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Anterior and distal tunnel orientation for anatomic reconstruction of the medial patellofemoral ligament is safer in patients with open growth plates

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Abstract

Purpose In patients with open growth plates, the direction of tunneling that avoids distal femoral physis (DFP) damage in anatomic reconstructions of the medial patellofemoral ligament (MPFL) has been a topic of discussion. The objective of this study was to determine the ideal orientation for anatomic reconstructions of MPFL tunneling that minimized DFP damage while avoiding breaching the intercondylar notch.

Methods Eighty magnetic resonance images of patients aged 10 through 17 were obtained, randomly sampled from the institutional database. A de novo software was developed to obtain 3D models of the distal femur and DFP. In each model, the anatomical insertion point of the MPFL was determined as defined by Stephen. A 20-mm-depth drilling was simulated, starting from the insertion point at every possible angle within a 90° cone using 5-, 6- and 7-mm drills. Physeal damage for each pair of angles and each drill size was determined. Damage was expressed as a percentage of total physis volume. Statistical analysis was conducted using Student's *t* test and one-way ANOVA.

Results Maximum physeal damage (5.35% [4.47–6.24]) was obtained with the 7-mm drill when drilling 3° cephalic and 15° posterior from insertion without differences between sexes (n.s.). Minimal physeal damage (0.22% [0.07–0.37]) was obtained using the 5-mm drill aimed 45° distal and 0° anteroposterior, not affected by sex (n.s.). Considering intra-articular drilling avoidance, the safest zone was obtained when aiming 30°–40° distal and 5°–35° anterior, regardless of sex.

Conclusion Ideal femoral tunnel orientation, avoiding physeal damage and breaching of the intercondylar notch, was obtained when aiming 30°–40° distal and 5°–35° anterior, regardless of sex. This area is a safe zone that allows anatomic MPFL reconstruction of patients with an open physis.

Keywords Pediatric patellar instability · MPFL reconstruction · Growth plate · Knee anatomy · Femoral tunnel positioning

Introduction

Patellofemoral dislocation is one of the most common acute knee injuries in skeletally immature patients [13, 37] with an annual incidence of 43 per 100,000 [23]. Subjects between 10 and 17 years of age have the highest risk for patellar dislocation with a peak incidence of first-time dislocation occurring at age 15 [2, 8, 13]. Recurrence rates have been reported to be as high as 60% in patients under 14 years old, highlighting the risk of recurrence and disability in this pediatric population [17].

The medial patellofemoral ligament (MPFL) is the primary restraint for lateral patellar translation between 0° and 30° of knee flexion before it engages the trochlear groove [1, 4, 31]. Injury to the MPFL following first-time lateral

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patellar dislocation occurs in more than 90% of cases, which may predispose patients to recurrent instability [3, 25]. Reconstruction of the MPFL is the most common surgical procedure to treat recurrent patellar dislocation [33, 35, 36], with favorable outcomes reported in pediatric cohorts [21]. The recent literature suggests the importance of anatomic MPFL reconstruction, since non-anatomic positioning may lead to altered biomechanics and higher rates of redislocation [4, 5, 7, 32, 34].

Anatomic studies have shown that the distal femoral physis (DFP) is in close proximity to the MPFL femoral attachment, adding another challenge to MPFL reconstruction in patients with open growth plates [29, 30]. Multiple animal studies have demonstrated that drilling the DFP may induce angular and length deformities [9, 10, 27]. Seitlinger et al. recently published the first case report of a physeal growth arrest and subsequent angular deformity after MPFL reconstruction, emphasizing the importance of avoiding growth plate damage during this procedure [28]. Optimal drilling orientation to prevent physeal damage and breaching of the intercondylar notch in anatomic MPFL reconstructions has not been clearly defined to date, nevertheless some studies have attempted to do so, showing that anterior and distal drilling would be safer [11, 22].

The aim of this study was to use a computer-assisted 3-dimensional model to compare the direction of every possible femoral tunnel orientation in anatomic MPFL reconstruction, to determine which approach minimizes the risk of growth plate damage while avoiding breaching the intercondylar notch.

Materials and methods

Institutional review board approval for this study was obtained (IRB no. 170906002, Pontifical Catholic University of Chile).

