A Sclerotic Rim Provides Mechanical Support for the Femoral Head in Osteonecrosis

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abstract

Osteonecrotic collapse of the femoral head is a common refractory disease in orthopedics, and the occurrence of collapse is an important factor in the prognosis of this condition. Osteonecrotic collapse of the femoral head can be delayed or prevented by the formation of a sclerotic rim. This study used finite element analysis to evaluate the mechanical role of a proximal sclerotic rim on stress on the femoral head. The study used a healthy man who underwent computed tomography of both hips to generate 3-dimensional finite element models with different proportions of proximal rim sclerosis (0%, 30%, 50%, and 100%). Using a negative directional mechanical load of 400 N along the Z-axis, total deformation, deformation in the negative Z-axial direction (ie, direction of longitudinal compression), maximum principal stress, minimum principal stress, and contact pressure on necrotic tissue were evaluated. For 0%, 30%, 50%, and 100% rim sclerosis, total femoral head deformation was 0.21, 0.205, 0.20, and 0.19 mm, respectively, and maximum principal stress in compression was 9.83, 9.67, 9.16, and 9.05 MPa, respectively. Increases in proximal rim sclerosis decreased all of the measured outcomes. These results suggest that proximal rim sclerosis provides effective mechanical support for the femoral head, offers mechanical protection for necrotic tissue, decreases deformation of the femoral head, and delays or prevents collapse in osteonecrosis. [Orthopedics. 2015; 38(5):e374-e379.]

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Osteonecrosis of the femoral head is a disease characterized by death of osteocytes and bone marrow components as a result of disruption of the blood supply to the femoral head. This disruption causes subsequent changes in the femoral structure and collapse of the femoral head, finally leading to joint pain and dysfunction. Artificial joint arthroplasty is the final solution in the event of femoral head collapse. However, because this disease is common in young people and the life expectancy of artificial joints is limited, the artificial joints of many young patients must be rebuilt repeatedly, reducing quality of life and increasing costs. Therefore, in the early stages of the disease, it is crucial to select the proper treatment to prevent collapse.

Currently, many methods are used to predict collapse of the femoral head, but most focus on the necrotic region. Recent studies found that the ability of necrotic tissue to repair itself also plays an important role in the prognosis of osteonecrosis of the femoral head and showed that the formation of a sclerotic rim is a form of repair. A sclerotic rim is irregular mottling or a striped high-density shadow on the border between necrotic tissue and normal tissue that is often seen on radiographic films and computed tomography (CT) scans of patients with osteonecrosis of the femoral head. In clinical practice, patients with osteonecrosis of the femoral head and a sclerotic rim did not always experience collapse and had better prognoses than those without a sclerotic rim. Some researchers also used the sclerotic rim to predict collapse in osteonecrosis of the femoral head during the early stages and found that collapse could be delayed when there was a complete sclerotic rim in the subchondral bone. However, most findings are based on theoretical speculation and clinical observation. Few studies have focused on mechanical analysis of the osteonecrotic femoral head after formation of a sclerotic rim.

Finite element analysis is a technique that uses mathematical approximation to simulate actual physical systems (geometry and loading). Finite element analysis originated from studies of elastic and structural analysis in engineering. Recently, finite element analysis has been used in medical science, particularly biomechanical studies, to evaluate proximal femoral head rigidity and damage and to analyze the stress distribution in different ranges of osteonecrosis of the femoral head. Does the sclerotic rim protect necrotic tissue? Does it improve the overall integrity of the femoral head? This study used finite element analysis to establish 3-dimensional finite element models with different proportions of rim sclerosis within the proximal necrotic tissue of the femoral head and to simulate mechanical loading to determine the effects of mechanical stress on the femoral head and necrotic tissue. This study also attempted to determine whether the formation of a proximal sclerotic rim conferred mechanical support within the femoral head to delay or prevent femoral head collapse and helped to determine the prognosis for osteonecrosis of the femoral head.

MATERIALS AND METHODS
Establishment of Finite Element Models for Rim Sclerosis in Osteonecrosis of the Femoral Head

Because the goal of this study was to observe the variation in stress on the femoral head with a sclerotic rim and the subject’s data would not affect the variation trend and observation results, a healthy adult male volunteer was selected from the Department of Orthopedics at the Guang’ anmen Hospital of the China Academy of Chinese Medical Sciences. The subject was 27 years old, with height of 166 cm and body weight of 59 kg. Femoral collodiaphyseal angle was 130°, femoral anteversion angle was 13°, and femoral diameter was 44 mm. Femoral head disease, damage, and congenital malformations were excluded.

This study was conducted in accordance with the Declaration of Helsinki. Approval was obtained from the Ethics Committee of Guang’ anmen Hospital of the China Academy of Chinese Medical Sciences (No. 11, 2010). Informed consent was obtained from the participant.

