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Effects of shape and direction of osteocyte lacunae on stress distribution of osteon

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Abstract. Scanning electron microscope (SEM) observations show that lacunae are non-uniform distribution and mainly located in the interface of thick lamellae and thin lamellae. These lacunae are elliptical and are along the circumferential direction of the osteon, which can be called as circumferential elliptical lacunae (CE). The observations also show that there are many circumferential microcracks in the osteons and these microcracks are initiated from two endpoints of the major axis of the CE. Nanoindentation technique is used to test the elastic modulus of the different circumferential lamella of the osteons. The test results shown that the average elastic modulus of the osteon wavily changes along its radial direction and that the average elastic modulus of the thick lamella is larger than that of the thin lamella. To learn the influence of the shape and direction of osteocyte lacunae on the stress distribution and understand the advantage of CE, three different osteon models, respectively with CE, radially elliptical lacunae (RE) and circular lacunae (CL), are created. The results show that the stress concentration factor of osteon with RE is maximal, that of CE is middle and CL is minimal. The crack-propagated route is along the circumferential direction of the osteon in CE model, which makes that the osteon possesses high fracture toughness.

1. Introduction
Bone possesses excellent mechanical properties, which is closely related to its complexly hierarchical structure. At the nanoscale, bone is mainly composed of organic phase, inorganic phase and water. The organic phase, whose main element is type I collagen, is soft but highly deformable, whereas the inorganic phase, which is composed of nano-sized crystal of the hydroxyapatite-like mineral (HA), is stiff and strong but brittle [1]. These components combine to form nature-optimized and mineralized collagen fibrils, which are stiff, strong and tough. At the microscale, the mineralized collagen fibrils are oriented in a preferential direction to form a single lamella of 3-7μm in thickness. Further, the lamellas surround the haversian canals of bone to compose osteons [2]. The osteon is a long and narrow cylinder of approximately 1cm in length and 200-300μm in diameter, running roughly parallel to the longitudinal axis of the bone [3]. There are some cavities inevitably in bone to enclose blood...
vessels and cells such as osteocyte lacunae. It is also indicated that these lacunae will cause stress concentration and microdamage initiation. Reilly et al. [4] provided empirical evidence that microcracks frequently arose from osteocyte lacunae under fatigue loading. Nicolletta et al. [5] measured perilacunar bone matrix strain in bovine cortical bone, and found that the average strain around osteocyte lacunae was 1.5-4.5 times greater than the strain applied on bone. Voide et al. [6] investigate the initiation and propagation of microcracks and described functional relations between the initiation and propagation of microcracks and the canal network as well as the osteocyte lacunar system. Liu et al. [7] investigate the effects of arrangement direction and shape of osteocyte lacunae on resisting impact.

Previous studies of the osteocyte lacunae are mainly focused on experimental observation [8] and effects of lacunae on stress concentration using finite element analysis [9]. However, there has been few works to research the effects of direction and shape of the lacunae on the stress distribution. In this study, SEM was used to observe the microstructure of bovine cortical bone and a nanoindenter was employed to test its elastic modulus. The observation results shown that the elliptical osteocyte lacunae are non-uniformly distributed around osteon, the direction of their major axis is along the circumferential direction of the osteon. The average elastic modulus of thick lamella of the osteons is larger than that of thin lamella. Then the stress distribution of the three different osteon models are compared and analyzed.

2. Materials and methods

2.1 SEM observation

The microstructure of bone was observed using SEM for learning its structural characteristics. The adopted bone is fresh bovine femora (age: 18-24 months). The SEM samples were prepared by segmenting it along the bone longitudinal directions by CNC grinding machine. Then a coat of gold-palladium about 10 nm was made on the surfaces of the samples using a sputter coater, the samples were observed using a TESCAN VEGA II LMU SEM under the voltage of about 15 kV and with magnification ranging from 20 to 15000×.

2.2 Nanoindentation tests

The nanoindenter is used to test the elastic modulus of the bone at its different locations for calculating the stress distribution of the bone. The specimens of the nanoindentation tests were first cut from the bone along the horizontal directions. The size of the specimen is 15mm×15mm×10mm (length × width × thickness). After cutting, the surfaces were ground using silicon carbide abrasive papers (P1000, P2000, P3000) and then polished using 1mm and 0.25mm polishing clothes to make sure the surfaces of the samples are slick and without any scratches. After the specimens are prepared, A CETR-APEX nanoindenter was used to test the elastic modulus of the osteons along the radial direction at the different locations. The indentations of the specimens were made as follows: ① loading the specimens at a rate of 10nm/s, until the applied force reached 500μN; ② holding period is 5s; ③ unloading at a rate of 100μN/s. The Elastic modulus (Eb) of the bone was calculated using the Oliver and Pharr method [10].

\[
\frac{1}{E_r} = \frac{1-\nu_b}{E_b} + \frac{1-\nu_i^2}{E_i} \tag{1}
\]

For a diamond indenter probe,\( E_i=1140\)Gpa and \( \nu_i=0.07; E_r \) is the effective indentation modulus, Poisson ratio of bone \( \nu_b=0.17[11] \).

