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Impact of graft width and chondrolabral junction preservation on labral suction seal integrity in bovine hip models

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Abstract. – OBJECTIVE: This study investigates the biomechanical effects of graft width and chondrolabral junction (CLJ) preservation on the labral suction seal in a bovine hip model and aims to validate this model as a practical alternative for hip biomechanical research by comparing it with human cadaver studies.

MATERIALS AND METHODS: Twenty hips from two-year-old male bovines were divided into two main groups: CLJ preserved (CLJ+) and CLJ excised (CLJ-). These groups were further divided into eight subgroups: Group 1 with an intact labrum; Group 2 with labrum excision preserving CLJ; Groups 3 and 4 with labral reconstruction on preserved CLJ using 4.5 mm and 9 mm grafts, respectively; Group 5 with a labral tear at 12 to 3 o'clock position without CLJ preservation; Group 6 with complete labrum excision without CLJ preservation; and Groups 7 and 8 with labral reconstruction on excised CLJ using 4.5 mm and 9 mm grafts. Mechanical tests measuring compression and distraction forces were conducted, recording force-displacement values.

RESULTS: Both CLJ+ and CLJ- groups showed that labrum excision resulted in the lowest distraction forces, emphasizing labral integrity. Notably, reconstruction with 9 mm grafts improved distraction forces more than 4.5 mm grafts (*p*<0.001). The change in distraction forces from intact to excised stages was nearly significant between CLJ+ and CLJ- groups (Δ Intact-excised: CLJ+ *vs.* CLJ-: 92 N *vs.* 105 N, *p*=0.08). Distraction forces were measured at 206±27 Newtons in the CLJ preserved group and 186±24 Newtons in the resected group.

CONCLUSIONS: This study demonstrates that increasing the width of the graft, despite being approximately half and a quarter of the native labrum's size, significantly enhances the distraction force in labral reconstruction within a bovine hip model. This improvement is more pronounced than the effects of preserving the CLJ, highlighting the critical role of graft size in maintaining the biomechanical integrity of the labral suction seal.

Key Words:
Hip, Labral reconstruction, Chondrolabral junction, Suction seal, Biomechanics.

Introduction

The acetabular labrum is a fibrocartilaginous structure that creates negative intra-articular pressure during distraction forces, known as the suction effect, crucial for hip joint stability. This structure also distributes load stress on the cartilage during compression forces by pressurizing the intra-articular fluid and distributing synovial fluid between the central and peripheral compartments through a sealing mechanism[1]. Additionally, it adds depth to the acetabulum, enhancing joint congruity and stability. These functions are essential in protecting the cartilage from up to 90% of compressive forces and reducing friction between cartilage surfaces[2,3]. Labrum injury compromises the seal mechanism and leads to early joint degeneration[4,5].

Acetabular labral tears can result from trauma, femoroacetabular impingement (FAI), dysplasia, degeneration, or a combination of these factors. The evolution of hip arthroscopy has allowed the development of specialized surgical techniques to address these pathologies, which include debridement, repair, reconstruction, and augmentation of the acetabular labrum. Labral debridement, once

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considered the gold standard treatment for labral pathology, yields less favorable clinical results than labral repair[6,7]. On the other hand, labral reconstruction is a surgical procedure in which native tissue is excised and substituted with a graft, indicated when the labral damage is extensive or irreparable, rendering primary repair unfeasible. However, prior human cadaver studies[4,5] have demonstrated partial restoration of this negative pressure gradient due to suction seal by labral repair or reconstruction. Moreover, labral augmentation is a relatively new technique used to supplement a damaged or repaired labrum with biological or synthetic materials, and it has been shown[8,9] to improve the labral suction seal better than labral reconstruction. Nevertheless, a study by Maldonado et al[10] suggested that graft width is crucial in restoring the labral suction seal, finding that wider allografts (>6.5 mm) restore the seal more effectively than thinner ones. These findings lead us to consider the possibility that the superior results of labral augmentation reported in literature might be associated with the use of smaller grafts during reconstruction.

