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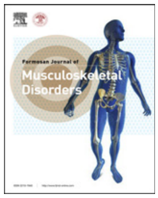

Original Article

Calculation of osteonecrotic volume using two-dimensional projections: Comparison between the current volumetric measurement methods

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A B S T R A C T

The prognosis of osteonecrosis of the femoral head is highly dependent on the grading of the lesion size. A small lesion (< 15% of involvement) is less likely to progress, a medium lesion (15%–30%) is at moderate risk, and a large lesion (> 30%) is doomed to collapse if left untreated. To calculate the necrosis volume, the most accurate method is to use three-dimensional magnetic resonance imaging (MRI) segmentation method. However, in clinical practice, the commonly used methods are to multiply the area percent of involvement or to use proxy, such as the necrotic index, by multiplying the angles of necrosis on two-dimensional (2D) images. The aim of this work was to find the relationship between the angular measurement proxy and the true necrosis volume. Results from different methods were compared with those of the MRI segmentation method in 29 hips. It was found that the area percent method tended to underestimate the volume and disagreed with 48% of the hips on the grading by the MRI segmentation method. As a contrast, the agreement could be improved to 90% of the hips by an index that was deduced from the original necrotic index. This study found that to estimate the necrosis volume by 2D projections is at the expense of inaccuracy but is still satisfying for clinical use. This study also found that the angular measurement proxy could be used to extrapolate the necrosis volume, whereas the bias of the measurement and grading could be decreased.

1. Introduction

Osteonecrosis of the hip is a debilitating disease that commonly affects young adults in their third to fifth decade of life. It is also the most common reason for total hip replacement in many regions especially in Asian countries.[1–3] The prognosis of osteonecrosis is highly related to the extent and location of the lesion involving the femoral head.[4–6] When the lesions involve more than 30% of the femoral head or in the weight-bearing zone, most of the hips will progress to collapsing if left untreated.[7–9] However, if the extent of the lesions is small, many of them will remain asymptomatic and some of them may resolve as demonstrated by magnetic resonance (MR) image analysis.[10–14] It is therefore important to estimate the extent of involvement accurately in order to identify those who need to be treated and those who need to be observed. Current staging systems integrate these concepts and stratify the extent and location of the osteonecrosis into three categories: (1) less than 15% of head involvement, (2) 15%–30% of head involvement, and (3) more than 30% of head involvement.[15,16] Ideally, these systems can make the staging more consistent and help the comparison

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between studies more reliable. However, in the study by Plakseychuk et al,[17] the reliability and reproducibility of the current staging systems were demonstrated to be poor and with high intraobserver and interobserver variations. The variations mostly come from the different results of necrosis volume calculation by different methods.

As proxies, other methods were used to assess the extent of involvement. The reliability and reproducibility of these proxies were high because the definitions were restrained and the methods of measurements were stringent.[18,19] In addition, these proxies were found highly predictable for the clinical outcomes. For example, in the studies by Ha et al[20] and Kerboul et al,[21] poor prognosis was found in cases that had a combined necrotic arc (adding the necrotic arc in two planes) greater than 200°. Similarly, an index of necrosis (calculated by multiplying the necrotic arc measured from coronal and sagittal MR images) was also found to be the prognostically significant predictor of subchondral fracture.[18,19] Although reliable and reproducible, the current staging systems do not use these proxies for the categorization because they do not equal the necrotic volume.

To investigate the relationship of necrotic volume and their proxies (here, the necrotic index) and calculate the necrotic volume according to the methods described in the literature,[16,22–25] MR images of osteonecrotic hips were collected for the measurement of necrotic volumes in this study. Because the volume estimation proxy (the necrotic index) is the product of two arcs measured in two perpendicular planes, the two arcs can be used to define a cone circumscribing the necrotic lesion. The volume of circular or elliptical cones circumscribing the necrotic lesions is calculated. Finally, the relationship between the necrotic index, cone volume ratio, and necrotic volume ratio calculated by different methods was analyzed.

2. Method

Twenty-nine osteonecrotic hips with MR imaging (MRI) were used for the calculation of necrotic volumes. The methods analyzed in this study can be classified as simplified method,[24,25] MRI-based volumetric calculation method,[22,23,26] and proxies for volumetric measurement (the necrotic index).[18,19] Because the necrotic index used the necrotic arcs in two perpendicular two-dimensional (2D) projections for the calculation, the volume of the cone formed by the necrotic arcs was calculated to analyze the relationships between them.

