# Possible Role of Lacunocanalicular Streaming Potential in Modeling of Trabeculae

Sungki Min[1], Taekyeong Lee[2], Junghwa Hong[2,3,*]

[1]R&D Center, BNR, [2]Department of Control and Instrumentation Engineering, Korea University, [3]Department of Medicine, Korea University

## Introduction

### Objectives of Study

- The purpose of this study is to discuss the endogeneous electric signals that are expected to effect on the modeling and remodeling process of cancellous bone.

### Background of Study

- In the early stage of the modeling (MD) process, trabeculae (TB) surrounded by the red marrow form directionally isotropic coarse mesh and show irregular shapes.
- During the MD, cancellous bone develops into normal architecture composed of the straight TB rod and plate. The modulation of this architecture and mass of the TB is caused by mechanical load condition to the cancellous bone, since the bone fluid shear stress and flow in the lacunocanaliculae(PLC) induced by the TB deformation stimulate the osteocytes(OS) for the MD.
- However, it is still not understood how the OS would control the TB shape since the OS could sense only the hydraulic pressure and flow. A previous research indicated that a new bone formation of the TB was influenced by local tissue deformation rather than the local OS population or density[1]. As a result, it can be assumed that the OS could command the whole TB MD process with signaling to cells in the bone (osteoblast: OB, osteoclast: OC, mesenchymal stem cell: MSC, bone lining cell: BLC, and hematopoietic cell: HC) with other assistive mechanisms for the shape MD. For humans, it is known that the OB and MSC migrated toward the positive electric potential(EP) after application of exogenous EP[2]. In addition, a higher EP induced more proliferation of the OB[3].
- It was reported that the endogenous EP by the piezoelectric bone matrix (BM) could be a main factor for the MD[4]. Thus, it can be hypothesized that bone EP would be an assistive mechanism for the TB MD. In a previous study, the two kinds of bone electricity (PLC streaming potential (SP) and BM piezoelectric potential (PZP)) were combined to predict an augmented PLC SP[5].
- To predict the TB MD, a two dimensional TB rod shape having one dimensional PLC was analyzed using the theory[5] to predict PLC flow and SP when a step pure bending moment was applied to induce compressive and tensile stress profiles on the concave and convex sides of the TB, respectively.

## Methods

### Model Configuration

- Bone matrix, lacunae, and canaliculae of TB rod were modeled using the two dimensional piezoelectric element(CPS4E), two dimensional fluid cavity(F2D2), and fluid link element(FLINK), respectively.
- Height of bone matrix were 200㎛ height and diameter of lacunae and canaliculae were 33㎛ and 0.2㎛, respectively.
- The one dimensional PLC(regularly spaced six lacuna and seven canaliculae) was connected five canaliculae between each lacuna on vertical axis.

### Material Properties

- Isotropic mechanical properties(E=13.0GPa, $\nu$=0.35)[6]and transversely isotropic electric properties[5] of bone were applied to this problem.

