Finite Element Study of the Effect of Osteon Morphology Variation Related Ageing, Osteoporosis, or Physical Activity Level on Its Poroelastic Behaviors

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Abstract: The alterations of osteon morphology were caused by many factors, such as age, osteoporosis, and physical activity level. It is known that fluid flow in osteon play an important role in osteocyte mechanotransduction and hard tissue health, but less is known about these alterations of osteon morphology affect the response of fluid flow. This study aims at using poroelastic finite element analysis to investigate whether these variations of osteon morphology caused by ageing, osteoporosis, or physical activity level can affect the responses of osteon poroelastic behaviors. In this paper, the COMSOL Multiphysics software was used to establish osteon model with different morphological parameters (shape, cross-section curvature, cross-section area and wall thickness), and the effects of these parameters on the fluid pressure (P) and velocity (V) were investigated. The results showed that the osteon shape had large effects on P and V, and the peak value of P and V increased with the increase of the osteon oblateness. Then, we noticed that, the P and V had obviously positive correlation with cross-section curvature in the same region or lamellar structure in an osteon. The larger cross-sectional area caused a smaller P and V. However, the effects of osteon wall thickness showed the opposite way, the P and V amplitudes increased with the increase of the wall thickness. Significantly, our findings indicated that the wall thickness have a larger effect on P and V than that of the cross-section area. The findings of this work indicate that the alterations of osteon morphology associated with age, osteoporosis or physical activity level had significant influence on P and V in the osteon, and affect the signal transduction in the bone which have the potential research and applications value in treatment osteoporosis and other skeletal diseases.

Key words: Finite element study, Osteon morphology, Osteoporosis, Poroelastic behaviors, Mechanotransduction

Introduction

Bones as living tissue, can be considered as poroelastic materials and always endure the cyclic physiological loads in daily life. Bone tissue constantly go through the processes of bone formation and bone resorption to adapt to the external environment. Studies have shown that mechanical stimuli induced bones to change its microstructure\textsuperscript{1-5}. The alterations of osteon morphology plays an important role in the effective realization of various functions of bone. Research has shown that osteon morphology have a great relationship with age\textsuperscript{6-9}, and as age increased, the shape was more regular, the cross-section was larger and the osteon population density was bigger\textsuperscript{6}. Osteoporosis can cause the wall thickness of osteon becomes thinner and the porosity increases which increases the risk of fracture\textsuperscript{9,10}. In addition, high physical activity level could increase the wall thickness of osteon and bone density and make the shape become irregular\textsuperscript{2,3,11,12}, and it was one of the effective methods to prevent and treat osteoporosis in clinical treatment. In recent researches, macroscopic physiologic load caused osteon deformation which induced fluid flow in osteon, and osteocytes were sensitive to mechanical stimuli and fluid flow\textsuperscript{5,13,14}. Fluid flow in osteon and its induced effects on osteocyte, osteoblasts, osteoclasts play important roles in triggering bone formation and bone resorption\textsuperscript{14,15}. Changes in osteon morphology is result of bone adaptation\textsuperscript{6,18}, therefore, these alterations may cause the changes of fluid region in bone, resulting in affecting signal transduction and the remodeling.

Previous studies have found that different kind of bone or same kind of bone in different regions may have different morphology\textsuperscript{2,19}. Most of studies selected weight-bearing cortical bones as research object, and found that osteon diameter showed a negative correlation with stress in different bone regions\textsuperscript{11}. Skedros and van Oers observed that osteon morphology of calcaneus dorsal and plantar part were significantly different, and they found that the morphology of osteon had much distinction between external and internal sides of some weight-bearing bone, which could be associated with different strain patterns\textsuperscript{1,11,20}. These strain patterns may contribute to mechanism of morphological difference through bone metabolism and bone remodeling\textsuperscript{11,12}. Rémont solved the poroelastic problem of hollow cylinder, and obtained an explicit close-form solution\textsuperscript{21}, and discussed the influence of spatial gradients of permeability or Poisson’s ratio\textsuperscript{21}. Based on the Biot poroelastic theory, Nguyen used analytical and finite element methods to investigate...
the behaviours of fluid flows in osteon\textsuperscript{23,24}. Previous study of our group considered osteon as poroelastic materials\textsuperscript{25}, and established mathematical and finite element model to analyse the poroelastic behaviors of osteon under different boundary conditions\textsuperscript{26,27}, and we considered the fluid flow in osteon induced the streaming potential\textsuperscript{28}. The poroelastic behaviors of microcracks in an osteon were evaluated\textsuperscript{29,30}, and the direction and morphology of microcracks were fully considered\textsuperscript{31}. However, few studies considered the alterations of osteon morphology associated with age, osteoporosis or physical activity level affect the biomechanical response of signal conduction and fluid flow.