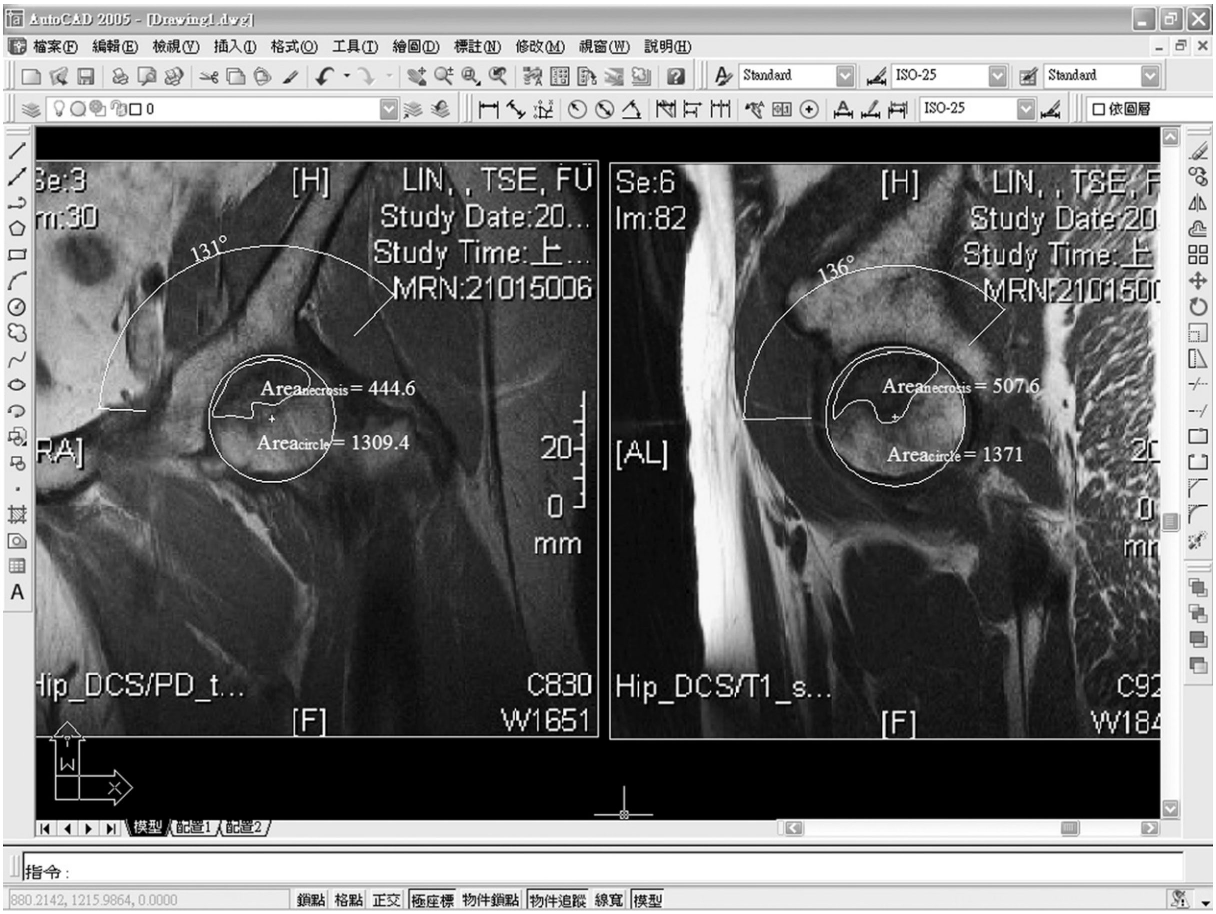

Fig. 1. The measurement of area percent of necrosis and the angular measurement of the necrotic arc on two-dimensional projections.

2.1. Necrotic volume ratio calculated by the Steinberg's method

According to the Steinberg's method,[16,24] the necrotic volume ratio is determined by multiplying the area percent of necrosis in the anteroposterior (AP) and lateral (LAT) radiographic projections (Fig. 1). The original method used digital processing of the images with computer software. In this study, the MR images were imported into the AutoCAD 2005 software (Autodesk, San Rafael, CA, USA) with magnification adjustment. The necrotic lesions, defined as the region with abnormal signals, were outlined by the tracing tool of the AutoCAD 2005 software in a Microsoft Windows XP operating system (Microsoft, Redmond, WA, USA). The femoral head was taken as a sphere defined by the largest radius measured from serial MRI slices. The necrotic volume ratio (α) was determined using the equation $\alpha = \text{Area}(\%)_{AP} \times \text{Area}(\%)_{LAT}$.

