EVALUATION OF FEMORAL HEAD NECROSIS USING A VALUMETRIC METHOD BASED ON MRI

A. Bassounas, D.I. Fotiadis, K.N. Malizos MD

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Department of Computer Science
University of Ioannina
45110 Ioannina, Greece

Evaluation of femoral head necrosis using a volumetric method based on MRI

A. Bassounas[1], D. I. Fotiadis[2], K. N. Malizos[3] MD

[1] Medical Physics Division, Medical School, University of Ioannina, Ioannina, GREECE

[2] Department of Computer Science, University of Ioannina, Ioannina, GREECE

[3] Department of Orthopaedics & Trauma, School of Health Sciences, University of Thessalia, Larissa, GREECE

Abstract-**Most studies agree that the fate of femoral head osteonecrosis is associated with the size and location of the necrotic lesion. We present a volumetric method, which is based on magnetic resonance imaging. The method evaluates the percentage of the necrotic volume in the femoral head and in each of the head segments (octants). We present also a classification system based on the geometrical features of the lesion. The system was used to classify 106 hips with osteonecrosis before treatment with vascularized fibular grafting. The hips were evaluated using the volumetric method. The follow up study indicates that the proposed method and the classification system can be reliable tools for the assessment of femoral head necrosis.**

Keywords- Osteonecrosis, Volumetric Feature Extraction, Automated Diagnosis

I. INTRODUCTION

Femoral head osteonecrosis is responsible for a large number of hip arthroplasties, especially in young patients. It is associated with certain risk factors (steroids, alcohol, injuries etc.) which reduce or block the blood supply of the bone marrow. One of the crucial factors for the fate of osteonecrosis is the size and location of the necrotic lesion of the femoral head. This fact is associated with the different loading conditions on the various segments of the articular surface of the head during the daily activities of the patient (walking, stair climbing etc.).

Several attempts have been made to assess the size and location of the lesion. Most recent studies agree that osteonecrosis assessment should be based on magnetic resonance images (MRI) which reveal the 3D distribution of the lesion and are more sensitive than other techniques (e.g. radiographs) at the early stages of the disease.

The method presented here uses MRI to assess the volume and 3D configuration of the lesion. The head is considered spherical and the necrotic portions of the entire head and of each head segment are calculated. Measurements reveal the association between the size and distribution of the lesion and the fate of femoral head osteonecrosis.

II. METHODOLOGY

A. The sphere equivalent

Our method uses MRI sections for the assessment of the lesion size. Since the size of the femoral head varies among individuals, the method estimates the percentage of the head volume affected by osteonecrosis. A major problem for the estimation of the necrotic percentage is the definition of the anatomical limits of the head. Our method uses the sphere equivalent concept [1] to resolve it. The sphere equivalent of the femoral head is the sphere with the smallest radius that encloses the head. The radius of the sphere is defined using the slice of the MRI sequence with the largest section of the head (usually the central slice). In fact, the volume of the sphere equivalent is larger that the actual head volume, therefore the calculated percentage is smaller than the actual. All the measurements thereafter refer to this descriptive and objective notion, the sphere equivalent.

To assess the distribution of the lesion within the femoral head, the sphere is divided into eight segments (octants[1]). Three planes (coronal, sagittal and transverse) which intersect at the centre of the sphere define the eight octants. For each octant, the percentage of its volume affected by osteonecrosis is estimated. The total affected percentage and the percentages of the 8 octants constitute a reliable assessment of the lesion size and 3D distribution.

B. Volumetric method

The input to the system is a sequence of coronal MRI slices. The first step requires the definition of the circle that circumscribes the femoral head on each slice (Fig. 1a). This is a task performed by the operator who has to use a pointing device (e.g. a mouse) to pick three points along the arc corresponding to the articular surface. The operator can use the mouse to adjust the size and position of the drawn circle. In most cases, circle definition is the only user action required.

