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Original article

Comparison of the thermal bone damage done by the oscillating saw and bone mill burr during total knee arthroplasty

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A R T I C L E I N F O

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Oscillating saw
Robotic-assisted total knee arthroplasty
Thermal osteonecrosis

A B S T R A C T

Background: Thermal osteonecrosis from bone cutting during total knee arthroplasty (TKA) may cause aseptic implant loosening. The study compares thermal bone injury from oscillating saw (CTKA) and bone milling burr treatments (RATKA).
Method: A prospective study comparing thermal necrosis during CTKA and RATKA was performed. The sample size ($n = 36$) was determined with 18 patients per group, assuming a 15 % relative increase in thermal necrosis with RATKA, with statistical thresholds set at $\alpha = 5$ % and $\beta = 10$ %. The upper tibia cut surface was analyzed, with histological sections examined from 20 randomly selected fields. Thermal necrosis was evaluated by determining the proportion of non-viable cells relative to viable ones and measuring the depth from the cut bone surface at which the first intact osteocyte was observed. Statistical analysis was conducted using appropriate comparative tests, including Chi-square and t-tests, with significance determined at a threshold of $p < 0.05$.
Results: There was no significant variability in preoperative patient characteristics (gender, age, body mass index, diagnosis, range of motion, deformity and comorbidities) between CTKA ($n = 18$) and RATKA ($n = 18$) groups. The percentage of dead osteocytes at the resected surface in CTKA and RATKA were 40.3 % and 46.5 % respectively ($p = 0.6309$). The minimum depth where viable osteocytes were found was 25.5 ± 3.5 μmm and 27.1 ± 3.6 μmm in CTKA and RATKA respectively (p value = 0.091).
Conclusion: Conventional TKA and RATKA produce similar thermal effects on bone, with no significant difference in osteocyte viability. This indicates that both surgical methods are comparable regarding thermal impact on bone health.

1. Introduction

Total knee arthroplasty (TKA) continues to be a primary surgical intervention for advanced knee osteoarthritis (OA), requiring meticulous bone preparation to ensure proper implant positioning and sustained functional outcomes.[1] Essential to the efficacy of TKA is the precise resection of bone surfaces, facilitating optimal positioning of implants and ensuring enduring functionality.[2] Conventionally, TKA procedures have relied on oscillating saws for bone resection, yet the emergence of robotic assisted (RA)-TKA has introduced bone milling burrs as an alternative modality. Nevertheless, both methodologies are associated with the generation of heat during bone cutting, posing a formidable risk of thermal necrosis, which could compromise implant integration and overall surgical outcomes.[3]

Bone cutting in TKA involves a balance between achieving accurate bone resection while minimizing collateral damage to the surrounding osseous structures.[4] Mechanical trauma and thermal injury to bone tissue during the cutting phase can compromise the biological environment, potentially affecting implant fixation, osseointegration, and compromises blood supply to the affected bone, resulting in ischemia—a condition termed thermal osteonecrosis. Typically, thermal necrosis manifests shortly following surgical intervention.[5] Studies have emphasized the importance of understanding the implications of heat generation during bone cutting, as elevated temperatures can induce thermal necrosis, negatively impacting bone healing and leading to implant instability.

Thermal osteonecrosis due to elevated temperatures was first

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List of abbreviations:

BMI	Body mass index
cpm	Cuts per minute
OA	Osteoarthritis
ROM	Range of motion
RA	Robotic-assisted
TKA	Total knee arthroplasty

documented in 1925 by Block, who described the impact of frictional heat during orthopaedic surgeries. He observed a reduction in bone vitality and concluded that thermal injury, while notable, was less significant compared to corrosion and infection.[6] Subsequent studies by Eriksson and Albrektsson revealed that exposing bone to 47 °C for 1 min significantly impairs its regenerative capacity, while exposure to 50 °C almost completely inhibits bone regeneration.[7]

The critical temperature for causing thermal necrosis is estimated to be around 56 °C, at which point bone alkaline phosphatase undergoes denaturation. However, studies have shown that during reaming in humans, the maximum recorded temperature rise typically reaches 51.6 °C, which is below the suggested critical temperature for inducing thermal osteonecrosis.[8] Sustained heat exposure at 47 °C for 1 min can disrupt bone integrity by triggering resorptive processes and subsequent structural adaptation, which may have implications for the long-term fixation and stability of implants.[3,9] A animal study showed that the temperature of titanium implants when raised to 50 °C for 60 s caused the resorption of about 30 % of the surrounding bone, which was subsequently replaced by fat cells. This mechanism interfered with the integration of bone cells into the implant's porous framework, ultimately weakening its stability.

