$ 72.4	112.2 $\pm$ 67.2	0.99
	PuM	107.1 $\pm$ 50.0	114.4 $\pm$ 66.6	110.8 $\pm$ 58.2	0.97
	CM	77.0 $\pm$ 41.2	76.2 $\pm$ 40.9	76.6 $\pm$ 40.8	0.99
	VL	57.7 $\pm$ 32.0	62.4 $\pm$ 42.4	60.1 $\pm$ 37.0	0.97
Left side	MD	108.7 $\pm$ 59.8	114.2 $\pm$ 71.7	111.4 $\pm$ 65.7	0.99
	PuM	113.4 $\pm$ 55.5	117.8 $\pm$ 67.6	115.6 $\pm$ 61.5	0.99
	CM	74.8 $\pm$ 36.1	79.1 $\pm$ 39.6	76.9 $\pm$ 37.6	0.99
	VL	58.5 $\pm$ 33.4	64.7 $\pm$ 39.3	61.6 $\pm$ 36.3	0.98

* ICC < 0.5 (poor); 0.5-0.75 (moderate); 0.75-0.9 (good); > 0.9 (excellent). CM, centromedian thalamic nucleus; ICC, intraclass correlation coefficient; MD, mediodorsal thalamic nucleus; PuM, medial pulvinar thalamic nucleus; SNR, signal-to-noise ratio; VL, ventrolateral thalamic nucleus.

Discussion

Our study suggests that the CM can be identified using the 3D FGATIR sequence on a 3 Tesla MRI in patients with epilepsy. While its borders are less sharply defined than more advanced techniques, such as QSM⁽⁶⁾, 3D FGATIR offers a practical alternative for hospitals without access to specialized imaging modalities. The CM is not visualized directly, but it is inferred by identifying the adjacent thalamic nuclei, including the MD, PuM, and VL nuclei, with the CM appearing as the residual region between them. This approach aligns with the clinical objective of not delineating the full extent of the CM but rather accurately localizing its central region for DBS electrode placement. In addition, 3D FGATIR is commercially available, requires no advanced postprocessing, and provides high-resolution, thin-slice imaging with multiplanar reconstruction.

Compared with other imaging sequences, FGATIR offers distinct contrast properties while retaining the ability to localize the CM. For example, a previous study that included 19 patients with Lennox-Gastaut syndrome used the MP2RAGE MRI sequence at 3 Tesla with Sobel edge detection to visualize the CM.⁽¹⁾ With the MP2RAGE sequence, the CM appears to be hyperintense relative to the hypointense neighboring PuM, MD, and parafascicular nuclei.⁽¹⁾ Conversely, in the 3D FGATIR sequence used in our study, the white matter signal intensity was suppressed and appeared hypointense relative to that of the gray matter.⁽¹⁰⁾ Moreover, the CM appeared to be hypointense relative to hyperintense neighboring PuM and MD, while slightly hyperintense relative to the more hypointense VL nucleus.

All CM nuclei were rated as visualized in the qualitative assessment, with 84.0% exhibiting good visualization. Two expert readers confirmed this with a high percentage of concordance. The cause of poor visualization we observed was the indistinct border between the CM and VL. In contrast, borders between the CM and the MD and PuM were easier to visualize. It is important to note that CM is a 3D structure, which makes it challenging to fully evaluate all its borders on every MRI section. The slightly higher good visualization rate for the left CM (88.0%) compared to the right (81.0%) may be influenced by anatomical or imaging-related factors. However, further research and correlation with handedness may help confirm this finding.

The mean SI and SNRs of the CM were significantly lower than those of the adjacent MD and PuM, whereas they were significantly higher than those of the VL, with P -values <0.001 . This supports the hypothesis that 3D FGATIR provides sufficient contrast to differentiate the CM from the adjacent thalamic structures. These findings align with a previous study using a white matter-nulled MPRAGE sequence on a 7 Tesla MRI, which reported the highest T1 values in the medial, mediodorsal, and posterior thalamic nuclei. In contrast, the lateral and anterior nuclei exhibited lower T1 values.⁽¹⁹⁾

The CNRs of the CM, referenced to the MD and PuM, are high, allowing for distinct visualization of the CM compared to these two nuclei. In contrast, the CNRs of the CM referenced to the VL are low, which is consistent with the poorer delineation of the CM's lateral border during visual inspection. Therefore, readers should have increased awareness when the delineation of CM and VL is made, and care should be taken to delineate this small difference.

The excellent interobserver agreement between the two readers of the mean SI, SNRs, and CNRs further validates the reliability of the technique. The strong correlation between the two readers indicates that 3D FGATIR is reproducible and has potential for clinical adoption. It is important to note that this study employed a nonwhole-brain scan, which resulted in greater image quality and a shorter scan time than a whole-brain scan.

This study has several limitations. First, MRI and histological atlases both exhibit interindividual variability. In addition, tissue shrinkage in histological atlases may affect their accuracy relative to MRI. Among the various histological thalamic atlases available, we selected the Morel thalamic histological atlas because it is specifically designed to enhance the visualization of thalamic nuclei for direct DBS targeting and has been effectively used to guide manual intrathalamic segmentation in previous studies.⁽²⁰⁾ Its thin histological sections are aligned parallel to the AC-PC line, which closely matches MRI orientation.⁽²¹⁾ Second, the small sample size (16 patients with epilepsy) may limit the generalizability of our findings. Another limitation is the absence of kappa statistics for interobserver agreement in the visual qualitative assessment. While kappa accounts for agreement that occurs by chance, it can paradoxically yield low values when the distribution of concordant and discordant pairs is unbalanced.

Therefore, we considered percentage concordance to be a more appropriate measure of interobserver reliability and have reported it accordingly.^(22, 23) Finally, there is a lack of pathological evidence and correlation between MRI-visualized CM and intraoperative microelectrode recordings. Future studies incorporating intraoperative validation techniques could further refine CM localization and improve the accuracy of MRI-based DBS targeting.

Conclusion

3D FGATIR enables the identification of the CM on a 3 Tesla MRI in patients with epilepsy and offers a practical alternative for centers without access to more specialized imaging modalities.

Author contributions

TP, TY, and SP contributed substantially to the concept and design of this study, data acquisition, literature review, and data analysis and interpretation. TP, TY, and SP contributed substantially to data acquisition. TP and TY contributed to drafting the manuscript. TP and SP edited the manuscript critically for important intellectual content. All authors approved the final version submitted for publication and take responsibility for statements made in the published article.

Acknowledgments

The authors would like to express their gratitude to all participants who were involved in this study.

Conflict of interest statement

The authors have each completed the International Committee of Medical Journal Editors Form for Disclosure of Conflicts of Interest. No author has any potential or actual conflict of interest to disclose related to the present article.

Data sharing statement

All data generated or analyzed during the present study are included in this published article. Further details are available for noncommercial purposes from the corresponding author upon reasonable request.

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