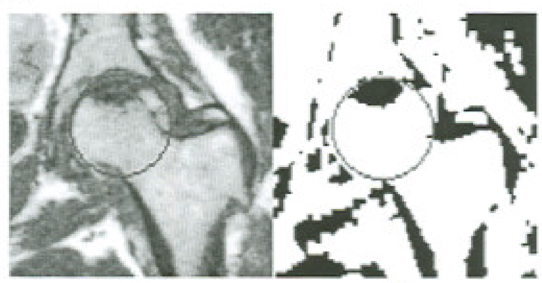

Fig. 1. a. The drawn circle on the femoral head, b. The binary image

[1] The abbreviations used for the octants are: ASL - Anterior Superior Lateral, ASM - Anterior Superior Medial, AIL - Anterior Inferior Lateral, AIM - Anterior Inferior Medial, PSL - Posterior Superior Lateral, PSM - Posterior Superior Medial, PIL - Posterior Inferior Lateral and PIM - Posterior Inferior Medial.

The next step is the detection of the lesion area. In most cases the lesion is a low-intensity (dark) area usually located at the superior medial part of the femoral head. In some cases the lesion is an area of normal intensity surrounded by a low-intensity band or line. This band or line is the boundary of the necrotic lesion. The method automatically chooses a point at the superior lateral area of the head. The distance q from the point to the centre of the circle is $q=3r/4$, where r is the circle radius (measured in pixels). The line that joins the point and the circle centre forms a 30^0 angle with the vertical diameter of the sphere (clockwise for the right hip and counterclockwise for the left hip). It has been found that in the majority of cases the selected point belongs to the necrotic area.

Having picked the point, the pixels belonging to the neighbourhood of the chosen pixel are located and the mean intensity of those pixels is computed. The neighbourhood is a square with side of length r/4. This size has been experimentally chosen so that the mean intensity of the neighbourhood pixels is a good approximation to the mean intensity M of the necrotic lesion. Next, the original grayscale image is thresholded using threshold value T = M + 20 (20 chosen experimentally) and the necrotic area is separated from the rest of the head. Thresholding produces a binary image, where the necrotic area is black ("0"). The morphological operator "OPEN" (erosion followed by dilation) is applied to the binary image in order to close small "islands" (single white pixels or small groups of connected white pixels) at the borders of the necrotic area. The operator can compare the output of this process (Fig. 1b) to the original image and decide if manual tracing or adjustment is needed. That is required in case of diffuse lesions that span the entire femoral head.

Having detected the necrotic area, the number of necrotic pixels in each of the four quadrants (SL – Superior Lateral, SM - Superior Medial, IL – Inferior Lateral and IM - Inferior Medial) is measured. These measurements will be used for the calculation of the octant percentages. This procedure is sequentially applied to all the MRI slices.

The next stage of the method uses the measurements of all slices to calculate the volume of the affected bone within each octant. The affected percentage within each octant is computed with integration along the coronal direction, using a trapezoidal rule. The central slice determines the anterior and the posterior slices and the anterior and the posterior octants respectively. To compute the affected volume of an anterior (posterior) octant, we use the affected area of the corresponding quadrant on all the anterior (posterior) slices, including the central slice [1].

The accuracy of the method has been evaluated using 9 femoral heads removed from patients during hip hemi-arthroplasty. The specimens were trimmed and rounded-up with wax, to take the shape of a sphere. In order to simulate the affected segment, part of the core of the femoral head was curetted out and was then filled with a measured volume of surgical wax. MRI images of the specimens were processed using the presented method. The measurements of the method were on average 5% larger than the actual measurements. However, the percentages are not affected since this error affects both the lesion volume and the sphere volume by the same proportion.