The rate at which implants used for osteosynthesis in the lower leg fails varies between 2.1 % and 7.1 %. Thermal osteonecrosis, resulting from heat produced during preparative drilling, plays a role in bone resorption around implanted screws, though it is not the primary contributing factor.[9]

Several variables influence the extent of thermal damage during bone cutting, including cutting tool geometry, rotational speed, applied force, feed rate, and the presence of cooling systems.[10] Studies have demonstrated a statistically significant difference in bone temperature increase with increasing speed of drilling (while maintaining a constant drill diameter), highlighting the predominant influence of drill speed over drill diameter. Notably, lowering the drill speeds (188 and 462 rpm) does not lead to bone temperatures reaching critical levels, even without external irrigation. In contrast, when a 4.5 mm drill operates at speeds of 1,140 or 1,820 rpm without external irrigation, bone temperatures can rise beyond critical limits.[9]

This study aims to compare thermal bone damage between the conventional oscillating saw and the bone milling burr in TKA procedures. Specifically, we aim to assess the extent of thermal necrosis and determine whether there are significant differences in thermal bone damage between the two techniques.

2. Methods

This prospective study aimed to compare thermal necrosis between CTKA and RATKA. It was performed in accordance with the principles of the Declaration of Helsinki. Approval was granted by the Institutional Ethics Committee (Date: 08-02-2023/No: HSH/EC/A/055/2023) and written informed consent was obtained from the enrolled patients.

The study involved 36 patients, with 18 undergoing RATKA utilizing a fully automated Cuvis Joint Robot (Curexo, South Korea, supported by Meril Healthcare Pvt Ltd, India) and 18 patients undergoing CTKA. All patients received a multi-radius, high-flexion, posterior cruciate-substituting knee implant (MAXX Freedom Total Knee system, MAXX Orthopedics, Inc., Norristown, Pennsylvania, USA).

The sample size (n = 36) was determined with 18 patients per group, assuming a 15 % relative increase in thermal necrosis with RATKA, with statistical thresholds set at $\alpha = 5$ % and $\beta = 10$ %.

The oscillating saw in CTKA was set at 12,000 oscillations per minute (cpm), a rate chosen to balance cutting efficiency while minimizing thermal damage. In RATKA, the bone milling burr used had a diameter of 6.2 mm and operated at 60,000 rpm. Additionally, continuous irrigation with normal saline was used during both CTKA and RATKA to mitigate the heat accumulation and reduce the risk of thermal osteonecrosis.

The upper tibia cut surface was selected as the site for comparison between the two groups and 20 random fields were chosen for analysis from each specimen. Histological sections were prepared, and the bone specimen was transported and fixed in 10 % neutral buffered formalin for 24 h. The tissue was then grossed and kept for decalcification in 5 percent nitric acid for 24–48 h. After that the tissue was taken for processing. The whole turnaround time was about 6 days.

Thermal necrosis was evaluated by determining the percentage of dead cells relative to viable cells in the selected histological fields. Furthermore, the measurement included the depth from the cut or milled bone surface to the spot where the first intact osteocyte was identified.

Statistical evaluation of categorical variables was conducted using the Chi-square test, whereas continuous variables were examined with Student's t-test. Statistical significance was defined as $p < 0.05$.

3. Result

A total of 36 patients participated in the study, evenly divided into two groups, with 18 undergoing CTKA and 18 receiving RATKA. Preoperative characteristics: age, body mass index (BMI), diagnosis, gender, deformity, comorbidities and range of motion (ROM) showed no statistically significant variation between the two groups (Table 1).

Microscopic examination of the bone sections following burr cutting revealed no significant difference in mechanical damage compared to the saw technique. The percentage of dead cells relative to viable cells was 40.3 % in the CTKA group (Fig. 1 and Table 2) and 46.5 % in the RA-TKA group (p = 0.6309), (Fig. 2 and Table 2).