2.2. Necrotic volume ratio calculated by MRI-based segmentation method

The MRI-based volume quantitative assessment uses segmentation of the medical images of the necrotic femoral head. In the study by Hemigou and Lambotte,[22] the necrotic volume in each MRI slice was calculated by multiplying the area of necrosis by the thickness of the slice. The total volume of necrosis was the sum of the individual volume of each slice. This method was proved to be highly accurate when it was compared with the results of anatomical measurement of the femoral heads obtained after total hip replacement. The segmentation methods can also be automated with improved computerized algorithm.[23,26] In this study, T1-weighted MR images with increments of 4 mm in coronal slices were used to reconstruct three-dimensional (3D) images of hips. The MR images were imported into the AutoCAD 2005 software. The boundaries of the necrotic lesions were defined as the region with abnormal T1 signal in each MRI slice. The central slice of the hip was used to construct the sphere equivalent to the femoral head based on the area measurement and the radius of the sphere (R) (Fig. 2). In order to compute the volume affected, a simplified Simpson's rule was used to integrate in the direction of the x-axis. The total affected volume was computed using the formula: $V_{\text{total}} = \sum_{n=1}^{N} A_n d_n$, where n is the MRI slice, A_n is the affected area of the MRI slice, and d_n is the distance of nth slice from the previous one. The volumetric ratio (α) of the lesion was computed as: $\alpha = \frac{V_{\text{total}}}{(\frac{4}{3}\pi R^3)}$.

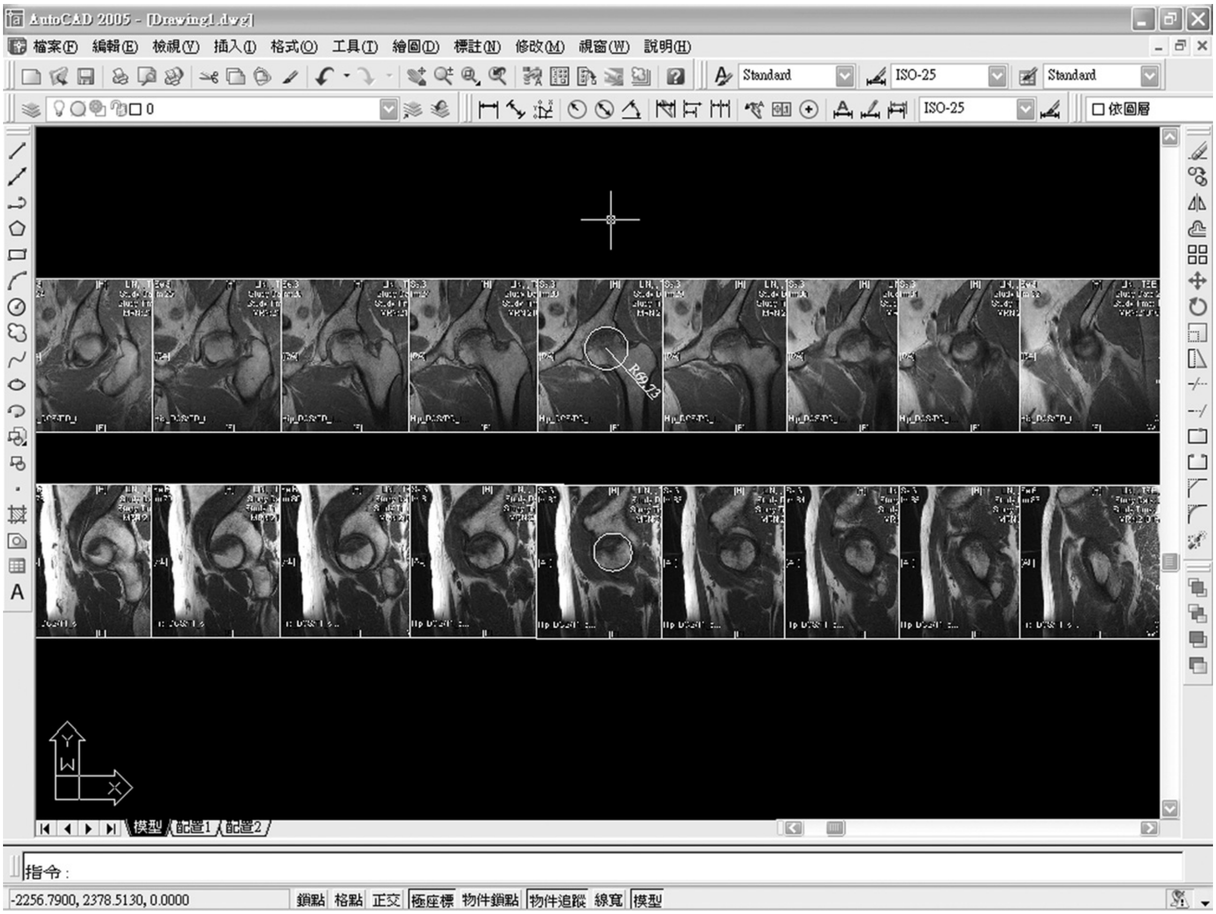

Fig. 2. Serial slices of magnetic resonance imaging segmentation images were used for the calculation of true necrotic volume.