The purpose of this study was to investigate how changes in the osteon morphology caused by age, osteoporosis or physical activity level affect its poroelastic behaviors. Poroelastic finite element osteon models with different morphology were used to investigate the P and V in osteon. Based on the previous experimental study and theoretical analysis, the properties of the solid structure and interstitial fluid were assumed as transverse isotropic poroelastic material and compressible liquid, respectively\textsuperscript{29}. In this article, we focus on analyzing the influence of the changes in morphological parameters as the shape, the cross-section, the cross-section area and the wall thickness on the P and V, and provide a further understanding of the mechanotransduction which trigger bone remodeling and bone metabolism.

**Materials and Methods**

**Governing equations for poroelastic osteon model**

In previous studies, we used the poroelastic theory to describe the
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Table 2. The geometric parameters of circular and elliptical osteon model with the same cross-sectional area and wall thickness

| Osteon shape                      | R(um)  | d(um) | s(um²) |
|----------------------------------|--------|-------|--------|
| Elliptical cylinder model 1, a=0.09 | a=157.14, b=142.86 | d=100 | s=62800 |
| Elliptical cylinder model 2, a=0.017 | a=163.64, b=136.36 | d=100 | s=62800 |
| Elliptical cylinder model 3, a=0.23  | a=169.57, b=130.43 | d=100 | s=62800 |
| Elliptical cylinder model 4, a=0.28  | a=147.5, b=125 | d=100 | s=62800 |
| Elliptical cylinder model 5, a=0.33  | a=180, b=120 | d=100 | s=62800 |
| Cylindrical model                | a=0    | R=150 | d=100 | s=62800 |

fluid–solid interactions in cortical bone, and no body forces were taken into account²⁶-²⁹. The model used the transverse isotropic materials. Constitutive laws for the solid matrix material and the saturating fluid can be written as:

\[ \sigma = Me - ap \]  
\[ p = M(\xi - tr(\alpha \epsilon)) \]

In Equation (1) and Equation (2), \( \sigma \) is the total stress tensor, \( M \) is the fourth order stiffness tensor of the drained porous matrix, \( \alpha \) is the apparent strain tensor, \( a \) is Biot-Willis coefficient in the isotropic plane (r-0), \( p \) is fluid pressure, \( M \) is Biot modulus, \( \xi \) is the variations in fluid content and \( tr() \) is the trace operator.

The equilibrium equation can be written as:

\[ \rho \ddot{u} - \nabla \cdot \sigma = 0 \]

Where \( \rho \) is the total density and \( \ddot{u} \) is the displacement vector of the solid matrix.

Liquid mass conservation equation can be written as:

\[ \frac{\partial \xi}{\partial t} = -\nabla \cdot V \]

Darcy’s law relates the fluid content to fluid pressure \( p \),

\[ V = -K(\nabla p + \rho, \ddot{u}) \]

Where \( V \) is velocity vector, \( K=K/\mu \) is permeability tensor, which is according to the intrinsic permeability \( k \) and the dynamic viscosity of interstitial fluid \( \mu \).

Based on the above equation, we eventually got the governing equations of poroelastic model for the osteon:

\[ a\ddot{w} = \nabla \cdot (Mc) \]

\[ \frac{1}{M} \frac{\partial}{\partial t} p = \nabla \cdot (k\nabla p) - \frac{\partial}{\partial t}[tr(\alpha \epsilon)] \]

As shown in Fig. 1, we considered the transverse isotropy and low frequency and obtained its theoretical solution in cylindrical coordinate system, and verified the virtual correctness of the corresponding finite element model²²,²³,²⁷.

Boundary conditions and material parameters

As shown in Fig. 2, the model ignores the Haversian canal and is defined as a hollow cylinder. The height (\( h = 1 \) mm) is the same in all conditions, and the detailed geometry parameters will be given in concrete analysis. The properties of poroelastic materials of osteon are applied in Table 1.