Furthermore, the minimum depth at which viable osteocytes were observed was 25.5 ± 3.5 μmm in the CTKA group and 27.1 ± 3.6 μmm in the RATKA group (p value = 0.091), again demonstrating no statistically significant variance between the groups (Table 3).

Table 1
Baseline characteristics of study patients.

Parameters	Conventional TKA (Group 1)	Robotic Assisted-TKA (Group 2)	p value
Number of patients (n)	18	18	-
Male:Female	3:15	2:16	
Mean age (years)	66.4 ± 12.5	64.8 ± 13.3	0.7123
Mean body mass index (kg/m^2)	28.5 ± 4.1	27.7 ± 5.1	0.6073
Pre-operative range of motion (ROM)	93.5 ± 18.5	96.1 ± 16.4	0.6583
Pre-operative degree of deformity	8.4 ± 2.5	7.8 ± 2.6	0.4852
Pre-operative associated co-morbidity			
- Cardiac	n = 5 (27.78 %)	n = 6 (33.33 %)	0.7215
- Renal	n = 4 (22.22 %)	n = 5 (27.78 %)	0.7041
- Respiratory	n = 1 (5.56 %)	n = 1 (5.56 %)	1.00
Primary diagnosis			
- Osteoarthritis	18	18	1.00

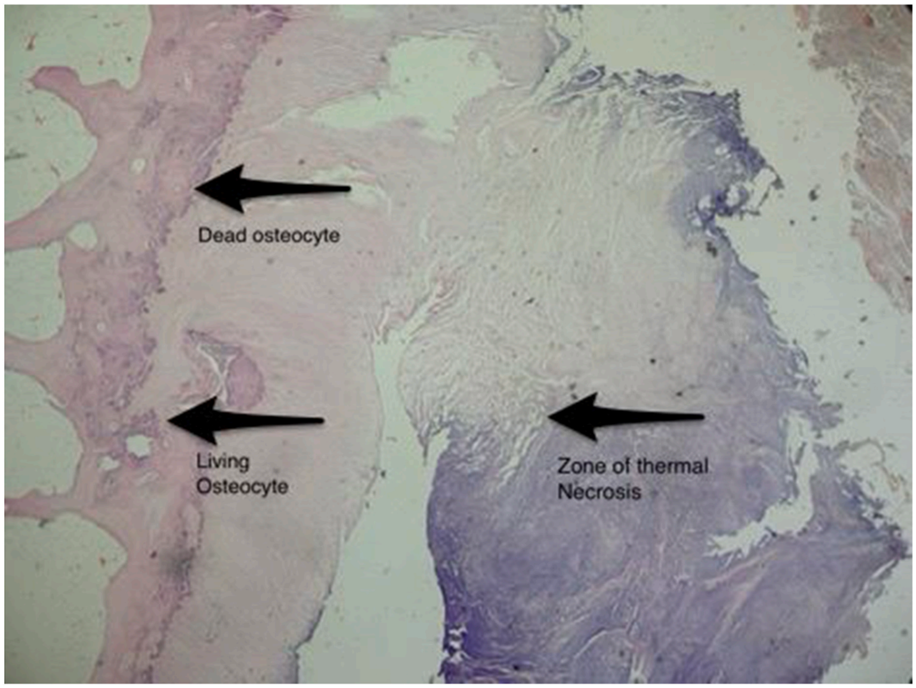

Fig. 1. Shows area of thermal necrosis with dead and living osteocytes in saw cut conventional TKA.

Table 2
Percentage of dead cells.

Technique	Conventional TKA group	Robotic assisted TKA group	p value
Percentage of dead osteocytes	40.3 %	46.5 %	0.6309 (Chi-square test)

4. Discussion

Our study found no significant difference in thermal bone damage between the use of a bone milling burr in RATKA and an oscillating saw in CTKA, contradicting previous hypotheses that suggested greater thermal damage from milling. Our results indicate that RATKA is comparable to the conventional approach regarding thermal osteonecrosis.