2.2.1. Validation of MRI-based method by finite element calculation

The method of the MRI-based volume calculation was validated by a finite element analysis in four hips that computed tomography (CT) scans were also available. The Digital Imaging and Communications in Medicine format of the CT images in the transverse planes of the osteonecrotic hips were used for image threshold adjustment, processing, and stacking. 3D solid model for the hips were created by computer-aided design (CAD) and subjected to mesh into finite elements (Fig. 3). The volume ratio of necrotic lesions was calculated by dividing the element counts of the necrosis by the total elements of the femoral head. The results of MRI-based method in the four hips were found to be highly consistent with the results of the finite element analysis.

2.3. Necrotic index as the proxy for necrotic volume estimation

The necrotic index is calculated from the arc of involvement in the sagittal and coronal MR images. In the study by Koo and Kim,[19] the mid-sagittal and the mid-coronal MR images were used to calculate the arcs of involvement. In this study, similar to the method described by Cherian et al,[18] we measure the arcs of involvement in the image that demonstrates the maximal lesion size in the sagittal and coronal planes rather than in the mid-sagittal and mid-coronal images. The maximal angle of the necrotic arc in the coronal (anteroposterior) plane was defined as θ_{AP}, and the maximal angle of the necrotic arc in the sagittal (lateral) plane was defined as θ_{LAT}. The necrotic index was calculated as $(\theta_{AP}/180) \times (\theta_{LAT}/180)$ (Fig. 1).

2.4. Calculation of the volume of a cone circumscribing the necrosis

The arc of involvement in the coronal and sagittal planes are used for generating the cone circumscribing the necrotic lesion. The femoral head is considered to be a sphere, and the necrotic cone is arbitrarily defined with the tip at the center of the sphere. The cone was considered as linear expansions from the center of the femoral head with different angles. With identical arc of involvement in both coronal and sagittal planes, the necrotic lesion formed a circular (ice cream) cone. With unequal arc of involvement, an elliptical cone projecting from the center of femoral head was formed. To be consistent throughout the study, the angle of the necrotic arc in the coronal (anteroposterior) plane was defined as θ_{AP}, and the angle of the necrotic arc in the sagittal (lateral) plane was defined as θ_{LAT}. In addition, the diameter (D) of the femoral head could be measured in either the coronal or the sagittal images. By investigating the geometry of the simplified model, the volume of the cone could be formed as a mathematical integration problem with three representations when θ_{AP} was not equal to θ_{LAT} (Fig. 4).

If we assume that θ_{AP} is greater than θ_{LT}, three representations can be discussed according to the distance from the center of the femoral head.

1. In the first representation (A–A cross section in Fig. 4), $\cos(\theta_{AP}/2) \times D/2 > r \geq 0$, the contour of the profile section formed an ellipse, where r is measured in the Z direction. The two axes of the ellipse are $[r \times \tan(\theta_{AP}/2)]$ and $[r \times \tan(\theta_{LT}/2)]$, respectively. Therefore, the volume of necrosis model during this period is as follows:

