Effect of periacetabular osteotomy on the distribution pattern of subchondral bone mineral density in patients with hip dysplasia

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Tomohiro Shimizu contributed to research design, data acquisition, analysis and interpretation of data, and drafting of the paper; Daisuke Takahashi contributed to data acquisition and analysis and interpretation of data; Yumejiro Nakamura contributed to data acquisition and analysis and interpretation of data; Takuji Miyazaki contributed to data acquisition; Shunichi Yokota contributed to data acquisition; Hotaka Ishizu contributed to data acquisition; Norimasa Iwasaki contributed to interpretation of data. All authors have read and approved the final submitted manuscript.

Abstract

Despite the availability of long-term follow-up data, the effect of pelvic osteotomy on the natural history of osteoarthritis is not yet fully understood, partly because there is untapped potential for radiographs to better describe osteoarthritis. Therefore, this study aimed to assess the distribution of subchondral bone mineral density (BMD) across the acetabulum in patients with hip dysplasia immediately (2 weeks) and 1 year after undergoing periacetabular osteotomy (PAO). To that end, we reviewed 40 hips from 33 patients with developmental dysplasia of the hip (DDH) who underwent PAO between January 2016 and July 2019 at our institution. We measured subchondral BMD through the articular surface of the acetabulum using computed tomography (CT) osteoabsorptiometry (OAM), dividing the distribution map into nine segments. We then compared the subchondral BMD between 2 weeks and 1 year after PAO in each area. At 2 weeks after PAO, the high-density area tended to be localized particularly in the lateral part of the acetabulum, whereas 1 year after PAO, the high-density area moved to the central and lateral parts. The percentage ratios of the subchondral BMD for the central-posterior, lateral-central, and lateral-posterior areas relative to the central-central area were significantly decreased at 1 year after PAO, as compared to those at 2 weeks after PAO. These findings suggest that loading was altered by PAO to be more similar to physiological loading. Long follow-up observational study is warranted to confirm the association between early changes in subchondral BMD by PAO and joint degeneration.

Keywords: hip dysplasia, bone mineral density, periacetabular osteotomy

Introduction

Developmental dysplasia of the hip (DDH) with associated structural instability is one of the more common causes of secondary osteoarthritis[1, 2]. Deficiency of the bony acetabulum results in hip instability and acetabular rim overload with subsequent damage to the labrum and articular cartilage[3]. Finite element analysis (FEA) has shown that DDH models showed stress concentration in the acetabular edge and contacting femoral head, as compared to the normal hip joint model[4]. As such, reducing articular cartilage contact stress by pelvic osteotomy may delay the appearance or reduce the severity of osteoarthritis[5, 6]. Multiple types of pelvic osteotomies have been described, with intermediate- and long-term clinical and radiographic results, suggesting that these procedures can prevent the progression of DDH to secondary osteoarthritis[7-10]. However, despite the availability of long-term follow-up data, the effect of pelvic osteotomy on the natural history of osteoarthritis is not yet fully understood, partly because there is untapped potential for radiographs to better describe osteoarthritis.

The pattern of subchondral bone density reportedly reflects the distribution of cumulative stresses acting on a joint surface under actual loading conditions[11]. As early changes in the subchondral bone can predict subsequent symptoms or disease structural progression, new tools may help clinicians to stratify different osteoarthritis phenotypes based on bone remodeling status[12]. Given this theoretical background, Müller-Gerbl et al. have developed a method of computed tomography (CT) osteoabsorptiometry (CTOAM) to assess the long-term stress distribution of individual joints in living subjects by measuring subchondral bone density as a surrogate for cumulative stress and loading abnormalities[11, 13]. Using this method, previous studies have evaluated the stress distribution of different joints under various loading conditions, from normal to pathologic or postoperative conditions[14-18]. Focusing on the hip joint, a previous study reported significant differences in the severity and patterns of loading based on the severity of dysplasia, as compared to the control group[18]. Therefore, CTOAM could detect the effect of pelvic osteotomy, as the subchondral bone mineral density (BMD) changes over time after PAO would be a good surrogate measure for loading changes.

We hypothesized that periacetabular osteotomy (PAO) would change the distribution of subchondral bone density across the acetabulum. In the present study, a modified method of CTOAM was employed to test this hypothesis[19, 20]. Thus, this study aimed to assess the distribution of subchondral BMD across the acetabulum in patients with DDH immediately (2 weeks) and 1 year after undergoing PAO.