MRI images

The institutional image database was reviewed for knee magnetic resonance imaging (MRI) taken of subjects aged from 10 to 17 years. All images were taken in 1.5 T standard clinical MRI using 3 mm thickness with no gap in between (3 mm increments) generating 0.3 × 0.3 × 3 mm boxcells, with resolution to the tenth of a millimeter (Siemens Magneton Avanto, Siemens Medical Solutions, Erlangen, Germany; or Philips Achieva, Philips Healthcare, Best, The Netherlands). Inclusion criteria were MRIs of patients without knee injuries noted in their radiological reports. A matrix of sex–age pairing was determined and filled each pair with MRI images of the database. Knee MRIs with any injury or indirect sign of injury, such as bone edema, were excluded.

Three-dimensional model generation of physes

All images were loaded into a de novo software designed specifically for this use. The segmentations were made with a semi-automatic software created with MATLAB software (MATLAB 8.0, The MathWorks, Inc., Natick, Massachusetts, United States). Initially, all MRIs went through an optimization, mainly of grayscale saturation and contrast, for the purpose of assisting the downstream steps. Then, each sagittal slice of the MRI was loaded separately. On each slice, the user was prompted to distinguish a finite amount of pixels (seeds) that defined the distal femur and physes. The software then executed a random walker algorithm based on the previously defined seeds. The semi-automatically generated boundaries of each structure were displayed for confirmation by the user. Once all slices were defined and confirmed, the software joined all slices and generated a three-dimensional (3D) model of the patient's knee (Fig. 1). Patients with calcified distal femoral physis were excluded from drilling analysis.

This semi-automatic segmentation was performed by trained medical students. The inter- and intrarater reliabilities were studied to determine the reproducibility of the semi-automatic segmentation method. Agreement was expressed using interclass correlation coefficients (ICC) [12].

Determination of the femoral anatomical insertion of the MPFL

Considering that MRI images of the MPFL femoral insertion point present high variability [29, 30], the anatomical insertion point was determined according to Stephen's anatomic point [32] (Fig. 2). Schöettle's point was not used given its potential higher inconsistency in this population, considering that it uses absolute measurements based on

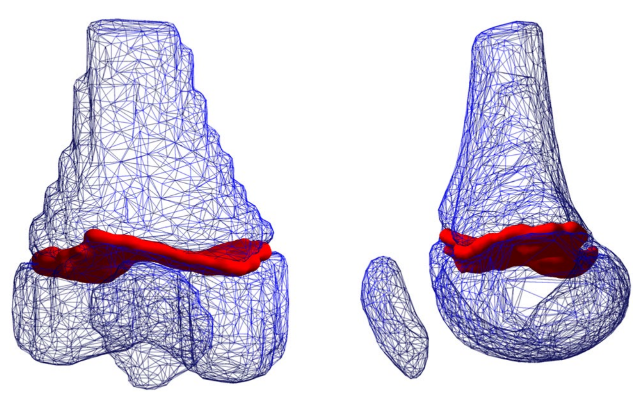

Fig. 1 Distal femur three-dimensional model, including the physis (red)

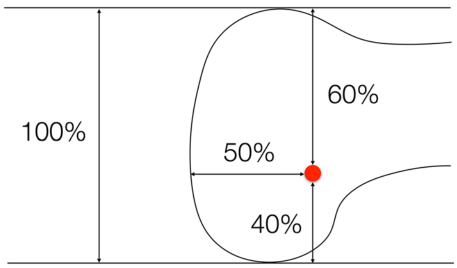

Fig. 2 Determination of the femoral anatomical insertion of the MPFL according to Stephen [29]. The anatomical femoral insertion point is defined in relation to the size of the medial femoral condyle (being 100% the anterior–posterior size, the insertion point was calculated as 40% anterior and 50% proximal from the distal and posterior borders, respectively)

Fig. 3 Determination of the femoral anatomical insertion of the MPFL according to Stephen in the 3D computational models. A "lateral X-ray image-like" composition was obtained from the overlapped MRI slices image, and the MPFL insertion point calculated in the 3D model

adult knees, and Stephen's point uses measurements which are proportional to the anatomy of the knee [15, 26, 32]. To determine Stephen's point in the 3D computational models, each of the MRI slices were overlapped, creating a "lateral X-ray image-like" (Fig. 3). The image was rotated such that the main axis of the femur was straight, and Stephen's point was automatically defined by the software in relation to the size of the medial femoral condyle (Figs. 2, 3).