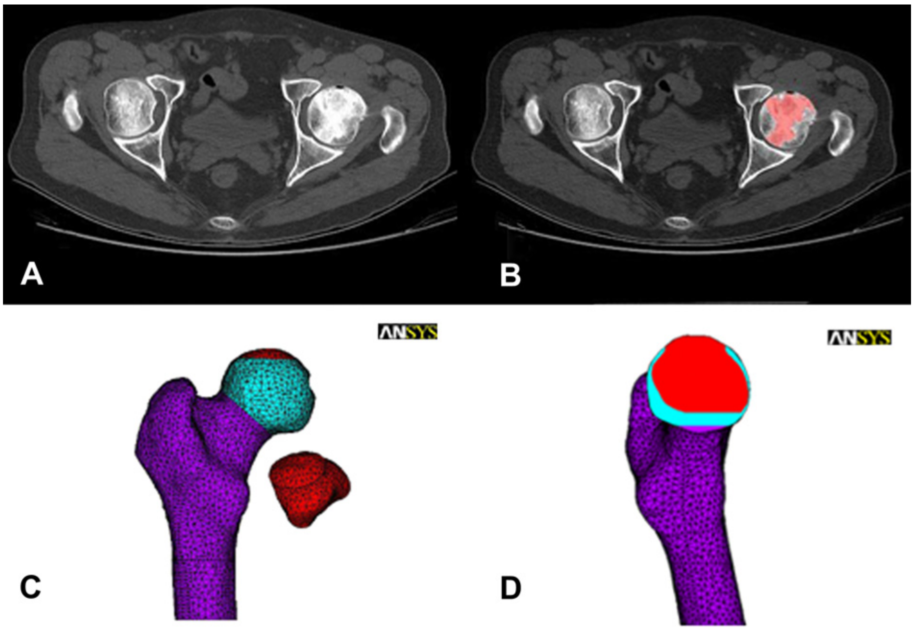

Fig. 3. Solid models of osteonecrotic hips created from computed tomography scans were used to validate the magnetic resonance imaging segmentation method in the calculation of the necrotic volume.

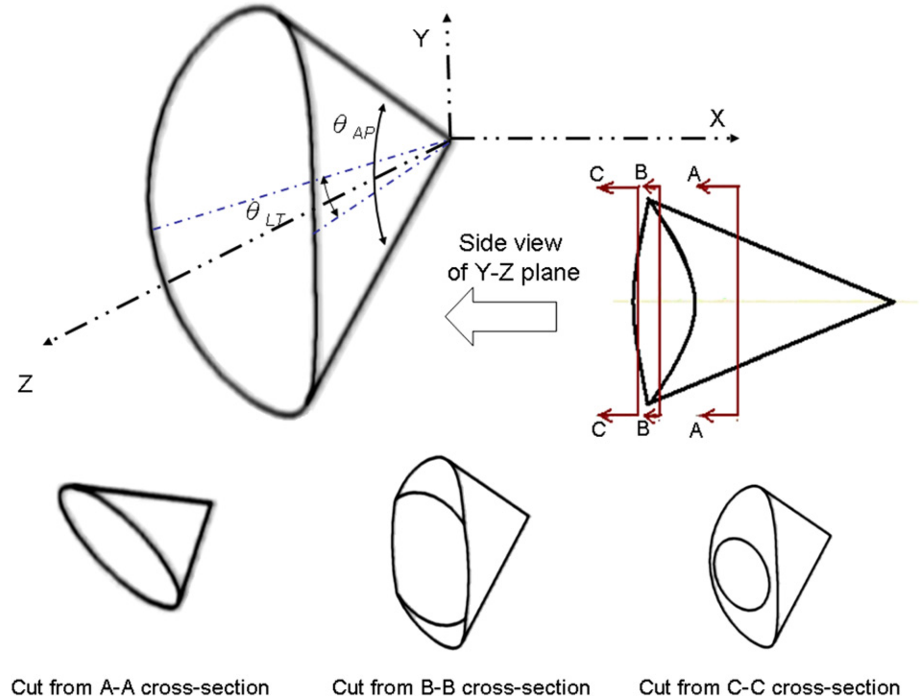

Fig. 4. The definition of a circular or an elliptical cone from different sections in the mathematical model.

$$\mathrm{Vol}_1 = \int_0^{\cos(\theta_{\mathrm{AP}}/2)\times D/2} \pi \times [r \times \tan(\theta_{\mathrm{AP}}/2)] \times [r \times \tan(\theta_{\mathrm{LAT}}/2)]\,\mathrm{d}r$$

2. In the second representation (B–B cross section in Fig. 4), $\cos(\theta_{\mathrm{LAT}}/2) \times D/2 > \mathrm{d}r \geq \cos(\theta_{\mathrm{AP}}/2) \times D/2$, the necrosis contour of the profile section will not form an ellipse; instead, the profile section forms the overlap area of an ellipse and a circle, as shown in Fig. 4. The axial radius of the circle is $[(D/2)^2 - r^2]^{1/2}$, and the two axes of the ellipse are $[r \times \tan(\theta_{\mathrm{AP}}/2)]$ and $[r \times \tan(\theta_{\mathrm{LT}}/2)]$, respectively. The ellipse and circle will intersect on four positions, and they are P_1, P_2, P_3, and P_4, respectively. If we assume that $L_r = [(D/2)^2 - r^2]^{1/2}$; $L_a = r \times \tan(\theta_{\mathrm{LT}}/2)$; and $L_b = r \times \tan(\theta_{\mathrm{AP}}/2)$, then the intersection positions can be calculated as follows:

$$Sx = \sqrt{L_a^2 L_b^2 - L_a^2 L_r^2 / L_b^2 - L_a^2}$$

$$Sy = \sqrt{Lr^2 - Sx^2}$$

To calculate the overlap area, four partitioned areas are defined. The partitioned areas are defined in terms of two dashed lines and they consist of two partial ellipse areas and two circular areas (Fig. 4). To calculate individual area, the partitioned angles of α and β are dealt with first.