2.3 Numerical model

To learn the influence of the shape and direction of osteocyte lacunae on the stress distribution of osteons and understand the advantage of the circumferential elliptical lacunae, three models of osteons are created, which are CE model, RE model and CL model, respectively. All models are half circular.
ring with 13 thin lamellae and 12 thick lamellae, whose thicknesses are 1μm and 3μm [12, 13], respectively. The diameter of the haversian canal is 40μm [12], the diameter of osteon models is 138 μm. The spatial distribution of the lacunae is 460 lacunae per mm² [14] and that the average lacunae area is about 30~40μm². The major and minor axes of elliptical lacunae are 10μm and 5μm, respectively [15]. The number of the lacunae is 10. The porosity rate of the circular lacunae is same as the elliptical lacunae and its diameter is 6.3μm.

Because the osteons mainly endure internal pressure from the haversian canal and external pressure from interstitial matrix, the symmetrical equivalent radial compressive load are applied on their inner and external surfaces. The geometry and loading-boundary conditions of the three models are shown in Fig.1. The stress distributions in three osteon models are obtained through 4-node bilinear element (CPS4).

![Fig. 1 Three different numerical models. (a) CE model, (b) RE model, (c) CL models](image)

### 3. Results and discussion

#### 3.1 Structural characteristic

Fig.2 shows an osteon of the cortical bone. The Haversion canal is surrounded by circumferential lamellas of mineralized collagen. The osteocyte lacunae are roughly elliptical shape and whose major axis is parallel to the circumferential lamellas (Fig.2a), and the lacunae are mainly located at between the circumferential lamellas (Fig.2b). The observations also show that the microcracks in the osteon are always along the circumferential direction of the osteon (Fig.2b).

![Fig. 2 Microstructure of osteon. (a) Non-uniform distribution of lacunae, (b) location and minor axis direction of lacunae.](image)

#### 3.2 Elastic modulus

The direction and results of nanoindentation-tested are shown in Fig.3. The tested direction of the nanoindentation is along the radial direction of the osteon (Fig. 3a). The test results show that the average elastic modulus of the osteon wavily changes along its radial direction. Fig.3 (b) shows the values of the average elastic modulus of the thick and thin lamellae. The elastic modulus of the thick lamella is 20GPa and that of thin lamella is 15.7GPa, respectively. The average elastic modulus of the
thick lamella is larger than that of the thin lamella, which is consistent to those of other bone materials tested/obtained by other researchers [16, 17].

![Nanoindentation test results](image)

Fig. 3 Nanoindentation test results. (a) Test direction, (b) elastic modulus of thick lamella and thin lamella.

### 3.3 Stress distribution

Fig. 4(a) shows the stress distribution of the osteon in CE model. It can be seen from Fig. 4(a) that there is obvious stress concentration at two ends of CE (the two ends of the major axis of CE). The value of the maximum miss stress is 25.42MPa while the corresponding stress concentration factor is 3.18. Fig.4 (b) indicates that the stress distribution of RE osteon model, the stress concentration is also obvious at the two ends of the major axis of the lacuna. However, the ends of the major axis are not at the interface between the circumferential lamellas. The maximum miss stress is 30.51MPa, while its stress concentration factor is 3.81. Fig.4 (c) denotes the stress distribution of CL osteon model, there is not obvious stress concentration at the brim of the CL. The maximum miss stress is 22.29MPa, its the stress concentration factor is 2.79. From the calculation result can be known, the stress concentration factor of RE model is maximal, the stress concentration factor of CE model is middle, while the stress concentration factor of CL model is the minimal, and the stress concentration factor of the elliptical lacunae are much larger than that of the circular lacunae. The CE make that the crack-propagated route is along the circumferential direction of the osteon rather than the radial direction of the osteon, which is consistent to observed result.

![Mises stress distribution](image)

Fig. 4 Mises stress distribution of three models (P=8MPa). (a) CE model, (b) RE model, (c) CL model.

The former calculated results shown that the stress concentration factors of the elliptical lacunae are much larger than that of the circular lacunae. The results can also be obtained by the stress analysis
for the model of an infinite plate including an elliptical hole (Fig.5). Suppose a remote stress $\sigma$ is applied to the plate, the maximum stress of the plate occurred at point A and it can be expressed as [18]

$$\sigma_A = \left( 1 + \frac{2a}{b} \right) \sigma$$

(4)

where $a$ and $b$ are the major and minor axes of the elliptical hole, respectively. However, if the hole is circular, namely, the size of the major axis of the elliptical hole is equal to that of its minor axis, one can obtain $\sigma_{Ac}>>3\sigma$. Because, generally, the size of the major axis of a elliptical hole is much larger than that of its minor axis, therefore, the maximum stress of the plate with the elliptical hole will be much larger than that of the plate with circular hole, namely, $\sigma_{Ac}>>3\sigma$, which is consistent with the former calculated results.

![Fig. 5 A schematic showing an elliptical hole in an infinite plate loaded](image)

4. Conclusions

The SEM observation shows that there are many osteocyte lacunae in osteons. The shape of these lacunae is elliptical and their major axis is along the circumferential direction of the osteon. The nanoindentation test results denote that the elastic modulus of the osteon fluctuates along its radial direction. The analysis results of the three different osteon indicate that the stress concentration factor of the RE model is maximal, CE model is middle and CL model is minimal. The CE make that the crack-propagated route is along the circumferential direction of the osteon rather than the radial direction of the osteon, which is consistent to observed result. The CE in the osteon is benefit to enhance fracture toughness of bone.

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