Drilling simulation and physeal damage calculation

Drilling simulation was based in the femoral socket surgical technique that is commonly used for anatomic MPFL reconstruction. From the calculated anatomic insertion point, drilling was simulated in every possible direction within a cone of 90° from the insertion point with 5-, 6- and 7-mm-diameter drills and to a 20 mm depth, considering that these measurements are the most commonly used in real-case scenarios [22]. Physeal damage was calculated for each pair of angles (coronal or cephalic-distal and sagittal or anteroposterior) and each drill size. Physeal damage was calculated as the physeal volume that was intersected by the virtual drilling cylinder, according to specified diameter and orientation. It was expressed as a percentage of total physis volume with a 95% confidence interval.

Statistical analysis

Statistical analysis was conducted on MATLAB 2018a (The MathWorks, Inc., Natick, Massachusetts, United States) and Stata v13 (StataCorp. 2013. Stata Statistical Software: Release 13. College Station, TX: StataCorp LP). Descriptive statistics are shown with mean and standard deviation. Bivariate comparisons were done using Student's *t* test for dichotomous variables. Multiple comparisons were tested with one-way ANOVA and when association was found, post hoc pairwise comparisons were conducted using Scheffer's test. Significance was set a priori for all statistical analysis at 5%.

Inter- and intrarater reliabilities were evaluated to determine the reproducibility of the semi-automatic segmentation method. Agreement was expressed using intraclass correlation coefficient (ICC) using a two-way random model, characterized by absolute agreement, with the ICC meant to quantify the agreement of evaluators based on average ratings. ICC for inter-observer agreement was determined by repeat measurement of all parameters in seven knees by three trained observers. ICC for intra-observer agreement was measured by repeat evaluations in five knees of a single trained observer, 6 months after initial assessment and blind to initial measurements.

Results

A total of 80 patients were included. Ten patients per age in years from 10 to 17 years old were obtained; 40 patients were female (50%). Of the 80 patients, 22 had a calcified DFP (27.5%) with a median age of physeal closure of 16 years old (interquartile range 15.9–17.5).

The mean femoral insertion point of the MPFL according to Stephen's anatomical point was located 1.9 mm (1.4–2.2) distal to the physis in the 58 patients with open physis, with variability between age groups (Fig. 4). While most patients had an insertion point distal to the physis (40 of 58 patients, 69%), 16 had an insertion point within the physeal width (16 of 58, 28%) and 2 patients had an anatomical insertion point proximal to the physis (2 of 58, 3%).

Maximum physeal damage (5.35% [4.47–6.24]) was obtained with the 7-mm drill when drilling 3° cephalic and 15° posterior from insertion without differences between sexes or age (n.s.). Minimal physeal damage (0.22% [0.07–0.37]) was obtained using the 5-mm drill aimed 45° distal and 0° anteroposterior without differences by sex or age (n.s.) (Table 1).

Considering specific age groups, maximum physeal damage was obtained in the 10-year-old group with the 7-mm drill when drilling 1° distal and 17° posterior, and minimal physeal damage was obtained in the 14-year-old group with the 5-mm drill when drilling 45° distal and 0° posterior (Table 1).

An intercondylar notch breach secondary to drilling was simulated, which was observed with more than 23 mm drilling towards the intercondylar notch. A safe drilling zone, considering minimal physeal damage (< 1%) and no intercondylar notch breaching, was calculated using a probability map, obtaining optimal angles of 30°–40° distal and 5°–35° anterior (Figs. 5, 6). A safe drilling zone more than 20 mm deep (bicondylar drilling) was achieved only when drilling 15° anterior and 20° distal.

Inter- and intra-observer agreements were measured for the semi-automatic segmentation method. Inter-observer ICC was 0.99 (0.98–0.99) and intra-observer agreement was 0.99 (0.99–0.99).