$$\alpha = 2\tan^{-1}(Sx/Sy)$$

$$\beta = 2\tan^{-1}(Sy/Sx)$$

In this manner, the area within the circular partitions are represented as A_{cir},

$$A_{\mathrm{cir}} = \left(\pi L_r^2\right) \times (2\alpha/2\pi) = L_r^2 \alpha$$

In addition, the area within the ellipse partitions can be further partitioned as the combinations of triangles and the remaining areas, and they are represented as A_{ellip},

$$A_{\mathrm{ellip}} = SxSy + 2\int_{Sx}^{L_a} \sqrt{L_a^2 L_b^2 - L_b^2 s^2 / L_a^2 \mathrm{d}s}$$

Consequently, the volume of necrosis model during this period is as follows:

$$\mathrm{Vol}_2 = \int_{\cos(\theta_{\mathrm{AP}}/2)\times D/2}^{\cos(\theta_{\mathrm{LAT}}/2)\times D/2} \left(A_{\mathrm{cir}} + A_{\mathrm{ellip}}\right)\mathrm{d}r,$$

where A_{cir} and A_{ellip} are all functions of r.

3. In the third representation (C–C cross section in Fig. 4), $D/2 \geq \mathrm{d}r \geq \cos(\theta_{\mathrm{LAT}}/2) \times D/2$, the necrosis contour of the profile section forms a circle. The axial radius of the circle is $[(D/2)^2 - r^2]^{1/2}$. Therefore, the volume of necrosis model during this period is as follows:

$$\mathrm{Vol}_3 = \int_{\cos(\theta_{\mathrm{LAT}}/2)\times D/2}^{D/2} \pi \times \left[(D/2)^2 - r^2\right]\mathrm{d}r.$$

Notice that the π indicates the ratio of the circumference of a circle to its diameter, and it is always a constant parameter; $\pi = 3.14159\ \ldots$; and the $\cos(\cdot)$ and $\tan(\cdot)$ indicate the cosine and tangent mathematical functions.

Finally, the ideal total volumetric necrosis of the femoral head ($Vol_{necrosis}$) can be calculated as the summation of the three volumetric representations:

$$
\begin{aligned}
Vol_{necrosis} = & \int_0^{\cos(\theta_{AP}/2)\times D/2} \pi \times [r \times \tan(\theta_{AP}/2)]dr \\
& \times [r \times \tan(\theta_{LAT}/2)]dr + \int_{\cos(\theta_{AP}/2)\times D/2}^{\cos(\theta_{LAT}/2)\times D/2} \pi \\
& \times \left[(D/2)^2 - r^2\right)]^{1/2} \times [r \times \tan(\theta_{LAT}/2)]dr \\
& + \int_{\cos(\theta_{LAT}/2)\times D/2}^{D/2} \pi \times \left[(D/2)^2 - r^2\right]dr
\end{aligned}
$$

Reciprocally, for the case of θ_{LAT} being greater than θ_{AP}, the solution can also be obtained in the same manner. In addition, such a calculation formula can be used for the case of θ_{LAT} being equal to θ_{AP}, and the second representation will be zero. In this work, the necrotic volume is calculated in terms of numerical integrations. The application program is coded using the Microsoft visual C++, and the surface models are recorded in the file for the further 3D investigation and shown as the graphical user interface of the application program.

2.4.1. Cross-examination of cone volume calculation by Pro/Engineer

The results of cone volume calculation using the mathematical model are cross-examined by commercial software, Pro/Engineer (Parametric Technology Corporation, Needham, MA, USA). The software is commonly used for CAD, computer-aided manufacturing, and computer-aided engineering in the engineering fields. Necrotic lesion volume either forming a circular cone or an elliptical cone could be calculated by the software.

The volume of the necrotic cone can be calculated by any given θ_{AP} and θ_{LAT}. The results calculated by the mathematical model robustly agree with those calculated by the Pro/Engineer software. The mean difference in the volume ratio calculation between these two methods was 0.000048.

2.5. Grading of necrotic extent

All lesions were graded according to measurement results of volume ratio (α) from each method based on the Association Research Circulation Osseous system of classification[15] with <15% as Grade A, 15%–30% as Grade B, and >30% as Grade C. The lesions were also graded according to the necrotic index[18,19] with <0.3 as Grade A, 0.3–0.4 as Grade B, and >0.4 as Grade C.