Dual-source, 64-slice spiral CT (Siemens Ltd, Berlin, Germany) was used to scan the volunteer’s bilateral hip joints in cross-section, using the following scanning parameters: scanning voltage of 12 kV, scanning current of 60 mA, bone tissue window scanning, and slice thickness of 0.75 mm. All of the obtained images were stored in Digital Imaging and Communications in Medicine format.

Thin-layer chromatography images of the bilateral hip joints were imported into Mimics software (Materialise, Leuven, Belgium). The femoral head was automatically identified by defining the bone tissue segmentation grade value threshold with a threshold segmentation tool. The identified images were edited manually, and information for the 3-dimensional surface model of the normal left femoral head was obtained with padding. A meshing model function was automatically generated by Magics (a functional module of Mimics software) to smooth the surface of the geometric model, process the number of grids, and create and optimize the triangular surface elements, making most elements equilateral and triangular and reducing the number of triangular surfaces. The generated femoral head model was exported in STL format. The 3-dimensional surface model of the femoral head generated by Mimics was imported into Solidworks software (Dassault Systemes S.A., Concord, Massachusetts). The model was detected automatically by the model diagnostic function in Solidworks, and the curved surfaces were closed. After the model was closed completely, the generated model was exported in X_T format. The femoral head model was imported into COMSOL multiphysics modeling and...
by assembling the preestablished finite element models of the femoral head with the necrotic areas, necrotic tissue, and sclerotic rim and exporting them in X_T format.

**Calculation of the Elastic Modulus**

All of the materials were assumed to be isotropic, uniform, and continuously distributed. Based on the gray value of bone and using the empirical formula derived from previous experimental studies\(^{14-16}\) (Density=-13.4+1017×Gray value, E-Modulus=-388.8+5925×Density), 5 slices of the CT images were selected and 10 sets were selected from each slice. The mean value of 50 sets was considered the density value. The elastic moduli of the femoral head, necrotic tissue, and sclerotic rim were 3.3, 2.3, and 5.5 GPa, respectively.

**Mechanical Analysis**

The assembly model was fed into ANSYS Workbench software (ANSYS, Pittsburgh, Pennsylvania), and the model was meshed with the program’s automatic meshing function. The surface of the automatically generated contact surfaces for each model was checked to determine the correct contact among the surfaces. The material parameters were set as follows: an elastic modulus of 3.3 GPa and Poisson’s ratio of 0.3 for the femoral head; an elastic modulus of 2.2 GPa and Poisson’s ratio of 0.3 for necrotic tissue; and an elastic modulus of 5.5 GPa and Poisson’s ratio of 0.3 for the sclerotic rim.

Mechanical loading was simulated. The bottom of the model was fixed to simulate the weight-bearing status of a unilateral hip joint in a normal human standing position. A load of approximately 400 N, equivalent to half of a normal human’s weight,\(^{17}\) was exerted at the highest point of the left femoral head in the negative Z-axial direction. A linear static structural analysis module was applied to compare and analyze the changes in total deformation, deformation of the negative Z-axis, maximum principal stress, minimum principal stress, and contact pressure of necrotic tissue for different amounts of proximal rim sclerosis (0%, 30%, 50%, and 100%).

**RESULTS**

**Left Femoral Stress**

The results for left femoral stress with different proportions of proximal sclerotic rim under the simulated mechanical load are summarized in the Table. With the increasing proportion of proximal rim sclerosis, total deformation of the necrotic femoral head (Figure 2), deformation of the negative Z-axis (ie, direction of longitudinal compression), maximum principal stress, minimum principal

| Simulated Mechanical Loading With Different Proportions of Proximal Rim Sclerosis |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Maximum Principal Stress, MPa | Minimum Principal Stress, MPa | Total Deformation, mm | Deformation of Negative Z-axis, mm | Contact Pressure for Necrotic Tissue, MPa |
| -400 N | Tensile Stress | Compressive Stress | Tensile Stress | Compressive Stress | Tensile Stress | Compressive Stress | Tensile Stress | Compressive Stress | Tensile Stress | Compressive Stress | Tensile Stress | Compressive Stress | Tensile Stress | Compressive Stress | Tensile Stress | Compressive Stress |
| Proximal rim sclerosis 0% | 4.61 | 9.83 | 0.81 | 6.71 | 0.21 | -0.134 | 0.41 |
| Proximal rim sclerosis 30% | 4.60 | 9.67 | 0.50 | 6.66 | 0.205 | -0.132 | 0.35 |
| Proximal rim sclerosis 50% | 4.59 | 9.16 | 0.46 | 5.76 | 0.20 | -0.130 | 0.34 |
| Proximal rim sclerosis 100% | 4.43 | 9.05 | 0.41 | 5.62 | 0.19 | -0.126 | 0.31 |
stress, and contact pressure for necrotic tissue decreased.

**Analysis of Mechanical Nephrograms for Necrotic Tissue**

Top (Figure 3A) and section (Figure 3B) views showed that maximum pressure developed at the interface of necrotic and normal tissue of the femoral head, followed by proximal necrotic tissue, indicating that the pressure aggregated above the 2 areas and the stress peaked at those 2 positions.