Methods

Subjects

This study was retrospective cohort study (level of evidence, level III). This study was conducted in accordance with the ethical standards of the Declaration of Helsinki and was approved by our Institutional Review Board (#017-0508). A total of 41 hips from 34 patients (4 males and 30 females) with DDH underwent PAO between January 2016 and July 2019 at our institution. This study only included 40 hips, excluding one patient who delayed rehabilitation due to fracture of the posterior column. The mean age of the patients at surgery was 32.8 years (range, 14–55 years), and the mean body mass index (BMI) was 23.1 kg/m^2 (range, 17.8–37.9 kg/m^2) (Table 1). Surgical indications for PAO included acetabular dysplasia with a lateral center of edge (CE) angle <20° and discontinuity of the Shenton's line[21], unsuccessful 6-month nonoperative treatment, age <60 years, an excellent or grade of the preoperative joint congruency in abduction according to classification of joint congruency described by Yasunaga[22], and no pain on hip flexion and extension with the extremity held in abduction[23].

Surgery and rehabilitation

All osteotomies were performed by one of four board-certified, fellowship-trained orthopedic surgeons at a single institution. The type of PAO used was eccentric rotational acetabular osteotomy (ERAO)[23], an improved version of rotational acetabular osteotomy[24]. The operative techniques have been described previously[23]. Briefly, a 20-cm curved skin incision was made 5 cm proximal to the tip of the greater trochanter. The greater trochanter was then retracted proximally after completion of osteotomy at its base, with an approximate thickness of 10–15 mm, and the gluteus minimus and medius muscles were reflected approximately 30 mm from the acetabular rim. The osteotomy site was approximately 15–20 mm or greater from the joint space according to the preoperative planning. Following osteotomy of the ilium and pubis, the acetabular fragment was rotated easily, wherein trimming of the inner cortex of the ilium was essential for medializing the acetabular fragment. Coverage of the femoral head by the rotated acetabular fragment was verified using an image intensifier before fixation of the acetabular fragment with two or three polylactide screws. Afterwards, the greater trochanter was repositioned and fixed with two AO cancellous screws. Postoperatively, one-third partial weight-bearing was permitted with a walker after 4 weeks, one-half partial weight bearing was permitted after 6 weeks, and full weight-bearing was allowed after 8 weeks. One year after PAO, the patients underwent surgery to remove the two AO cancellous screws.

Clinical and radiological evaluation

Clinical evaluations were performed using the Harris hip score (HHS)[25] and the Japanese Orthopedic Association Hip-Disease Evaluation Questionnaire (JHEQ)[26] preoperatively and 1 year after PAO. Range of motion was measured by goniometry. Supine anterior–posterior (AP) pelvic radiographs and CT scans were taken preoperatively, 2 weeks after PAO, and 1 year after PAO (average radiation exposure per examination, 5.5 mSv). The radiographs were obtained using Siebenrock's standardized technique[27], and the CE angle, Sharp angle, acetabular head index (AHI)[28], and acetabular roof obliquity (ARO) were evaluated[29]. All digital measurements and calculations were performed using the Centricity™ Web-J 3.0 HD software (GE Healthcare Japan, Tokyo, Japan). Measurements were performed two times with a 3-month interval by the first two authors (T.S. and N.Y.), showing almost excellent intra- and inter-class correlation coefficients (0.943, $P < 0.001$, and 0.873, $P < 0.001$; respectively). A high-resolution (pixel matrix, 512×512) helical CT scanner (CT High Speed Advantage; GE Medical Systems, Milwaukee, WI, USA) was used to obtain axial images of the bilateral hips with an intensity calibration phantom (B-MAS200, Kyoto Kagaku, Kyoto, Japan). The slice thickness and interval were set to 1 mm each, and the table speed was set to 1 mm/s. Imaging data were analyzed using the Aquilion One image analysis system (Toshiba Medical Systems, Tokyo, Japan), and a three-dimensional bone model was generated from the axial image stack. Thereafter, anterior pelvic plane-based coronal views at 1-mm intervals were reconstructed using the multiplanar reconstruction model.