Bovine acetabulum, long bones, and labrum have been used[11-16] widely for biomechanical testing because they closely mimic human bone and labrum. As bovine tissue is more convenient, easy to handle and has previously been used in hip biomechanical studies[17-19], the present study primarily aimed to report the bovine hip suction model for the first time and to demonstrate whether maximum distraction force would be at the range that had been reported for human cadaver studies[4,5,8,10]. Our focus was on the biomechanical properties of the labral suction seal in the native labrum after labral resection, which was performed with or without 3.5 mm chondrolabral junction (CLJ) preservation. Following this, labral reconstruction was carried out using grafts of either 4.5 mm or 9 mm width in a bovine hip model. The aim was to evaluate the effect of CLJ preservation and graft width on distraction force in labral reconstruction. We hypothesize that a larger '9 mm' graft, the largest size used in a human study, with preserved CLJ, would produce distraction forces similar to the intact stage and higher than those in specimens reconstructed with a smaller '4.5 mm' graft, the smallest size used in a human study, and/or an excised CLJ[8,10].

Materials and Methods

Twenty hips of two-year-old male bovines were included in this study. Institutional Review Board approval was not required for unidentified bovine cadaver specimens that were obtained post-mortem from animals that were not specifically euthanized for the purposes of our study but were instead sourced from animals already deceased for reasons unrelated to our research. Any specimens with the signs of a calcified labrum, labral tear, or complete ligamentum teres tear were excluded. The hemipelvises were potted in a plastic container filled with saline solution and stored at -20°C immediately after collection. Prior to dissection and biomechanical testing, specimens were thawed in a refrigerator at 2°C for six hours. All soft tissues, including the capsule, were carefully dissected to expose the joint while preserving the CLJ.

Twenty hip specimens were divided into two groups: the CLJ preserved group (CLJ+) and the CLJ excised group (CLJ-). In the CLJ+ group, 3.5 mm of CLJ was preserved, which approximates half of the diameter of the human labrum[8,20]. Labral height and width at the 12 o'clock position were measured in each specimen. Then, these two groups were further divided into four groups. As a result, this study consisted of eight groups: Group 1 with an intact labrum; Group 2 with the labrum excised but preserving the CLJ; Group 3 undergoing labral reconstruction on preserved CLJ with a 4.5 mm graft; Group 4 with labral reconstruction on preserved CLJ using a 9 mm graft; Group 5 featuring a 12 to 3 o'clock position labral tear without preserving the CLJ; Group 6 with the labrum excised and no CLJ preservation; Group 7 undergoing labral reconstruction on excised CLJ with a 4.5 mm graft; and Group 8 with labral reconstruction on excised CLJ using a 9 mm graft.

The anterior-superior aspect of the labrum from the 12 to 3 o'clock position was chosen as the surgical site because most labral tears due to femoroacetabular impingement syndrome occur in this location[8,21,22]. Extensor tendons were collected and used for segmental reconstruction due to having similar physiological properties to human hamstring tendons[22,23]. Grafts were prepared by folding the extensor tendons into thirds and tubularized using multiple No. 2-0 absorbable sutures (Vicryl, Ethicon, Johnson and Johnson Ltd., New Delhi, India)[10,24]. The final width was both mea-