In TKA, a reciprocating sagittal saw is utilized to shape the distal femur and proximal tibia to accommodate the prosthetic implant. The high-frequency oscillating blades, functioning at 10,000–20,000 cycles per minute with a slight oscillation angle of 4–5°, generate heat as mechanical energy is transferred to the bone through conduction.[11] Since bone has limited thermal conductivity, this heat accumulates at the cutting site, increasing surface temperature and potentially causing osteocyte death and irreversible bone damage, ultimately leading to thermal osteonecrosis.[12]

Earlier studies has indicated that the bone can tolerate a maximum temperature of 47 °C for up to 1 min to avoid thermal osteonecrosis.[12,13] Studies in controlled animal models by Eriksson et al. found that bone regeneration is substantially impaired at 47 °C for 60 s and is completely halted at temperatures above 50 °C.[7] Krause et al. demonstrated that osteocyte death begins at 50 °C, and at 70 °C, protein regeneration is not possible.[14] The duration that bone can tolerate heat decreases exponentially with each degree increase in temperature. Exposure to temperatures above 53 °C, even for less than 1 s, can greatly diminish the bone's ability to generate new tissue.[15] These studies involved sustained heat exposure in experimental settings, which differs from real-world TKA, where heat dissipation mechanisms, blood circulation, and transient exposure play a mitigating role. Unlike in controlled laboratory models, bone begins cooling as soon as the cutting process is completed, limiting continuous thermal injury.

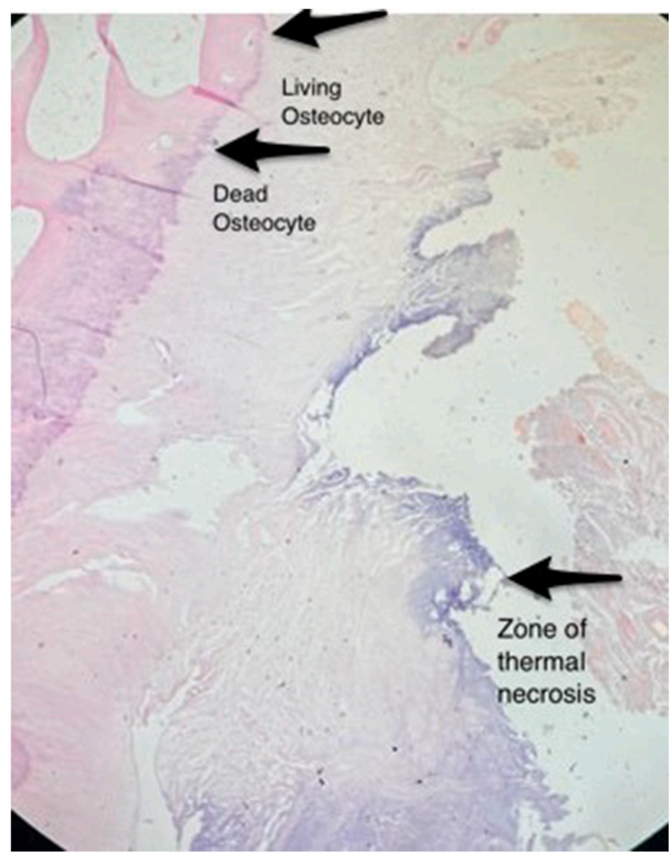

Fig. 2. Shows area of thermal necrosis, dead and living osteocytes in burr milled robotic assisted TKA.

Further, dull cutting orthopaedic tools are shown to increase the heat at the surgical site. Reusing surgical saw blades and burrs leads to

Table 3
Depth where viable osteocytes were found.

Technique	Conventional TKA group	Robotic assisted TKA group	p value
Depth where viable osteocytes were found (μmm)	25.5 ± 3.5	27.1 ± 3.6	0.091 (Student's T-test)

increased temperatures and heat generation at the bone surface during surgery.[10] James et al. showed that thermal osteonecrosis of the bone will lead to aseptic loosening of the TKA implant.[11] Berman et al. and Haddad et al. identified heat generation from oscillating saws as a key factor contributing to thermal osteonecrosis, which was linked to early aseptic loosening of joint prostheses.[16,17] While this provides a theoretical foundation, the direct clinical correlation remains underexplored in real-world surgical settings. Our study represents a preliminary clinical investigation, aiming to address this gap by assessing thermal bone injury in actual TKA procedures using both conventional and robotic techniques.