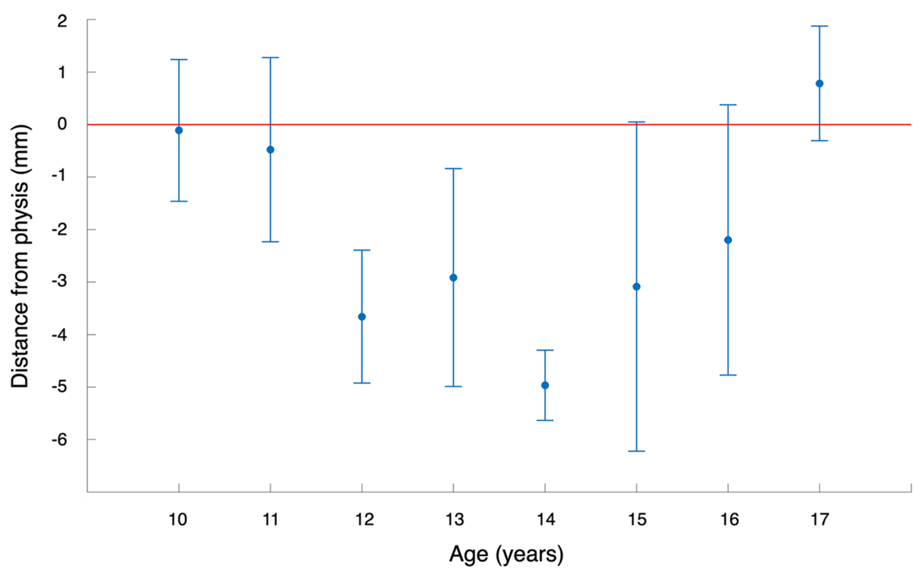

Fig. 4 Distance from the calculated femoral insertion point of the MPFL and DFP distal border in each age group (positive values on the distance axis are cephalic, and negative ones are distal)

Table 1 Maximum and minimal physeal damage according to age groups, drilling diameter and drilling angles

Age	*n*	Maximum physeal damage (7-mm drill)			Minimal physeal damage (5-mm drill)		
		%	Coronal angle (+: distal)	Sagittal angle (+: posterior)	%	Coronal angle (+: distal)	Sagittal angle (+: posterior)
10	10	8.5 [4.5–12.3]	1	− 17	0.43 [− 0.11 to 0.97]	45	0
11	10	5.3 [4.2–6.5]	0	− 19	0.24 [− 0.12 to 0.62]	45	0
12	9	4.3 [2.5–6.1]	1	− 25	0.07 [− 0.09 to 0.23]	45	0
13	10	5.1 [3.7–6.5]	− 1	14	0.36 [− 0.20–0.94]	45	0
14	6	4.0 [1.5–6.5]	− 5	15	0.001 [− 0.004 to 0.007]	45	0
15	8	6.2 [2.1–10.3]	− 3	22	0.24 [− 0.26 to 0.74]	45	0
Total group 10–17	58	5.35 [4.47–6.24]	− 3	15	0.22 [0.07–0.37]	45	0