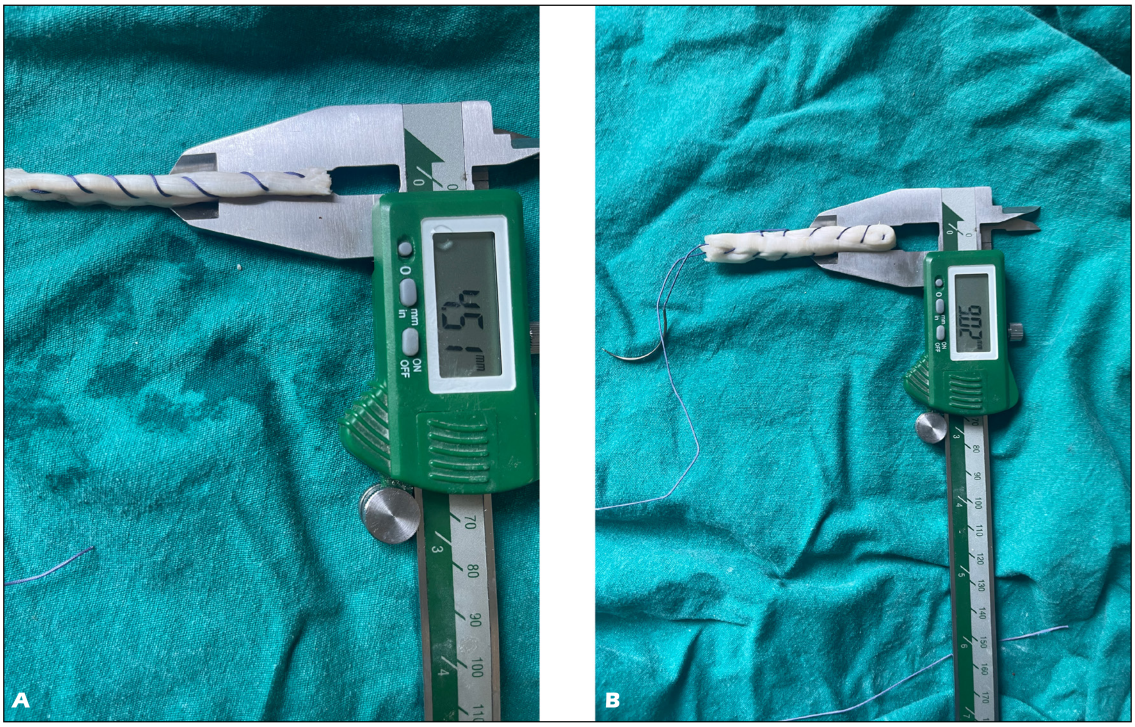

Figure 1. Extensor tendon grafts. **A**, 4.5 mm graft. **B**, 9 mm graft.

sured using a graft sizing block and digital caliper (Figure 1). The graft was stabilized using three 2.3 mm suture anchors (Osteoraptor; Smith & Nephew, Andover, MA, USA), which were placed in a looped fashion. These anchors were positioned as close as possible to the acetabular rim at 12 o'clock, 3 o'clock, and midway between these two points (Figure 2). There were two sizes of autograft (4.5 mm and 9 mm), which have been reported[8,10] to be the smallest and largest sizes.

At the biomechanical testing setup, the proximal femur and acetabular section of the pelvis were potted using polymethyl methacrylate and securely fixed to the frame of an electromechanical testing system. To ensure safe and reproducible results during the application of tensile force, the testing setup was securely fixed with a monoaxial pedicle screw placed in the center of the femoral head and by connecting the mold to a clamping lug (Figure 3). The mechanical analysis was performed using an axial tensile machine (AG-IS 5 kN; Shimadzu Corporation, Kyoto, Japan) in a tensile loading test. In each condition, a preload of 400 N was applied to the acetabulum for 30 seconds. Afterward, tests were performed at a displacement rate of 60 mm/min. The force (N) – displacement (mm)

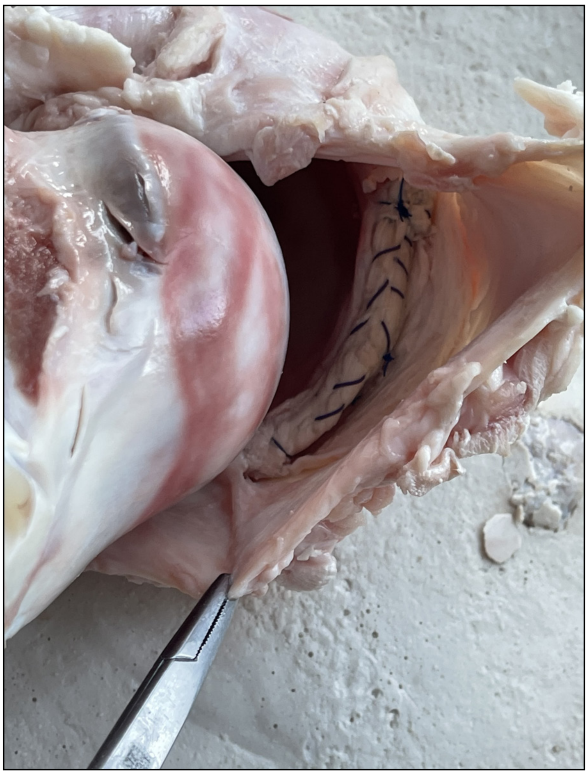

Figure 2. Labral graft reconstruction (in this example, the labrum was excised between 12 and 3 o'clock position, preserving the CLJ, and was reconstructed with a 4.5 mm extensor tendon graft).