2.6. Statistical analysis

SPSS software package (SPSS, Chicago, IL, USA) was used for analysis. The differences in the necrotic volume calculation by the Steinberg's method, the MRI-based method, and the cone volume were analyzed by the repeated-measures analysis of variance (ANOVA) with p value less than 0.05 as statistically significantly different. The agreement on the grading by different methods was determined by calculating the kappa values. Kappa values were interpreted as follows: 0–0.50 was poor agreement, 0.51–0.75 was moderate agreement, and 0.76–1.00 was excellent agreement.

3. Results

3.1. Necrotic volume calculated by different methods

The volume ratios of the necrotic lesions calculated by the MRI segmentation method ranged from 4.4% to 45.9% in the 29 hips. By using the Steinberg's method, the volume ratios in the 29 hips were between 0.4% and 52.9%. The volume ratios of the cones circumscribing osteonecrotic lesions were between 3.7% and 49.9%. Results are shown in Fig. 5. It was found that the Steinberg's method tended to underestimate the lesions, whereas the cone volume tended to overestimate the lesions. Taking the MRI-based segmentation method as the reference method, the results of the Steinberg's method was significantly lower than those calculated by the MRI segmentation method and the cone volume measurement (repeated-measures ANOVA, $p < 0.001$).

3.2. Grading of the lesions based on the calculated necrotic volume

Among the 29 hips, 11 were graded as small-sized lesions (<15% of involvement), 11 were graded as medium-sized lesions (15%–30% of involvement), and 7 were graded as large-sized lesions (>30% of involvement), by using the MRI segmentation method (Fig. 6). With the use of the Steinberg's method, 14 of the 29 hips (48%) were downgraded as compared with the use of the MRI segmentation method. The overall agreement on the grading was poor (kappa value = 0.25). All of the 11 Grade B lesions were downgraded as Grade A, and 3 of the 7 Grade C lesions were downgraded as Grade B. As a contrast, with the use of the

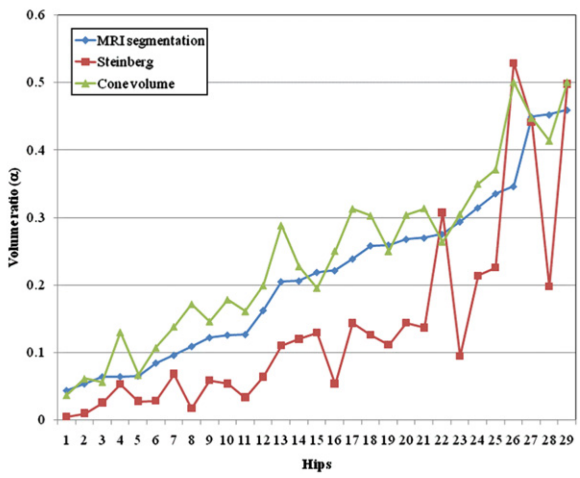

Fig. 5. Results of volume measurement using the magnetic resonance imaging segmentation method, Steinberg's method, and cone volume method in the 29 hips.

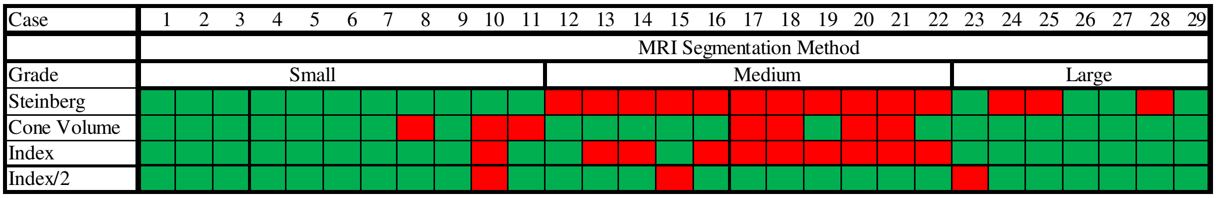

Fig. 6. Results of the grading using the Steinberg's method, cone volume ratio, necrotic index, and index/2 as compared with the grading using the magnetic resonance imaging (MRI) segmentation method. The accurately graded hips are highlighted in green, and the inaccurately graded hips are highlighted in red.

cone volume ratio as the estimation of the necrotic volume, 22 of the 29 hips (76%) were graded in the similar category as compared with the MRI segmentation method. The overall agreement on the grading was improved from poor to moderate (kappa value = 0.64).

3.3. Correlation between necrotic index and cone volume ratio

Since the cone circumscribing necrotic lesion was defined by the necrotic arcs in 2D projections, the necrotic index and cone volume were confirmed to be linearly correlated (Pearson correlation, $R^2 = 0.984$). The cone volume ratio thus could be extrapolated by the necrotic index, whereas the cone volume ratio is approximated to be half of the necrotic index. By using the index/2 to represent the cone volume ratio for the grading, the grading in 90% of the hips coincided with the MRI segmentation method. The agreement on the grading resulted in an excellent agreement (kappa value = 0.84) (Fig. 6).