III.RESULTS

A. The classification system

The understanding and description of the evolution of femoral head necrosis requires the use of a classification system. Most systems are either based on radiographs and ignore MRI or are very complex and awkward. For this reason, we created a new classification system based on MRI, which incorporates the geometrical features of the lesion. The system consists of five classes:

Class 0

Hips of class 0 present no pain or other clinical symptoms. The MRI, bone scan and radiographs are normal, but osteonecrosis has been already detected on the opposite hip and the patient presents one or more risk factors (steroids, alcoholism, anaemia, SLE etc). The presence of the risk factors indicates that there is a high probability for osteonecrosis to appear on that hip. Observation of the hip is required.

Class I

The patient has no pain or other clinical symptoms (silent hip). MRI and/or bone scan is positive, although the radiographs are still negative. MRI is much more sensitive than radiographic methods for the diagnosis in the early stages of the osteonecrosis because it detects changes of the bone marrow that happen at this stage. The inorganic component of the bone (bone matrix) is still intact.

Class II

In hips of stage II clinical symptoms (pain, limitation of movement) are present. All imaging techniques are positive, but the femoral head retains its shape (there is no collapse of the articular surface). Class II is divided into two sub-classes:

Class IIa: The lesion is contained within the acetabulum weight bearing area. A pillar of intact bone shields the necrotic area from the weight forces. Those hips have good prognosis and better outcome when treated surgically.

Class IIb: The affected area is not contained within the weight bearing area. The weak necrotic bone is bearing the full load of the body weight, and microfractures appear that subsequently lead to collapse of the articular surface.

Class III

Severe clinical symptoms are usually present in hips of class III. The articular surface has collapsed (head flattening). Class III is divided into two subclasses:

Class IIIa: The lesion is contained within the weight bearing area. The remaining pillar protects the necrotic area, so the necrosis progresses slowly.

Class IIIb: The lesion extends beyond the lip of the acetabulum. As a result, the necrosis progresses rapidly and destroys the joint. Surgical methods for the preservation of the femoral head can be applied in cases of small, contained lesion (class IIIa), although the prognosis for them is worse than that of Class II hips.

Class IV

Advanced joint degeneration, with severe pain and restriction of movements.

B. Preoperative results

The method was used for the evaluation of 106 hips of stages II and III. Those hips were treated with free vascularized fibular grafting and are followed-up since then. Pre-operative MRI was used. They were T1 coronal sequences, with distance between slices from 3.3mm to 5mm. The MRI films were digitized by a Vidar VXR 12 Film Digitizer (Vidar Systems Corporation, Virginia, USA).

The mean lesion percentage was 30.7% (2.3% - 68.5%) of the head volume. The mean percentage for class IIa was 17% (2.3-34.2%), for class IIb 33.2% (15.6%-68.5%), for class IIIa 29% (12.9%-50.3%) and for class IIIb 34.5% (10.2-55.5%). The mean percentage per octant for the entire population is displayed on Fig. 2.

C. Follow-up results

The mean follow-up period is 5.5 years (3-10). Within 3 years from the operation 11 of the 106 hips (10.4%) failed and had to undergo total hip replacement. One of the failed hips was of class IIIa (1 of 8, that is 12.5% of class IIIa hips failed) and the other 10 were of class IIIb (10 of 56, 17.9% of class IIIb hips). No hip of class IIa or IIb failed. The mean affected volume of the 11 hips that had to undergo total hip replacement is 38.9% (25.6%-55.4%), which is quite higher than the mean volume of the total population (30.7%). Also the volume of each of the 8 octants of the 11 hips is higher than the volume of the corresponding octant of the total population. PSM, PSL and ASL are the octants with the highest differences from the total population (Fig. 3).