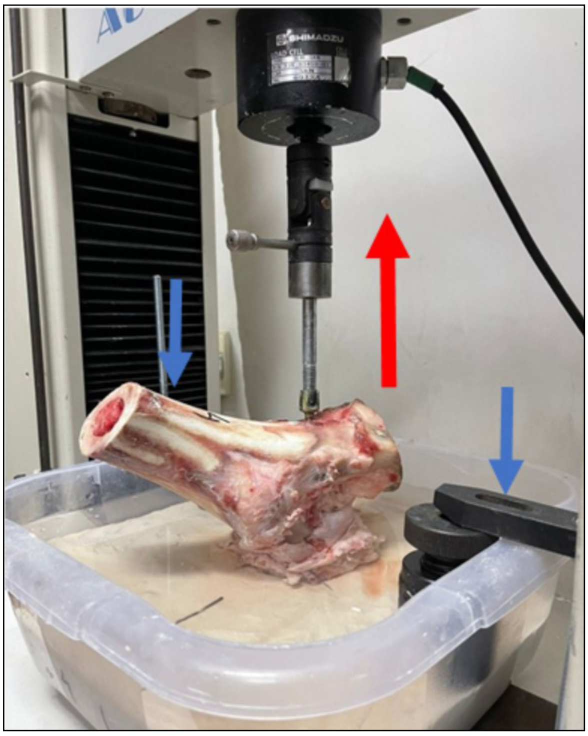

Figure 3. Biomechanical testing setup. Hemipelvis was potted in a plastic container and stored at -20°C. Supports were placed on both sides to prevent the movement of the plaster after dissolution in the plastic container (blue arrows). A monoaxial pedicle screw was placed in the center of the femoral head and attached to the test device, while the tensile force was applied with a force of 400 Newton (red arrow).

values were recorded by TRAPEZIUM X software (Shimadzu, Japan).

Statistical Analysis

Statistical testing was performed *via* a repeated-measures analysis of variance with a post hoc Tukey analysis. Statistical significance was set at $p<0.05$. The statistical analysis was conducted using the SPSS software package (version 17.0, SPSS Inc., Chicago, IL, USA).

Results

The mean width of the labrum in the CLJ+ group was higher compared to the CLJ- group (14 mm *vs.* 12 mm, p=0.007). Height did not differ between groups (18.8 *vs.* 18 mm, p=0.08).

Statistically significant differences were observed between labral reconstructions using 9 mm and 4.5 mm width grafts, which ranked as the second and third highest groups, respectively ($p<0.001$) (Figure 4).

When comparing the change in distraction force applied at the intact stage between CLJ+ and CLJ- groups, only the decrease from the intact to the excised stage was nearly statistically significant (change from intact to excised: CLJ+ *vs.* CLJ-: 92 N *vs.* 105 N, p=0.08). No other comparisons showed significant differences (Table I).

Within the CLJ+ group, statistically significant differences were observed between the subgroups (all p-values=0.000). Similarly, within the CLJ- group, significant differences were found between the subgroups (all p=0.000).