Given the important implications of thermal osteonecrosis on implant survival, several methods have been investigated to mitigate thermal damage. Shakouri et al. explored the impact of different blade speeds and feed rates on bone temperature during sawing.[18] Their study found that a blade speed of 10,000 cpm combined with a maximum feed rate of 30 mm/min resulted in the lowest temperature increase, reaching 65.45 °C. In contrast, when no irrigation was applied, the highest temperature rise occurred at 18,000 cpm with a feed rate of 10 mm/min. However, with irrigation, bone temperature remained within safe limits, staying below 47 °C for oscillation rates between 10,000 and 16,000 cpm and a median feed rate of 20 mm/min. Based on these observations, they suggested that, in the absence of irrigation, maintaining a saw speed of 10,000 cpm with a feed rate of 30 mm/min could help minimize the risk of thermal osteonecrosis.[18] This combination minimizes heat generation and reduces the risk of bone damage during surgery. Based on our study findings, we recommend the following settings for the Cuvis Joint Robot to minimize thermal damage: a cutting speed of 15–25 mm/s, a burr diameter of 6.2 mm, at an RPM of 60,000. External irrigation is preferable to further reduce heat generation. Additionally, a new drill, burr, or saw blade should be used for each procedure to maintain cutting efficiency and minimize thermal necrosis. These parameters help optimize bone cutting efficiency while reducing the risk of thermal osteonecrosis.

Limited research exists on the extent of thermal bone damage in TKA. Previous studies have assessed histological changes to quantify the degree of thermal necrosis. Histomorphometric analysis using hematoxylin and eosin (H&E) staining has demonstrated that heat-induced alterations reduce eosin affinity while increasing hematoxylin uptake.[11,19] This staining pattern serves as an indicator of thermal damage, allowing for an estimation of necrotic depth. According to these studies, regions of bone that have undergone irreversible damage exhibit empty osteocyte lacunae. The extent of bone necrosis can be quantified by calculating the percentage of dead versus viable osteocytes and measuring the depth of thermal damage. Utilizing this staining procedure, we found that the minimum depth at which viable osteocytes were observed was 25.5 ± 3.5 μmm in the CTKA group and 27.1 ± 3.6 μmm which did not significantly vary from the RATKA group (p value = 0.091). An earlier study analyzed the depth of bone damage by examining histological sections, measuring the maximum thermal damage depth as the distance to the deepest empty osteocyte lacunae observed.[11] In contrast, our study measured the minimum depth of bone damage. Due to these methodological differences, our results are not directly comparable to those of James et al.[11]

Robotic-assisted surgical systems generally prefer using burrs instead of saw blades for bone resection due to burrs' higher precision in preparing bone surfaces.[20,21] While milling knee resections may take longer than sawing due to the intricate tool trajectories and surface machining, it generally remains within safe exposure limits for bone tissue. Consequently, the overall temperature exposure during milling is preferable to sawing.[22] Preservation of the bone microstructure is crucial for maintaining its mechanical integrity, potentially enhancing long-term implant stability and osseointegration.[23]

Saw blades typically feature negative rake angles, causing bone fragments to be pushed into uncut bone during oscillating motion, potentially leading to elevated cutting forces and temperatures surpassing the thermal necrosis threshold during CTKA.[24] Conversely, milling tools rotate in a single direction, allowing for positive rake angles and optimal cuts. Positive rake angles can assist in lowering temperatures by reducing cutting forces and improving the removal of bone fragments from the cutting site.[25]

To achieve long-term stability, carefully controlling intra-operative temperature is important for bone healing and ingrowth, particularly when using cementless implants.[26,27] Avoiding bone necrosis during machining is crucial, as cell death can hinder the integration of bone tissue with the implanted prosthesis. Thus, regulating milling forces and maintaining optimal temperatures throughout the procedure is essential to preserve bone viability.[28] The reduced thermal impact associated with the burr technique using fully automated Cuvis joint robot may contribute to a more favorable surgical environment, mitigating the risk of thermal damage to surrounding tissues and promoting better post-operative outcomes.