The boundary conditions on the porous matrix are shown in Fig. 1, the cement line is impermeable and constrained, which means we consider the horizontal displacement to zero and set no-flow conditions on the surface of cement line. The pore pressure and solid surface for the inner wall are considered to be zero and stress-free, respectively. As shown in Equation (1), the cyclic physiological loads are axial and symmetrical to represent longitudinal compression and its amplitude of harmonic displacement (w) and frequency (f) are 0.5 µm and 1 Hz, respectively²²,²³. The maximum axial strain (e) amplitude is 0.001 at about 0.5 s in one cycle, however, the maximum responses of P and V occurs at about at 0.25 s²²,²³.

\[ w_{P=10.5\text{mm}} = \pm 0.00025[\cos(2\pi ft) - 1][\text{mm}] \]

In this work, the fluid–solid interactions were conducted using the Comsol Multiphysics software to investigate the poroelastic behaviors of osteon under physiological loading. The model uses the poroelasticity interface, which includes the time rate of change in strain from the solid-deformation equations in the Darcy’s Law interface and the fluid pressure gradient in the Plane Strain interface. The boundary conditions and material parameters are the same in all conditions.

Model generation with different morphology

In order to analyze the effects of osteon morphology on the biomechanical responses in osteon, the morphology parameters of osteon are considered in detail: the shape, cross-section curvature, cross-sectional area and wall thickness.

The shape

Studies have shown that activity, implants and age can change the shape of osteon. For investigating the effects of shape on the poroelastic behaviors of osteon, two models with different cross-section shape (Fig. 3 (A) ellipse model, (B) circular model) were constructed. The cross-sectional area and wall thickness are the same in the two models to exclude the influence of other variables. In the elliptical model, we considered the influence of 5 different oblateness \( \alpha \) (\( \alpha = (a-b)/a \)), the value were 0.09, 0.17, 0.23, 0.28, 0.33, respectively. Oblateness \( \alpha \) reflects the oblat degree of ellipse. With \( \alpha \) increased, the elliptical osteon become more oblat. The geometric parameters are grouped in Table 2, and \( a, b, R, S \) and \( d \) represent semi-major axis, semi-minor axis, osteon radius, cross-sectional area and wall thickness, respectively.

The cross section curvature

Different regions of a single osteon may have different biomechanical responses. In this part, an elliptical cylinder osteon model with different osteon lamella (Fig. 4) was built to evaluate the effect of cross-section curvature on the osteon poroelastic behavior. Osteon lamella near the external wall and inner wall were selected to investigate the P and V amplitudes, respectively (Fig. 4).
Figure 5. The different cross-sectional area of osteon with same wall thickness. (A, B, C, D, E and a, b, c, d, e are the locations near inner wall and outer wall, respectively). The detailed parameters are grouped in Table 3.

Figure 6. The cross-sectional area and wall thickness change simultaneously. (A, B, C, D, E and a, b, c, d, e are the locations near inner wall and outer wall, respectively). The detailed parameters are grouped in Table 4.

Figure 7. The cross-sectional area and wall thickness change simultaneously. (A, B, C, D, E and a, b, c, d, e are the locations near inner wall and outer wall, respectively). The detailed parameters are grouped in Table 5.

| Table 3. Elements and degrees used in osteon model with different cross-section area |
|---------------------------------|--------|--------|
| S(um²) | R(um) | d(um) |
| 20000 | 150 | 100 |
| 22000 | 160 | 100 |
| 24000 | 170 | 100 |
| 26000 | 180 | 100 |
| 28000 | 190 | 100 |

| Table 4. The geometric parameters of osteon model with different wall thickness |
|---------------------------------|--------|--------|
| d(um) | R(um) | S(um²) |
| 10 | 150 | 2900 |
| 20 | 82.5 | 2900 |
| 30 | 63.33 | 2900 |
| 40 | 56.25 | 2900 |
| 50 | 54 | 2900 |

| Table 5. The geometric parameters of osteon model with different wall thickness and cross-sectional area |
|---------------------------------|--------|--------|
| d(um) | R(um) | S(um²) |
| 100 | 150 | 62831.85 |
| 110 | 160 | 72570.79 |
| 120 | 170 | 82938.05 |
| 130 | 180 | 93933.62 |
| 140 | 190 | 105557.51 |
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The cross-sectional area
As shown in Fig. 5, in order to evaluate the effect of cross-sectional area on the osteon fluid flow behavior, osteon models with different cross-section area and same wall thickness were created. The parameters are grouped in Table 3, and R, r, S and d represent internal radius, external radius, cross-sectional area and wall thickness, respectively.