To evaluate subchondral bone density, we used OsteoDens 4.0, a noncommercial software developed at our institution[16-19]. The target area was the subchondral bone region of the weight-bearing acetabular surface. In the coronal image, the region-of-interest was manually selected to include the entire subchondral bone layer of the acetabulum in all slices, numbering an average of 102.4 coronal slices (range, 92–115 slices) to capture the acetabulum. After establishing the region-of-interest, we automatically measured the subchondral bone of the undersurface of the acetabular at each coordinate point at 1-mm intervals in Hounsfield units

(HU), which is defined as the radiograph attenuation whereby water is 0 and compact bone is 1000 (Fig. 1). Measurement and mapping were repeated in each slice, and the data were stacked to create a two-dimensional mapping image showing the distribution of subchondral bone density. We then divided the acetabulum automatically into three equal parts following the front-back and medial-lateral directions, and the measured target area was divided into nine regions: medial anterior (MA), medial central (MC), medial posterior (MP), central anterior (CA), central center (CC), central posterior (CP), lateral anterior (LA), lateral central (LC), and lateral posterior (LP) (Fig. 1B). The mean bone density, corrected using the phantom (B-MAS200, Kyoto Kagaku, Kyoto, Japan), was measured for each region. Additionally, to evaluate the distribution, we investigated the ratios of the subchondral BMD of each area to that of the CC area.

Furthermore, we calculated the intra- and interobserver reproducibility of the CTOAM based on the five consecutive measurements and based on the measurements of the two orthopedic surgeons (T.S. and N.Y.), respectively. The reliabilities between and within each observer were calculated according to the intraobserver, interobserver, and residual variances estimated by the analysis of variance table based on Proc Mixed in the SAS software (SAS Institute, Cary, NC, USA). The intra-class correlation coefficients for intra- and interobserver reproducibility were 0.86 (95% confidence interval [CI], 0.73–0.97) and 0.79 (95% CI, 0.65–0.91), respectively.

Statistical analysis

Paired *t*-tests with Bonferroni correction were used to compare the clinical evaluation and BMD of the subchondral bone preoperatively, 2 weeks after PAO, and 1 year after PAO. Correlations between BMI and subchondral BMD were performed using Pearson's product–

moment correlation coefficient. All statistical analyses were performed using the IBM SPSS version software (SPSS Inc., Chicago, IL, USA), and statistical significance was set at $p < 0.05$.

Results

Demographic characteristics, clinical score, and radiographic parameters

Table 1 summarizes the longitudinal clinical scores and radiographic parameters in this study. Although internal rotation was limited at 1 year postoperatively ($P = 0.005$), clinical scores, including the HHS and JHEQ, were significantly improved, as compared to those preoperatively ($P < 0.001$). The mean CE angle and mean AHI increased, whereas the mean Sharp angle and mean ARO decreased significantly from the preoperative to postoperative values (all $P < 0.001$).

Analysis of patients treated with PAO

At 2 weeks after PAO (immediately after surgery), the high-density area tended to be localized in the lateral part of the acetabulum (Fig. 2A), whereas at 1 year after PAO, the high-density area moved to the central and lateral parts. In the quantitative evaluation of the subchondral BMD calibrated according to the phantom, mean BMD values in the medial, CA, and CC areas at 1 year after PAO were significantly higher than those at 2 weeks after PAO (Fig. 2B). To evaluate subchondral BMD distribution, we investigated the ratios of the subchondral BMD of each area to that of the CC area (Fig. 2C). The percentage ratios of the subchondral BMD for the CP, LC, and LP areas relative to the CC area were significantly decreased at 1 year after PAO, as compared to those at 2 weeks after PAO. No significant associations between BMI and subchondral BMD were observed (Supplemental Table 1).

Discussion

Clinically, PAO has been reported to be an effective treatment for early osteoarthritis in young or active patients with DDH[30-32]. Moreover, this study showed the significant improvement of HHS and patient-based clinical outcomes (JHEQ) from preoperative to 1 year after surgery. Despite this, although simulation studies using finite or discrete element analysis showed alterations of contact stress by PAO[4, 33], findings on changes in the mechanical environment due to PAO have not yet been fully clarified. In this study using CTOAM, we found that PAO shifted the area with the highest subchondral BMD from the lateral to the central region and reduced the ratio of subchondral BMD in the CP, LC, and LP areas relative to that in the CC area, thus confirming our hypothesis.