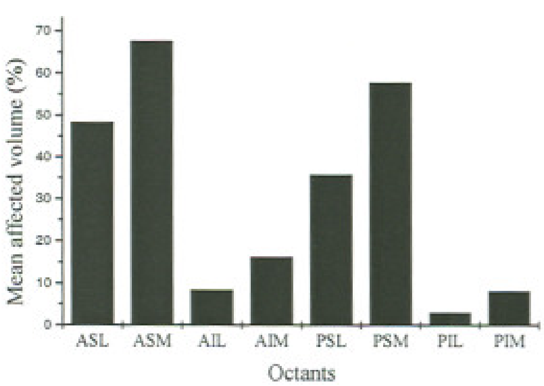

Fig. 2. The mean affected volume per quadrant for the entire population

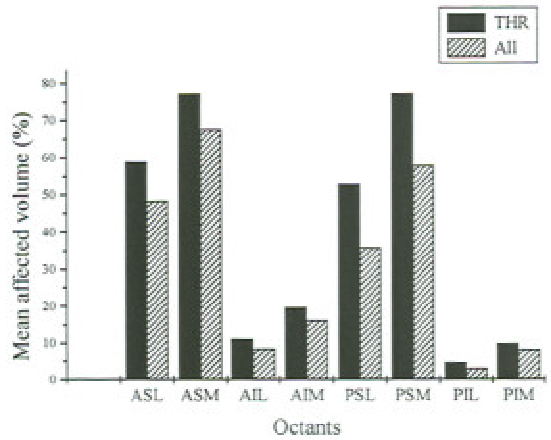

Fig. 3. The mean affected volume per quadrant for THR hips and for the entire population

IV. Discussion

Recent studies [2,3,4,5,6] indicate that size, location and distribution of the necrotic lesion affect the fate of femoral head necrosis. Attempts to estimate the volume of the lesion based on radiographs [2,3] had poor results. Researchers agree the MRI is the most suitable technique for volume estimation but none of the proposed method performs 3D reconstruction of the lesion. Most methods perform 2D measurements on some MRI slices [7,8,9]. Even methods that attempt to estimate (in 3D) the volume of the head and the lesion [10] require the user to manually outline the borders of the head and lesion. The main problem is the subjective definition of the head boundaries. Our method uses the sphere equivalent to resolve this problem.

Classification of osteonecrosis is very important for diagnosis, treatment, prognosis, evaluation of the treatment outcome and comparison of different treatments. Early classification systems were based only on radiographs [11,12,13]. Recent systems use MRI but most of them are too complicated [14]. The major advantage of the classification system we introduced is its prognostic value. Follow up studies show that hips of class IIIb have the higher possibility for rapid joint deterioration. The possibility is lower for hips of class IIIa and least for hips of classes IIa and IIb. The proposed system is also quite simple (with a limited number of stages and substages). It is easy to apply in the clinical practice since it does not require excessive time and effort.

The necrotic lesion is generally located towards the superior, medial and anterior areas of the femoral head. The most affected octants are ASM and PSM, in all classes. The next most affected octants are ASL and PSL. ASL and PSL are also the octants that present the greatest variability of all. They are slightly affected in cases of narrow lesions that are contained within the weight bearing area of the acetabulum (classes IIa and IIIa). In such cases these is an intact pillar of healthy bone that protects the head from collapse under the body weight. These hips have a better prognosis than hips where the lesion is not contained within the limits of the acetabulum (IIb and IIIb). Of cource ASL and PSL octants are much more affected in IIb and IIIb hips compared to IIa and IIIa hips.

The follow-up study validates the proposed lesion quantification method. Hips that failed and collapsed after fibular grafting had a mean affected volume higher than the total population. Also the volume of each of the 8 octants of the 11 hips is higher than the volume of the corresponding octant of the total population.

V. Conclusion

We described a quantitative method to assess the size and location of the necrotic lesion in femoral head necrosis. The method requires limited user interaction and the measurements are objective. The follow-up study indicates that the fate of the disease is associated with the size and distribution of the lesion.

The method, in combination with the proposed classification system, can be a useful tool for the orthopaedist for the diagnosis, treatment, prognosis and outcome evaluation of femoral head necrosis. Future work should focus on improving the lesion detection and on automatic detection of the head circle, reducing the effort required from the human operator.

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