4. Discussion

The prognosis of osteonecrosis of the femoral head is highly associated with the extent of necrosis involving the femoral head.[3,6,10,19,20] Unfortunately, current staging systems for determining the extent of necrosis are often associated with high intraobserver and interobserver variation and low reproducibility as described before.[17] It is because the measurement of the volume based on 2D projections is at the expense of inaccuracy by qualitative measurement rather than quantitative measurement. Instead, Kerboul et al[21] used 2D radiographs and suggested that the combined angles in anteroposterior and lateral views greater than 200° are associated with poor prognosis. The concept was recently modified by using MR images and proven to be a useful predictor of prognosis.[20] Koo and Kim[19] proposed that the necrotic index higher than 0.4 was associated with the predictive value of a positive test of 100% and of a negative test of 82% for future collapse of the femoral head. Cherian et al[18] modified the equation by measuring the maximal necrotic arcs on the sagittal and coronal planes instead of the mid-sagittal and mid-coronal planes described by Koo and Kim. These authors have found high reliability and reproducibility and low interobserver or intraobserver errors by using the necrotic index from angular measurements for identifying hips at greater risk for collapse.

In spite of the fact that necrotic index is simpler to calculate and more reproducible than the 2D volumetric measurement methods, current staging systems nevertheless use the volume of necrosis for the grading criteria.[15,16] It is because the necrotic lesions are often varied in shape and location in the femoral head. To accurately determine the volume of the lesion, more sophisticated methods integrate 3D segmentation technology and image analysis software are needed to yield accurate results.[13,22,23,25,26] However, these technologies are not always available in clinical practice, and CT or MR images are often not needed, especially when the lesions are clearly demonstrated in plain radiographs. Although practically impossible to calculate the necrotic volume based on the 2D images, Steinberg et al[24] proposed a method by multiplying the area percent of necrosis measured in two perpendicular planes, and this method was acknowledged as the best way to apprehend the true volume of the necrotic lesion. This concept has been put into practice and used unanimously.[16,24,25,27] In this study, it was shown that the Steinberg's method was inaccurate in the necrotic volume measurement and had the poorest agreement on the grading as compared with the MRI segmentation method. The Steinberg's method tends to underestimate the necrotic volume because by multiplying the area percent of necrosis from two perpendicular 2D planes, it results in a four-dimensional equation instead of a 3D equation for the volume calculation. We had modified the Steinberg's equation by substituting the area percent of necrosis in one plane with the necrosis arc ratio (θ/180) or the chord ratio (chord/diameter of the femoral head). The pitfall of underestimation could be amended partly (data not shown).

In this study, we used a cone to encase the entire necrotic lesion by considering the maximal lesion size. Overestimation of the necrotic volume is expected by using this method. However, in the management of osteonecrosis, overestimation would be more robust than underestimation because osteonecrosis of the femoral head is a relentless disease if left untreated.[1–3,10,14] Based on the volume ratio of a cone, it was noted that the minimal necrotic arc in the coronal and sagittal planes to reach 30% of femoral head involvement would be between 130° and 140° (Kerboul combined angle = 270°; necrotic index = 0.61). The maximal necrotic arc in the two planes to reach 15% of femoral head involvement would be between 110° and 80° (Kerboul combined angle = 190°; necrotic index = 0.27). According to the results of previous studies,[18,19] an index greater than 0.4 is associated with poorer prognosis. With the index around 0.4, the volume ratio is around 21%, and the minimal necrotic arcs are around 100° and 110° (Kerboul combined angle = 210°). The results of the

Kerboul combined angle >200° and the necrotic index >0.4 are not coincidentally matched because they are in fact the same condition by different measurements. These also imply that many cases in the Group B (around 20% of femoral head involvement) would be at risk for progression if left untreated. However, this study is limited because the osteonecrotic lesion is often irregular in shape and not a cone shape lesion centered on the femoral head. The location of the lesion related to the weight-bearing area was also not considered in this study. Nevertheless, this study demonstrated that the necrotic index is a useful tool for the volumetric analysis in osteonecrosis of the femoral head. The volume ratio of a cone circumscribing the osteonecrotic lesion can be estimated by calculating the necrotic index from the 2D projections. In this way, the necrotic index can be integrated into the current staging system that decreases the bias of measurement and makes the staging of osteonecrosis of the femoral head more reliable and reproducible.

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