The finding that the subchondral BMD on the lateral side tended to be higher than that on the medial and center areas at 2 weeks after PAO showed a similar tendency to a previously described study on severe dysplasia subjects[18], suggesting that CTOAM data at 2 weeks after PAO may reflect the preoperative mechanical environment. Moreover, the finding that the subchondral BMD in the central area tended to be higher than that in other areas at 1 year after PAO showed a similar tendency to the control subjects (25° < CE angle < 35°) of that same study[18]. Although one of the main limitations of the current study was the indirect measure of mechanical stress with acetabular subchondral BMD using CTOAM, we believe that these findings suggest that loading was altered by PAO to be more similar to physiological loading.

Contrary to our expectations and previous reports using FEA[34, 35], this study showed that the absolute subchondral BMD in the medial, CA, and CC areas increased significantly from 2 weeks to 1 year after PAO. Since PAO transfers the medial part, which is considered to be a lower mechanical stress area, to the central area, it is possible that the subchondral BMD in the medial and central areas were relatively low at 2 weeks after PAO. Furthermore, it is possible that this finding may have been affected by the limitation of weight-bearing immediately after PAO. However, since this study was only a 1-year longitudinal follow-up study, a longer follow-up period is necessary to address whether the increase in subchondral BMD from 2 weeks to 1 year after PAO would affect future joint degeneration.

Despite these findings, this study had a few limitations. First, we could not directly measure the contact stress pressure and stress distribution patterns in the live patients' hips. However, the measurements of BMD were more clinically accessible. Second, although we performed fixation of the acetabular fragment with two or three polylactide screws and compared the CT data on the same setting between 2 weeks and 1 year after PAO, the artifact from the screws could have affected BMD distribution in this setting. Third, postoperative alterations in the pattern of subchondral bone mineralization may depend not only on the biomechanical effects of PAO but also on the individual loading conditions. To clarify this point, we should perform further analysis based on CT data from more patients treated with PAO. Fourth, this was a short follow-up observational study. Although we targeted the early changes in the subchondral bone during PAO, a longer follow-up study is required to understand the association between subchondral BMD and joint degeneration. Finally, because reductions in vascular supply are associated with bone loss[36], BMD may also depend on the vascularity of the acetabular fragment. As this study did not investigate the vascularity of the acetabular fragment, further studies should address this concern in the future.

In conclusion, the findings of this study using the CTOAM method suggest that loading was altered by PAO to be more similar to physiological loading. Long follow-up observational studies should be performed to confirm the association between early changes in subchondral BMD by PAO and joint degeneration.

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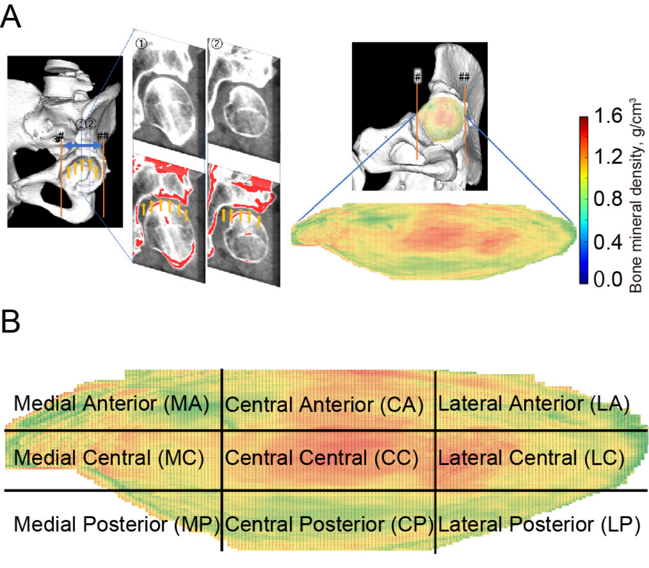
Figure legends

Fig. 1. (A) The image shows how the subchondral bone region of the acetabulum was identified automatically using the customized software. In each coronal slice, we measured the Hounsfield units of radiograph absorption in the subchondral bone at each coordinate point in 1-mm intervals. For quantitative analysis, the distribution pattern is represented as a surface-mapping image depicted by a color scale. (B) The image shows segments used for quantitative analysis of the bone density mapping data for the acetabulum.