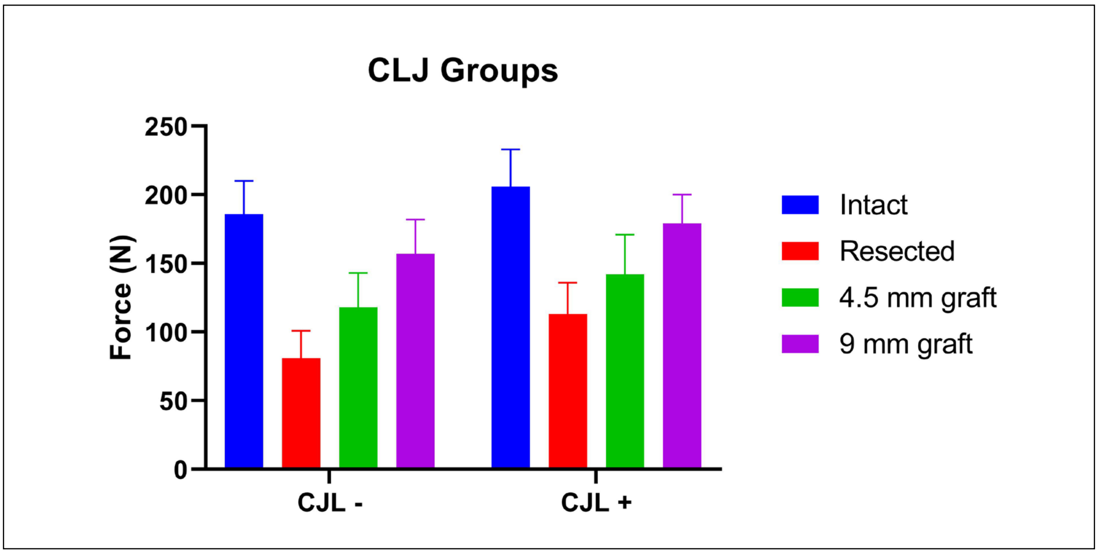

Figure 4. Force (N) graph for each CLJ group. Chondrolabral junction (CLJ).

When testing whether there is a statistically significant difference between the CLJ+ and CLJ- groups in terms of maximum distraction force, significant differences were found between the means, which were 160.74 and 135.87, respectively (*p*=0.000).

The differences in the mean maximum distraction forces between the labrum-intact and labrum-excised subgroups were calculated and were denoted as Δ1. Similarly, the differences between the means of maximum distraction force for the labrum intact and the labral reconstruction with 9 mm width graft subgroups were calculated and named Δ2. Finally, the differences between the means of maximum distraction force for the intact labrum group and labral reconstruction with a 4.5 mm width graft group were calculated and designated as Δ3. The differences between Δ1, Δ2, and Δ3 for the CLJ+ and CLJ- groups were tested using independent samples *t*-test. The results indicate that there were no statistically significant differences between the groups, with *p*-values for Δ1, Δ2, and Δ3 being 0.085, 0.642, and 0.560, respectively.

Discussion

The main findings of the present study are as follows: the measured distraction forces in the CLJ+ group were notably higher, whereas in the CLJ- group, they closely approached the upper limits (186 *vs.* 177-181 N) observed in human cadaver studies[4,5,8,10]. A 9 mm width graft was more effective in restoring the suction seal compared to a 4.5 mm width graft, although it was still significantly lower than the intact stage. While preservation of the CLJ led to a smaller decrease in force, only the reduction in force at the resected stages compared to intact stages was statistically significant (*p*=0.08)

A recent biomechanical study[8] reported that labral augmentation better restored the suction seal compared to labral reconstruction. However, both were still lower than those in the intact stage. They reported a similar peak force of 137±40 N and a similar ratio relative to the intact ratio (54%±27%) in previous studies[4,5]. Their augmentation technique was the preservation of half the length of the labrum and the excision of the capsular half. Considering the normal height of the human labrum, approximately 6.48 mm, we preserved 3.5 mm of the labrum above the CLJ[8,20]. This amount may not have been sufficient to demonstrate the effect of CLJ preservation on suction seal parameters, possibly due to the greater height and width of the bovine labrum.

A more recent biomechanical study[10] advocated the usage of thicker allografts (>6.5 mm) to enhance distraction force. They cited that the usage of a thinner graft (5 mm) in the study of Suppauksorn et al[8] led to the insufficient restoration of the suction seal at the reconstruction group. Distraction force at the intact stage (148±33 N) was higher than that in the previous study[8] due to the use of a saline bath and hydraulic mechanical testing system instead of manual distraction force like the one used in the present study[10]. Unlike the present study, they[10] reported comparable distraction values with hips having intact labrum in the allografts >6.5 mm group. The present study still could not find comparable values, although CLJ was left intact, and the thickest graft reported (9 mm) was used. This was due to a notably wider and thicker bovine labrum compared to a human labrum (18 mm *vs.* 6.48 mm)[10,20]. However, the present study still clarified the beneficial effects of an increase in the width of the graft on distraction force. Although the size of the graft was approximately ½ and ¼ of the native labrum, this beneficial effect was observed to be more import-

Table I. CJL+/- maximum distract force in Newton.

Groups (max distract force N)		Mean±SD	95% CI
CLJ+	Group 1	206±27	196-217
	Group 2	113±23	105-122
	Group 3	142±29	131-153
	Group 4	179±21	171-187
CLJ-	Group 5	186±24	177-196
	Group 6	81±20	73-89
	Group 7	118±25	108-127
	Group 8	157±25	147-166

Chondrolabral junction (CLJ).

ant and/or had a major impact than the effect of CLJ preservation.

