Estimation of Loading-Driven Fluid-Flow Pattern in Lacunar-Canalicul space Using Fluid Structure Interaction

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Abstract. Bone cells namely osteoblasts and osteocytes are assumed responsible for loading-induced osteogenesis. Osteocytes lie within the bone and connect to each other via cell process passing through canalicular spaces which forms a canalicular network. Fluid motion across this network acts as a medium of communication with neighbouring cells. Mechanical loading-induced pressure gradients in lacunar canalicular space (LCS) causes canalicular fluid to flow. However, it remains unclear how canalicular fluid motion and solid structure interact with each other under loading derived strain environment. In the present study, a two-way fluid structure interaction model is developed to estimate canalicular fluid flow behaviour. Flow streamlines and wall shear stress are computed. Results indicates that wall shear due to fluid flow on the pores wall is also in the same pattern as the velocity streams and velocity is maximum at those regions where the wall shear is also maximum. The outcomes provide a better understanding for developing strategies to enhance the fluid flow in bone, which may ultimately be useful in the development of effective countermeasure for the reversal of bone loss.

1. Introduction

Biomechanical signals which regulate bone modelling and remodelling are not well known. Loading induced fluid motion inside bone is assumed primary stimulus of new bone formation [1]. Weinbaum et al., 1994 [2] substantiated that fluid flow in lacunar-canalicular space (LCS) induces shear stress on osteocyte’s cell-process. This flow is regulated through mechanical deformation-induced pore-pressure gradient [2–5]. The fluid shear developed on cell process elicits a biological response in osteocytes to further activate the osteogenic activities through selection of osteoblasts. In vivo studies [6,7] reported that bone micro-architectural properties such as porosity and permeability alter with age. It is expected that alterations in these properties of bone may affect canalicular fluid motion in bone and may also diminish osteogenic response of bone cells to mechanical loading. Fluid motion in lacunar-space below physiological value may affect the mechanosensitivity of the osteocytes which may further impair the bone formation and resorption processes. Loading-driven canalicular fluid motion however desired to be understood in response mechanical loading e.g. physiological or any exogenously applied loading. A fluid-solid interaction may be useful in characterizing the fluid flow in lacunar-canalicular space. The model may also be useful in studying the fluid motion as a function of age change. The objective of the present study is to establish a fluid-structure interaction (FSI) model to compute bone tissue deformation-induced pressure gradient and velocity of the canalicular fluid flow. The FSI model specifically aims to estimates fluid flow pattern in response to trapezoidal loading which a most commonly used loading regimen to study bone adaptation. The model attempts to explain Generally fluid structure interaction (FSI) is a novel approach in which bone is modelled as a rigid structure to describe the fluid shear stress coupled to bone deformation. This work may be of help in understanding the fluid flow in bone canalicular network. The outcomes can be useful in...
designing optimal loading regimen to enhance osteogenic activities in bone which may also be beneficial in mitigating bone loss.

2. Material and Method

2.1 The model
A three-dimensional idealized structure of bone tissue with network is developed shown in Figure 1. Bone is assumed as a porous rigid structure with presence of osteocyte canalicular channels. Poromechanical properties are assigned to bone tissue in accordance with healthy bones as mentioned in the literature. A cantilever bending load [8] is applied on bone reported in the literature as bone is usually subjected to habitual bending. A fluid-structure interaction module available in ANSYS Multiphysics is used to simulate the interface between the solid bone deformation and canalicular fluid motion. Fluid motion under the effect of applied loading pattern is studied. The models are meshed before performing the computation.

Figure 1. (a) Model geometry with bone (solid) and (pores) fluid domain, (b) and (c) represents Solid domain (Bone) geometry and (d) and (e) shows the Fluid domain (pores) geometry

2.2 Mesh Characteristics and Boundary condition
The models are meshed before performing the computation (Figure 2). The bone and fluid model are meshed using free mesh elements. The total of nodes and elements for solid bone is 1445489 and 1020074 respectively. Whereas, the total number of nodes and elements for fluid domain is 52444 and
246194 respectively. The skewness checks were also done to improve the results as it prevents a node from being moved. For both solid domain and fluid domain the average value is minimum (Table 1 and 2).