The wall thickness
As shown in Fig. 6, in order to evaluate the role of the wall thickness on the poroelastic behavior of osteon, osteon models with different wall thickness were established. The mash parameters are grouped in Table 4, and R, S and d represent external radius, cross-sectional area and wall thickness, respectively. The p near the outer wall (cement line) and the v near the inner wall (Haversian canal) were observed.

The cross-sectional area and wall thickness always change simultaneously. As shown in Fig. 7, in order to assess the relationship between the wall thickness and cross-section area on the poroelastic behavior of osteon, we established an osteon model that the cross-section area and wall thickness simultaneously change. The parameters are shown in Table 5, where R, s and d represent osteon radius, cross-section area and wall thickness, respectively.

Result
Effect of the osteon shape and cross section curvature
In the previous study, finite element method has been proved effective in researching osteon, and the maximum compression effect occurs at about $t = 0.25s^{29}$ in a cycle. The distribution of $P$ and $V$ obtained by simulation was in accordance with the previous researches, and the numerical simulation data was also approach to our previous theoretical research $^{26}$.

The $P$ (Fig. 8A and B) and $V$ amplitudes (Fig. 8C and D) along the $x$ and $y$ axis of osteon model were plotted, respectively. In the direction of the $x$ axis, the peak $P$ amplitudes in ellipse osteon significantly larger than circular osteon, and there is a point critical $O_1$, where the $P$ nearly same in all models, and in the lateral side of $O_1$ (near cement line) the bigger of oblateness, the larger of $P$. However, the variation of $P$ in the medial side of $O_1$ (near Haversian canal) showed the opposite tendency with increasing oblateness. The $V$ increases with oblateness increases along the $x$ axis (Fig. 8C). In the direction of the $y$ axis, the peak $P$ (Fig. 8B) and $V$ (Fig. 8D) amplitudes are all obviously less than that in the direction of the $x$ axis. There is also a point critical $O_2$, and the $P$ decrease with oblateness in the lateral side of $O_2$ (near cement line) and increase with oblateness in the medial side of $O_1$ (near Haversian canal) (Fig. 8B). The $v$ decreases with oblateness increases along the $y$ axis (Fig. 8D).

As shown in Fig. 8, the shape of the osteon has a great influence on the $P$ and $V$. Under the same cross-section area and wall thickness, the peak $P$ and $V$ of the osteon increase with oblateness. The larger the oblateness, the greater the $P$ and $V$ difference between in $x$ and $y$ axis direction.

Osteon cross-section can be regarded as curved surface, and the $P$ and $V$ of the osteon are related to the bending degree of the cross-section, so we consider the influence of sectional curvature. Each osteon consists of 5-20 concentric lamellae of compact tissue that surround the Haversian canal. The lamellar structure is arranged parallel to the surface of the osteon called osteon lamella. Based on the cross-section shape of ellipse osteon, the cross-section curve of concentric ellipse osteon lamella was obtained. As shown in Fig. 4, due to symmetry, only 1/4 osteon was observed in the computations. The osteon model was
surrounded by 10 concentric layers of osteon lamella, and 10 points on each 1/4 osteon lamella was calculated. As the P near the outer wall (cement line) and the V near the inner wall (Haversian canal) can cause the biomechanical response in osteon, we selected 5 curves near the inner wall to test the relationship between the V and the cross-section curvature, and take 5 curves near the outer wall to test the relationship between the P and the cross-section curvature. We matched cross-section curvature of different osteon lamella with the corresponding P and V data, and compared and evaluated them by linear fitting.

The results of curve fitting are as follows:

Curve 1: \( y = 2E + 06x + 22177 \) \( R^2 = 0.9611 \) (8)
Curve 2: \( y = 1E + 06x + 21857 \) \( R^2 = 0.9646 \) (9)
Curve 3: \( y = 1E + 06x + 19849 \) \( R^2 = 0.9684 \) (10)
Curve 4: \( y = 863649x + 16490 \) \( R^2 = 0.9749 \) (11)
Curve 5: \( y = 582090x + 11247 \) \( R^2 = 0.9807 \) (12)
Curve 6: \( y = 1E - 06x + 6E - 08 \) \( R^2 = 0.9868 \) (13)
Curve 7: \( y = 9E - 07x + 7E - 08 \) \( R^2 = 0.961 \) (14)
Curve 8: \( y = 6E - 07x + 7E - 08 \) \( R^2 = 0.9278 \) (15)
Curve 9: \( y = 5E - 07x + 6E - 08 \) \( R^2 = 0.9774 \) (16)
Curve 10: \( y = 5E - 07x + 6E - 08 \) \( R^2 = 0.9876 \) (17)