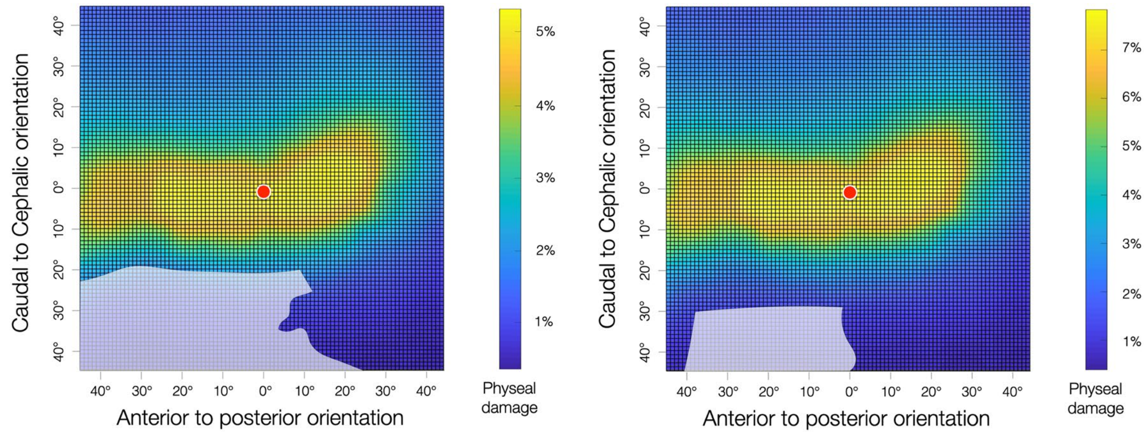

Fig. 5 Color map showing the percentage of physeal damage of each drill direction starting from the anatomic insertion of the MPFL (red dot) using a 5-mm drill (left) and a 7-mm drill (right). The vertical axis shows caudal to cephalic orientation (bottom and top, respectively), while the horizontal axis shows anterior to posterior orientation (left to right respectively). The distal and anterior demarcated white areas show the safe zone for each drill diameter

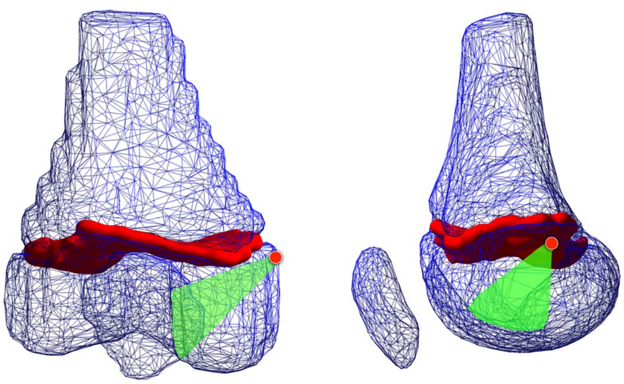

Fig. 6: 3D model of the distal femur in an anteroposterior (left) and lateral view (right). Red zone shows distal femoral physis. The green cone projecting from the anatomic femoral insertion from the MPFL (red dot) shows drilling safe zone for the 7-mm drill bit

Discussion

The most important finding of this study was that the optimal direction for femoral drilling in an anatomic MPFL reconstruction was obtained when aiming 30°–40° distal and 5°–35° anterior, regardless of sex. This direction was considered a safe drilling orientation since it granted tunnels of up to 20 mm without intra-articular drilling and compromised < 1% of the growth plate volume, considering that studies in animal models that have proposed 7% of physeal damage as the clinical relevance threshold [16, 19].

Anatomic MPFL reconstruction has been described as the gold standard of this surgical technique, considering that non-anatomic MPFL reconstructions, such as the adductor tendon loop technique, might overload the medial patellofemoral joint and lead to early failure [4, 5, 7, 32, 34]. Therefore, attempting an anatomic MPFL reconstruction in pediatric patients requires strategies to minimize the risks of physeal arrest or intercondylar notch breach.

Other studies have attempted to calculate the physeal damage risk. Greenrod et al., in a retrospective review of the MRI scans of 159 skeletally immature patients, confirmed that irrespective of age, parallel screw placement risks physeal damage in over 60% of the cases [11]. These researchers advocated for an oblique tunnel of 20 mm aimed 45° distal, since it avoids the growth plate and showed a joint breach incidence of 13%, mainly in the younger age group. It is important to highlight that this study was a 2D model study that did not address the extent of a cylinder-shaped tunnel with high accuracy, hence limiting the scope of its findings. Nguyen et al., in a cadaveric study of 23 distal femoral epiphyses (of 13 individuals) scanned into high-resolution 3D images, simulated 8 × 20 mm tunnels at varying angles [22]. In agreement with the actual study findings, these researchers also recommend angling the drill 15°–20° both distally and anteriorly to achieve the longest tunnel while minimizing damage to the physis, notch and distal femoral cartilage. These researchers also found that 41% of the tunnels angled less than 10° distally violated the growth plate before 20 mm and 40% of those angled more than 10° distal but less than 10° anterior violated the notch [22].