The importance of other factors such as graft geometry, the quality of the surrounding cartilage tissue, joint congruence, and the forces exerted on the joint during motion should be kept in mind, in addition to graft width and preservation of the chondral junction, when considering the suction seal feature of the hip. However, there is a lack of consistent restoration of the articular contact areas, suction seal function, and material properties found with allografts compared to the native labrum. Additionally, these reconstructions are linked to treatment failure rates up to 24.3%[25,26]. The ideal graft in labral reconstruction should accurately replicate both the anatomical structure and functionality of the original acetabular labrum. As elucidated by Yu et al[27], the shape, size, and placement of the graft significantly influence the biomechanical behavior of the hip joint. The geometric compatibility of the graft with the surrounding articular surfaces is essential for maintaining joint congruence and stability. A graft that closely mirrors the natural curvature and thickness of the native labrum can more effectively restore the natural biomechanics of the hip, thereby maintaining the suction seal and reducing the risk of joint incongruence. This congruence is vital for the distribution of forces across the hip joint during motion, which, if altered, can lead to abnormal wear patterns and potential joint degeneration[27]. Similarly, in patients with acetabular dysplasia, when planning periacetabular osteotomy, the contribution of the labrum to joint congruence, in addition to the acetabular bone structure, should not be overlooked due to its impact on joint function[28]. On the other hand, the graft fixation technique classically involves the use of knotted and knotless anchors, both loop fashion and pass-through intrasubstance techniques, to restore the labrum against the femoral head. Ideal fixation must be secure enough not to stretch when subjected to radial forces during the axial loading of the joint while maintaining the natural triangular cross-sectional shape of the labrum at its optimal refixation position without eversion or inversion to restore the anatomical structure[29-32]. When evaluating graft options, it has been reported in a biomechanical study[31] that the iliotibial band, semitendinosus, gracilis, and anterior tibialis grafts demonstrated similar cyclic elongation under simulated physiological loads. While performing the surgery, care must also be taken to prevent iatrogenic damage to the chondrolabral junction and articular cartilage caused by surgical instruments and/or surgical manipulation. This iatrogenic damage has the potential to alter hip biomechanics, resulting in instability and increased pressures on articular cartilage, leading to recalcitrant hip pain, functional limitation, degeneration, and the development of early osteoarthritis necessitating the need for additional surgery[33-35].

Limitations

There are some limitations in this study. The use of bovine labrum rather than cadaveric tissue may have affected the absolute values obtained in testing. Although bovine labrum and hip tissue have been validated for use in previous biomechanical tests[11-16], the larger size of the bovine labrum precluded the present study from getting comparable results with the intact stage and with the usage of a 9 mm width graft. Considering that the bovine labrum is 3 times larger than the human labrum, even the 9 mm width graft should have been calibrated to fit the bovine. However, this demonstrates that the normalized height and width of the labrum, considering the localization and size of the acetabulum, must be known. In addition to this, the bovine acetabular contact area is also likely to have a significant impact on the effectiveness of the labral suction seal. Nevertheless, in terms of the labral suction seal, the width of the graft seems to be more important than the preservation of CLJ.

Conclusions

The increase in the width of the graft has a beneficial effect on distraction force, although the size of the graft was approximately ½ and ¼ of the native labrum. This beneficial effect was observed to be more important than the effect of CLJ preservation.

Conflict of Interest

The authors declare that they have no conflict of interest to disclose.

Ethics Approval and Informed Consent

Not applicable. The specimens in this study were obtained post-mortem from animals that were not specifically euthanized for the purposes of our study but were instead sourced from animals already deceased for reasons unrelated to our research.

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Authors' Contributions
AEA has made a substantial contribution to the design of the work and manuscript drafting and supervision. OG has also contribution to the research conception and design. SA, GT, MO have enrolled in the acquisition, analysis and interpretation of data. RBH was a major contributor in the design of the work and interpretation of data. OH has made substantial contribution to the conception of the work, interpretation of data and critical revision of the manuscript.

Availability of Data and Materials
The datasets generated during and/or analyzed during the current study are not publicly available due to their privacy but are available from the corresponding author upon reasonable request.

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