The relationship between the P and V and cross-section curvature in osteon were evaluated by a linear fitting method and their coefficients of determination were 0.9611 (8), 0.9646 (9), 0.9684 (10), 0.9749 (11), 0.9807 (12) and 0.9868 (13), 0.961 (14), 0.9278 (15), 0.9774 (16), 0.9876 (17), respectively. We found that the cross-section curvature has a positive correlation relationship with the distribution of P near the external wall and V amplitudes near the inner wall, respectively.

As shown in Fig. 9, the P amplitudes of the location of the minimum and maximum cross-section curvature of in same osteon lamella were: 31000 pa - 380000 pa (curve 1), 30000 pa - 36000 pa (curve 2), 28000 pa - 340000 pa (curve 3), 24000 pa - 29000 pa (curve 4), 17000 pa - 22000 pa (curve 5), respectively, and that of the P were 7.20e-8 m/s - 7.80e-8 m/s (curve 6), 7.60e-8 m/s - 8.30e-8 m/s (curve 7), 7.9e-8 m/s - 8.50e-8 m/s (curve 8), 8.30e-8 m/s - 9.30e-8 m/s (curve 9), 8.50e-8 m/s - 1.10e-7 m/s (curve 10).

Effect of the cross-sectional area

Studies showed that age and stress were significantly related to osteon diameter\(^4,6,7\). In this part, five models with different cross-sectional area and same wall thickness were established (Fig. 5). Since the fluid pressures (P) near the inner wall (Haversian canal wall) and velocities (V) near the outer wall (cement line) are too small to cause biomechanical responses of the osteon, we selected two points of each model near the outer wall (Fig. 5A, B, C, D, E) and inner wall (Fig. 5a, b, c, d, e) to investigate the P and V, respectively. Fig. 10 presented the results of the P (Point a, b, c, d and e) and V (Point A, B, C, D and E) amplitudes at

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different locations. The P and V of point A and a in smallest cross-sectional area model are both larger than other points, respectively. The maximum P and V of osteon with different cross-sectional area were found to be $2.7 \times 10^4$ Pa, $2.54 \times 10^4$ Pa, $2.41 \times 10^4$ Pa, $2.3 \times 10^4$ Pa and $2.21 \times 10^4$ Pa and $7.2 \times 10^{-8}$ m/s, $6.45 \times 10^{-8}$ m/s, $5.92 \times 10^{-8}$ m/s, $5.54 \times 10^{-8}$ m/s and $5.17 \times 10^{-8}$ m/s at 0.25 s, respectively.

**Effect of the wall thickness**

In order to evaluate the influence of osteon wall thickness on mechanotransduction of bone, five points near the external wall (Fig. 6a, b, c, d, e) and the inner wall (Fig. 6A, B, C, D, E), which the fluid shear effects can be felt by the osteocytes for analyses \(^{4,32}\), were selected to investigate effective P and V, respectively. Detailed analyses of the P and V with loading time in a cycle at these ten different locations are shown in Fig. 11. The P and V amplitudes are increasing with the increase of wall thickness. This result indicates that osteon wall thickness and cross-section area have the opposite effects on the response of poroelastic behavior.

The cross-sectional area and wall thickness always change simultaneously. As shown in Fig. 7, in order to assess the effect of the relationship between the wall thickness and cross-section area on the poroelastic behavior of osteon, we established an osteon model that the cross-section area and wall thickness simultaneously change. And 5 points near the outer wall (Fig. 7a, B, C, D, E) and 5 points near the inner wall (Fig. 7A, B, C, D, E) of the osteon were observed and analyzed. Fig. 12 shows the P near the outer wall and V near the inner wall in a cycle. The result showed that the P and V increased with the cross-section area and wall thickness. And due to larger cross-section area led to smaller P and V, the result indicate that the influence of wall thickness is obviously bigger than cross-section area.

**Discussion**

Morphology of osteons which play an important role in implementing the various functions of bone vary between individual, different region in same individual, and even same regions based on the factors such as its mechanical environment where the osteon experienced. In this study, a 3D poroelastic FE model was established by using the Comsol Multiphysics software to investigate the influences of morphological parameters on the biomechanical behaviours of a single osteon under cyclic physiological loading. This study divided osteon morphological parameters into four parts: shape, cross-section curvature, cross-section area and wall thickness, and evaluated the effect of these morphological parameters on the poroelastic behavior of osteon.