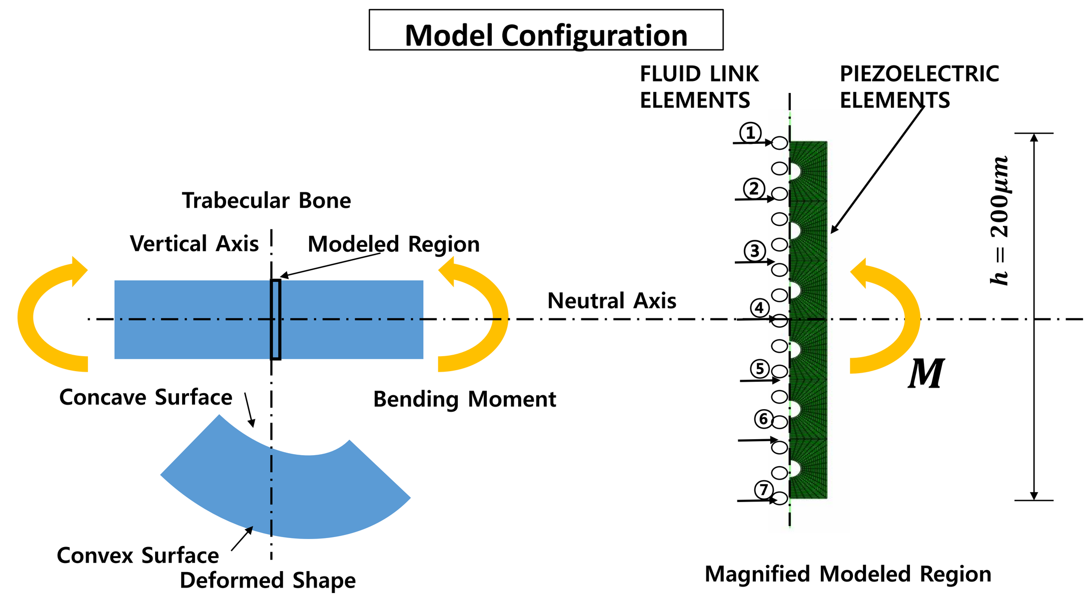
### Boundary and Loading conditions

- All nodes on vertical axis and on neutral axis were constrained to the X-axis and Y-axis, respectively.
- The applied step pure bending moment (a loading duration of 0.5 sec: a rate of 1 Hz) to the TB was 0.0294 N ㎛ to induce the stresses of ± 0.15 MPa on the convex and concave faces of the TB.
- Porepressure on the concave and convex face are always zero.

### Initial Conditions

- Initial electric potential of nodes on the vertical axis are always 0.1 ㎷

**Model Configuration**




## Results

### Stress Distribution

- The presence of lacuna results in a nonuniform stress distribution. The maximum tensile and compressive stress of ± 0.255 MPa occurred at lacuna near convex and concave face, respectively.

### Piezoelectric Potential Distribution

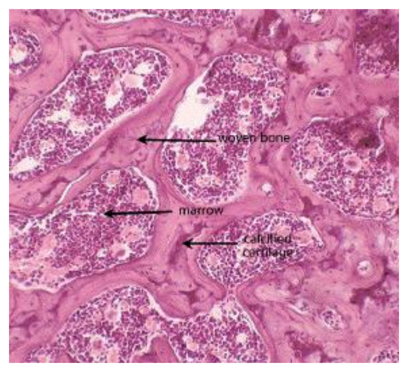
- Piezoelectric potentials are different in the vertical axis direction. In the calculation of the streaming potential, the piezoelectric potential around the vertical axis used as a boundary condition is positive.

### Porepressure Distribution

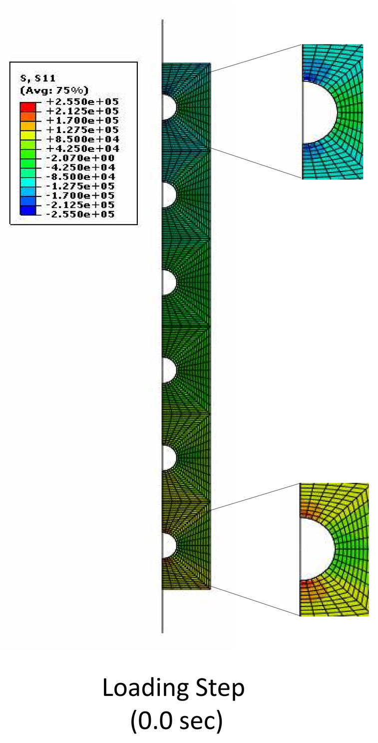
- At the beginning of step loading, the maximum porepressure occurs, and the maximum positive porepressure and maximum negative porepressure of ± 0.0788 MPa, respectively, are reversed at the beginning of step unloading.