A proper understanding of the DFP morphology is the key to explaining the findings in this study. Lui et al. described growth plate morphology in a 3D scan model of 26 pediatric specimens between 3 and 18 years of age [18]. The DFP has a central ridge and two main undulations located in the anteromedial and posterolateral portions of the physes. The growth plate concavity reaches its deepest undulation towards the epiphysis at 13 years old, and with increasing age, the height of the central ridge decreases, whereas the posterolateral and anteromedial notches deepen [18]. This finding explains why maximal physeal damage in the present model was obtained when drilling was aimed anteriorly in younger groups (10–12 years old) and posteriorly in older groups (13–17 years old).

Regarding drilling length, most surgeons agree that sockets of at least 20 mm are enough to secure a graft with an interference screw [22]. Nevertheless, drilling distally can produce an intra-articular violation. For example, a tunnel angled 45° distal in this model, which produced the minimal physeal damage, was not considered optimal, since the intercondylar notch breach could occur at 23 mm of length. This is why a safe drilling greater than 20 mm that allowed for a bicondylar tunnel was only observed in a very precise combination of angles (15° anterior and 20° distal). A secure drilling orientation must preclude joint violation and damage to the distal femoral articular cartilage; therefore, it was calculated distally and anteriorly in this series.

In light of the findings of this study, slight variations of these drilling recommendations may generate significant physeal damage or intercondylar notch breach. In addition to the theoretical thermal damage from the heat of the drill spinning or bony compression from the hardware used for fixation, secure drilling orientations leave little range for mistakes. Meeting precise drilling angles during surgery can be both challenging and easily misleading. Consequently, the use of intraoperative fluoroscopy is fundamental for the individualized evaluation of the anatomy of the physis of each patient and to avoid errors. Also, the use of computer navigation system or other fixation methods, such as bony anchors, might be alternatives to avoid these complications [6, 14]. Also, other non-anatomical reconstruction techniques without drilling (i.e. adductor magnus tendon sling) have been proposed that will require future studies to confirm their reported good outcomes and physeal safety [20, 24].

One of the main limitations of the study was the supposition that the anatomical insertion of the MPFL is at Stephen's point [32]. This supposition was adopted given that the insertion point is not possible to determine with accuracy in the MRI, considering the resolution of cuts of 3 mm commonly used in this exam. In this scenario, Stephen's point would be the most recommendable reference to use in subjects with skeletally immature knees, since the Schöttle point is extrapolated from a series of adult knees and uses absolute measurements [26]. Other limitations are the small sample size in some of the age subgroups, and that the sample was not selected among patients that have recurrent patellar dislocations whom are frequently associated with varying degrees of trochlear dysplasia. Changes in femoral morphology could limit the conclusions that were made in general population patients.

The main strengths of this study are the use of a precise 3D model and a larger sample size in comparison with previous reports, enhancing the scope of its conclusions. As stated previously, allowing an anatomic reconstruction of the MPFL could lead to improved results in patients that usually are subject to non-anatomic alternatives. This study dissipates the apprehension of physeal damage when tunneling distally and anteriorly, impacting clinical decision-making in the future.

Conclusions

In this model, an ideal orientation for femoral drilling during anatomic reconstruction of MPFL was obtained when aiming 30°–40° distal and 5°–35° anterior, regardless of sex. This area constitutes a safe zone that allows anatomic MPFL reconstruction of patients with an open physis.

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Author contributions SI: conception and design, analysis and interpretation of data; drafting the manuscript and revising it critically for important intellectual content; final approval of the version to be published; agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; PB: conception and design, analysis and interpretation of data; drafting the manuscript and revising it critically for important intellectual content; final approval of the version to be published; agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; FF: acquisition of data, analysis and interpretation of data; revising the manuscript critically for important intellectual content; final approval of the version to be published; agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; TF: acquisition of data, analysis and interpretation of data; revising the manuscript critically for important intellectual content; final approval of the version to be published; agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; MJT: conception and design, analysis and interpretation of data; revising the manuscript critically for important intellectual content; final approval of the version to be published; agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; MJL: acquisition of data, analysis and interpretation of data; revising the manuscript critically for important intellectual content; final approval of the version to be published; agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; MO: conception and design, analysis and interpretation of data; revising the manuscript critically for important intellectual content; final approval of the version to be published; agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Compliance with ethical standards

Conflict of interest There are no authors' disclosures or conflicts of interest.

Ethical approval Institutional review board.

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