In terms of shape, we considered circular and elliptic. As shown in Fig. 8, with the increase of oblateness, the P and V increase along the long axis and decrease along the short axis. The maximum V in ellipse
models is about 2 times that of the circular (Fig. 8C). It can be predicted that when the oblateness becomes bigger, the greater difference between the circular model and elliptical model of osteon cross-section. The changes of osteon morphologic have a great relationship with age. As the age increases, the shape of the osteon is rounder\(^{30}\), which means that the changes in osteon shape with age lead to a decrease of its P and V, resulting in the reduction of the stimulation of the osteocytes in the same activity.

Then, the effect of cross-section curvature was investigated and the results showed that the P and V amplitudes increase linearly with the increase of cross-section curvature in same osteon lamella. Some osteocytes were distributed on each of the osteon lamella. This result indicate that the osteocytes may be under a stronger fluid flow stimulation in the regions where the cross-section curvature is larger in same osteon lamella. As shown in Fig. 9, the maximum difference in V on the same osteon lamella is 20%. The oblateness of the chosen model is 0.17. It predicted that with the oblateness increasing, the maximum difference in P and V are greater on the same osteon lamella, and the maximum value of P and V are higher in the case of equal section area and wall thickness. Lambers et al used computed tomography (CT) scans observed loaded implant can lead to the morphological changes of bone\(^{33}\), which means osteon morphology can be induced to change. In further studies, it may be possible to change the osteon shape through implants to achieve greater fluid stimulation for the osteocyte.

The formation of different morphology of bone is still unclear, and the morphology vary greatly in different regions of bone\(^{3,35}\). Van Oers et al found that the relationship between strain and osteon diameter suggested the function of bone resorption of osteoclastic\(^{4,34}\). Moreover, the relationship between osteoclastic activity and osteon size was found\(^{40}\). In order to investigate the influences of osteon size on poroelastic behaviours of osteon, this study established three case (1) different cross-sectional area and same wall thickness, (2) different wall thickness and same cross-sectional area, (3) different cross-sectional area and wall thickness. Case (1) and case (2) eliminate the potential influences of wall thickness and cross-sectional area, respectively, and they showed the opposite result (Fig. 11). The results of case (3) indicated that wall thickness have greater impact on the poroelastic behaviors of a single osteon than cross-section area (Fig. 12). Specifically, the larger cross-sectional area may cause smaller fluid flow stimulation and thicker wall thickness may produce higher fluid flow stimulation, and when we use morphometry features to evaluate fluid shear stress we should first consider the wall thickness. The cross-sectional area of osteon increases with age and the wall thickness of the osteon decrease with osteoporosis, which means that age and osteoporosis can induce a smaller P and V. This results make the osteocyte feel a smaller signal of fluid shear stress and streaming potential, which may be one of the causes of some bone diseases in the elderly, and further research is needed to confirm this hypothesis.

Osteocyte’s mechanoreceptors is sensible to the stimulation of fluid flow and influence the process of signal transmission, bone remodeling and bone metabolism\(^{14-17,32}\). The P and V in osteon lead a vital effect on transport of nutrients, exchange of metabolic waste, streaming potentials and flow shear stress\(^{15,18,20,35,36}\). Simulation results indicated that the P and V magnitudes have a potential influence on fluid shear stress which is the most important signal of mechanical stimulation in osteon\(^{3,35}\). Recent studies confirmed that bone cells can feel the stimulation of FSS to achieve the function of mechanotransduction\(^{5,32}\). The P and V is the key in the formation of FSS. In this study, the P and V amplitudes were observed in different morphology osteon model. Variations in the morphology of osteon have been investigated in osteoporosis, and these alterations include more circular osteons and thinning of wall-thickness. The findings of this study suggest that the alterations of osteon morphology during osteoporosis can lead to decrease of the P and V, and may alter mechanical stimulation of osteocyte-lacunar-canalicular system\(^{37}\). This research provides a new way to elucidate how morphologic changes of the osteon alter the mechanical stimulation of osteocyte-lacunar-canalicular system. The in-depth study of these processes have potential clinical significance.

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**Conflict of Interest**

The authors have declared that no COI exists.

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