Figure 2. (a) Meshed model of solid domain (bone), (b) Meshed model of fluid domain (pores)

| Table 1. Skewness for solid domain (bone) and fluid domain (pores) |
|---------------------------------------------------------------|
| **Solid domain** | **Fluid domain** |
| Mesh Metric  | Skewness  | Mesh Metric | Skewness |
| Min         | 7.7023e-005 | Min         | 3.9768e-004 |
| Max         | 0.94611    | Max         | 0.80061    |
| Average     | 0.21936    | Average     | 0.24682    |

| Table 2. Aspect Ratio for solid domain (bone) and fluid domain pores |
|---------------------------------------------------------------|
| **Solid domain** | **Fluid domain** |
| Mesh Metric  | Aspect Ratio  | Mesh Metric | Aspect Ratio |
| Min         | 1.1637       | Min         | 1.1659       |
| Max         | 6.732        | Max         | 8.9349       |
| Average     | 1.8156       | Average     | 1.894        |

Two-way FSI between flowing fluid and solid is analysed simultaneously on both fluid and solid domain. Both fluid and solid systems are coupled, and iterations are carried out between computational fluid dynamics (CFD) and finite element analysis (FEA) codes. The schematic of arrangement of physic for two-way FSI applied in ANSYS Multiphysics is shown in figure 3.
After setting up the transient structural and fluid flow FLUENT setup in ANSYS both these setups are linked with the setup in the system coupling. Analysis setting are to be done in the system coupling as shown in figure 3 and after setting up the analysis setting data transfer is to be done. Data transfer is done between the fluid solid interface region given in transient structural boundary condition and the wall region given in FLUENT setup. Two data transfers are done in which one the source is transient structural system and the target is fluid flow FLUENT and in other data transfer the case is vice versa.

Table 3. Boundary condition for fluid domain (pores)

| Reference                  | Parameter       | Value               |
|----------------------------|-----------------|---------------------|
| [9] Pereira and Shefelbine, (2014) | Inlet Velocity | $6 \times 10^{-6}$ m/sec |
| [10] Rodriguez-Florez et al., (2014) | Permeability    | $2.1 \times 10^{-21}$ m$^2$ |
| [11] Cardoso et al., (2013)     | Porosity        | 0.4                 |
3. Result and Discussion

3.1 Fluid Velocity
Two-way FSI analysis explains how the fluid interact with the solid domain. Fluid flow patterns have shown using streamlines. Velocity streamlines are plotted on a scale ranging from min 2.158 X 10^-1 to max 2.199 X 10^2 as shown in figure 5. Streamlines appears approximately same because of very less velocity of the interstitial fluid (6 × 10^-6 m/sec) which is close to fluid flow observed in the literature. It is also noticeable that fluid velocity magnitude increases with increase in axial position and is maximum at the center of the channel where all the pores get merged. At mid of the channel where the pores merged trapping is observed. Fluid motion is relatively high in the pores at the inlet direction and whereas, it decreases near the boundary where displacement is constrained. According to in vivo studies, this fluid motion induces shear stress on osteocyte cell process. As a result, cell process acts as experiences mechanobiological stimulus for osteogenesis. This work does not consider the variation of permeability and porosity. This model also does not consider vascular porosities. Nevertheless, these limitations will be addressed with a more robust model in the future work.

![Figure 5. Velocity streamlines in case of bending](image1)

![Figure 6. Wall shear stress distribution](image2)

3.2 Wall shear (Fluid shear)
The fluid wall shear through the pores is shown in figure 6. It can be observed that wall shear pattern is same as the velocity streamlines. Wall shear stress is also maximum at those regions where the fluid motion is maximum. The maximum shear is found in the lower region of the pores where the velocity is maximum due reduction in size of pores in all the three cases. Maximum shear is found because due to maximum velocity the velocity gradient increases which is directly proportional to the shear stress. Average magnitude (10-20 dyne/cm^2) also matched with literature as indicated in Weinbaum et al.

4. Conclusions
The present study is preliminary attempt to understand the fluid structure interaction of solid bone matrix with canalicular fluid flow which predicts fluid velocity and wall shear stress. The wall shear stress responsible for bone mechanotransduction can also be estimated. An improved model is however required to be developed using computed tomography technique to fully characterize the fluid flow behaviour. The work also describes the role of fluids in regulation of bone adaptation. The fluid structure interaction model can be useful in designing of such loading regimen or exercise which can enhance the fluid motion to promote osteogenic activities in order to improve the bone health.
5. References

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