The flatness of the tibial surface is essential in cementless TKA for several reasons: it helps maintain prosthesis stability, ensures even distribution of stress on the bone, and facilitates bone ingrowth. The optimal gap for bone ingrowth between tibial component and the bone ranges from 0.3 to 0.5 mm.[21] For tibial cut using an oscillating saw during CTKA, the surface flatness typically falls between 0.15 and 0.40 mm, often resulting in a slight depression in the center of the surface.[29] However, with milling this depression is not seen. Unlike in CTKA, where an oscillating saw is used for the tibial cut, this milling technique prevents the temperature from exceeding the allowable limit.[21]

Various factors, such as rotational speed, tool geometry, feed rate, and cutting depth, significantly influence the forces exerted and the temperatures produced during bone cutting.[30]

Augustin et al. emphasized the critical role of external irrigation in preventing thermal osteonecrosis during bone drilling.[9] Volunteers applied direct cooling to the bone during sawing, while saline solution flowed through tubing attached to the drill to cool the burr before it contacted the tissue during burring. However, limitations arose as the drill heated up, potentially warming the saline. Unlike burring tools, saws lacked irrigation channels.[23] Experimental evidence suggests that irrigation during cutting procedures can restrict bone and saw blade temperature rise to less than 10 °C.[27]

Osseointegration, crucial for bone anchorage, necessitates minimal tissue trauma, highlighting the significance of avoiding thermal necrosis in prosthetic devices to prevent tibial component loosening during knee arthroplasty.[30] The findings from this study highlight the critical role of optimizing surgical parameters to minimize heat generation during bone cutting. By providing intraoperative histological evidence of thermal necrosis, this study enhances the understanding of how cutting techniques impact bone viability, filling an essential gap in the literature. Unlike previous experimental studies, this research evaluates real-world surgical conditions, offering clinically relevant insights into thermal effects during TKA.

4.1. Limitations

Our study provides valuable preliminary insights into thermal bone damage during TKA, offering one of the first intraoperative histological assessments of osteocyte viability in a real-world surgical setting. Prospective design enhances data accuracy, and the standardized methodology ensures a reliable comparison between conventional and robotic-assisted techniques. However, the study has limitations. The small sample size may restrict generalizability, and a larger multicenter trial would improve statistical power. Conducting the study at a single center may introduce institutional biases, and including multiple institutions in future research would enhance applicability. While we provide histological evidence of thermal necrosis, we did not directly correlate it with long-term clinical outcomes such as implant loosening or functional recovery. Though histological bone damage is a known precursor to compromised osseointegration, long-term follow-up with imaging and functional assessments are essential. Additionally, intraoperative temperature measurements were not recorded, and integrating thermographic monitoring in future studies could provide real-time validation of heat exposure. Lastly, as this study evaluates the Cuvis Joint Robot, findings may not be generalized to other robotic systems with different cutting technologies. Despite these limitations, this study establishes a foundation for optimizing surgical parameters to minimize thermal necrosis and improve implant longevity, guiding future research in robotic-assisted TKA.

4.2. Conclusion

Our study indicates that the thermal damage incurred by employing a bone milling burr in RATKA with the fully automated Cuvis Joint robot does not exhibit a statistically significant difference compared to that caused by the oscillating saw blade in CTKA. Nonetheless, both methods pose a risk of thermal necrosis due to heat production during bone cutting. Thermal necrosis, marked by bone cell death and compromised blood flow, may hinder implant integration and surgical results. Thus, further investigation into refining drilling parameters, such as speed, feed rate, and irrigation strategies, could help reduce the likelihood of thermal osteonecrosis, thereby enhancing the safety and effectiveness of orthopedic procedures in TKA.

Informed consent

Written informed consent has been obtained from the patient or guardian for participation and publication.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Holy Spirit Hospital, Andheri, Mumbai, Maharashtra, India (Date: 08-02-2023/No: HSH/EC/A/055/2023)

Part of the study was presented at the **World Arthroplasty Congress**, jointly hosted by the **European Knee Society**, **European Hip Society, Knee Society USA**, and **Hip Society USA in Madrid, Spain** on April 18–19, 2024.

Author contribution

S.B.L contributed to the study's conception and design. Material preparation, data collection and analysis were performed by S.B.L, N.A, R.V.S, S.M.A, and A.R. N.A, S.M.A and A.R. also contributed towards imaging data. The first draft of the manuscript was written by S.B.L, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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None.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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