Fig. 2. (A) The images show the distribution of bone density values across the articular surface of the acetabulum at 2 weeks and 1 year after periacetabular osteotomy. (B) Comparisons of the subchondral bone mineral density between 2 weeks and 1 year after periacetabular osteotomy in each area. (C) Comparisons of the percentage ratio of each area relative to the subchondral bone mineral density in the central center area between 2 weeks and 1 year after periacetabular osteotomy. Data are presented as means ± standard deviation. Asterisks indicate $P < 0.05$.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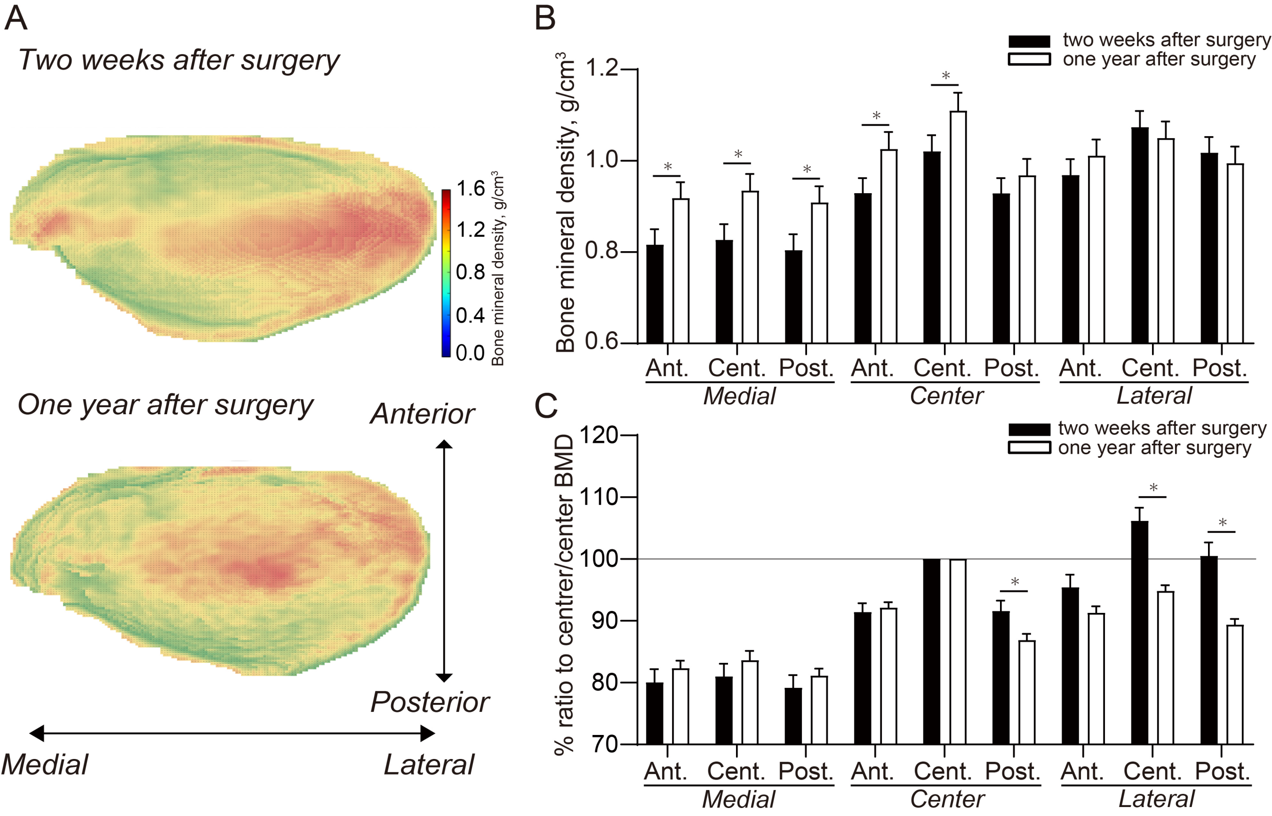
Lateral Anterior (LA)
Medial Central (MC)
Central Central (CC)
Lateral Central (LC)
Medial Posterior (MP)
Central Posterior (CP)
Lateral Posterior (LP)



A
Two weeks after surgery
1.6
1.2
0.8
0.4
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Bone mineral density, g/cm³
One year after surgery
Anterior
Posterior
Medial
Lateral
B
two weeks after surgery
one year after surgery
Bone mineral density, g/cm³
1.2
1.0
0.8
0.6
Ant.
Cent.
Post.
Medial
Center
Lateral
C
two weeks after surgery
one year after surgery
% ratio to centrer/center BMD
120
110
100
90
80
70
Ant.
Cent.
Post.
Medial
Center
Lateral