**DISCUSSION**

To explore the biomechanical role of the sclerotic rim, the authors used finite element analysis to simulate the formation of proximal rim sclerosis in osteonecrosis of the femoral head and then conducted mechanical analysis of the femoral head and necrotic tissue. The authors established 3-dimensional finite element models of osteonecrosis of the femoral head with different proportions of proximal rim sclerosis (0%, 30%, 50%, and 100%). Then they simulated the weight-bearing status of a unilateral hip joint in a normal human standing position to observe the mechanical changes in the femoral head and necrotic tissue. As the degree of proximal rim sclerosis increased, total deformation, deformation of the negative Z-axis, maximum principal pressure, minimum principal pressure, and contact pressure of necrotic tissue decreased.

This microfracture decreases mechanical strength and causes instability within the femoral head. In addition, this microfracture of bone trabecula disturbs the stable, curved mechanical support within the femoral head. The spongy bone loses effective protection and experiences increased pressure. Finally, collapse occurs, accompanying disruption of the subchondral bone. The results of this study showed that the maximum stress peak value of necrotic tissue was located at its interface with normal tissue, followed by the proximal end of necrotic tissue. This finding indicates that these 2 regions are the most susceptible to collapse. Zhan found that, with 30% necrotic area during osteonecrosis of the femoral head, the greatest aggregated pressure occurred at the junction of normal and dead bone, and when the necrotic area increased to 50%, pressure was more likely to aggregate. Shi et al. found through finite element analysis that the collapse area of the femoral head was located at the deep junction of necrotic and normal tissue, and this finding was in accordance with what actually occurs. Korean researchers Yang et al. used 3-dimensional finite element analysis and found that when the angle was greater than 110°, the stress value in subchondral bone or in the junction of deep necrotic and normal tissue increased markedly, so these 2 areas would be at greatest risk for fracture. The current findings were consistent with previous studies.

Clinical observations showed that patients with osteonecrosis of the femoral head and a large and relatively complete sclerotic rim always have better prognoses.
and collapse does not easily occur. The resulting sclerotic rim becomes a particularly hardened edge within the femoral head, providing mechanical support to the subchondral bone at the interface of necrotic and normal tissue. The formation of a sclerotic rim can prevent premature collapse and helps to preserve the femoral head. Ficat suggested that the formation of rim sclerosis during repair of osteonecrosis of the femoral head may delay collapse of the femoral head. Liu et al analyzed the risk factors for femoral head collapse and necrosis, based on an analysis of different magnetic resonance imaging and CT phases, and found that femoral head collapse could be delayed when there was a uniformly thick sclerotic rim in the subchondral bone. The results of the current study showed that, with an increase in the amount of proximal rim sclerosis in necrotic tissue, total deformation of the femoral head, deformation of the negative Z-axis (ie, direction of longitudinal compression), and tensile and compression stresses for the maximum and minimum principal stresses all decreased. Therefore, with an increase in the proportion of proximal rim sclerosis, the antideformation ability of the necrotic femoral head as a whole and the equivalent stiffness of the femoral head increased, and reduced deformation resulted in reduced strain. Stress is a function of elastic modulus and strain, and the elastic modulus of the femoral head did not change. Thus, increasing proximal rim sclerosis decreased the probability and degree of osteonecrosis of the femoral head collapse. At the same time, the force on the contact surfaces of necrotic tissue decreased as proximal rim sclerosis increased (ie, stress decreased at the area most likely to collapse in osteonecrosis of the femoral head, indicating that the resulting sclerotic rim could effectively tolerate the stress load and protect the surface of necrotic tissue and that the sclerotic rim could help to prevent collapse of the femoral head). Furthermore, the formation of a sclerotic rim increased the structural resistance and antideformity of the femoral head, thereby delaying or preventing collapse of an osteonecrotic femoral head.

**Limitations**

This study had some limitations. The major goal of this study was to observe stress changes in the necrotic femoral head and in tissues with increasing rim sclerosis. It did not simulate the breaking stress that the necrotic femoral head can endure after formation of different proportions of proximal sclerotic rim. In addition, because this study simulated and constructed models of necrotic tissue and the sclerotic rim based on a model of a normal femoral rim, only a single healthy subject was enrolled. During mechanical loading, only the weight-bearing status of a unilateral hip joint in a normal human standing position was simulated. No other positions, such as climbing stairs or rising from a chair, were used. Stress analysis of the femoral head in these conditions may be an important direction for future studies, which can be conducted based on the models constructed in this study.

**Conclusion**

This study showed that formation of a sclerotic rim proximal to necrotic tissue provides effective mechanical support for the femoral head. This rim can protect necrotic tissue and enhance the structural tolerance and antideformation ability of the femoral head, thereby delaying or preventing the collapse of the osteonecrotic femoral head. These findings provide the groundwork for future studies that may help to determine the clinical prognosis of collapse of an osteonecrotic femoral head.

**References**