### Streaming Potential Trends

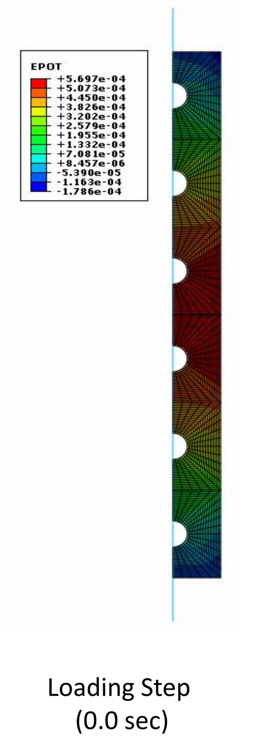
- The absolute peak PLC SP values on the concave (+4.47 mV) and convex (-3.83 mV) faces of the TB during the loading were significantly higher than those (concave: -0.917 mV, and convex: +0.861 mV) during the unloading. The mean PLC SP values on the concave and convex faces of the TB during the loading cycle were +1.23 mV and -1.04 mV, respectively.



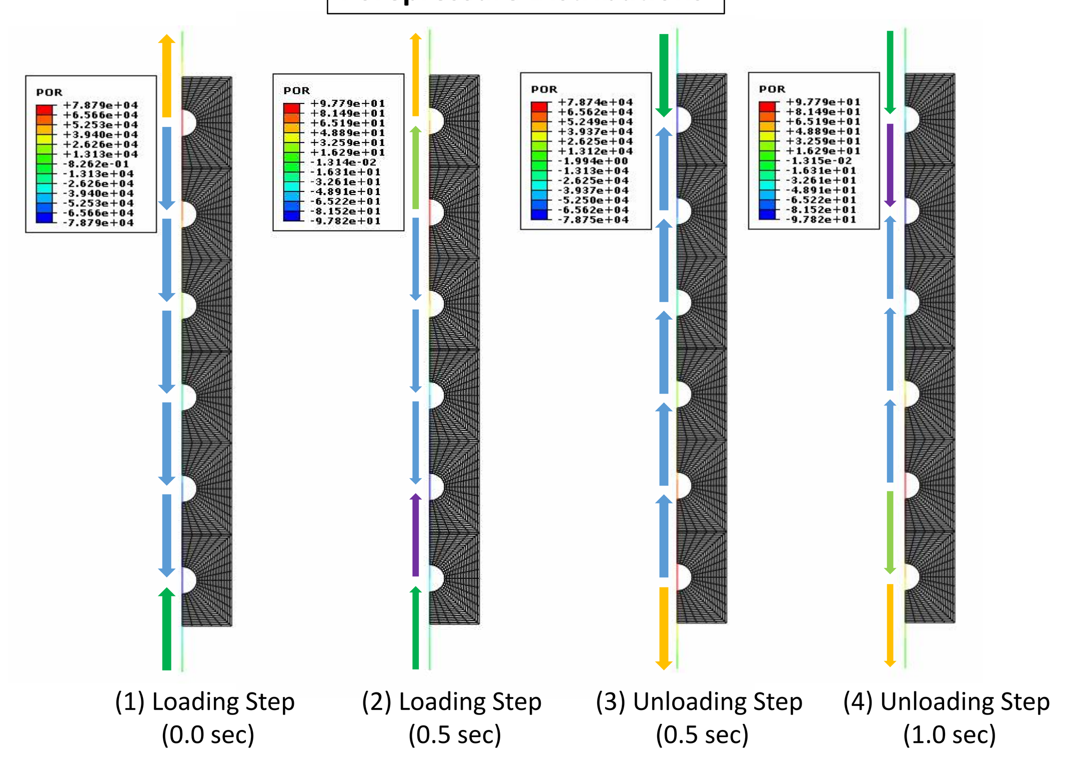
**Stress Distribution**



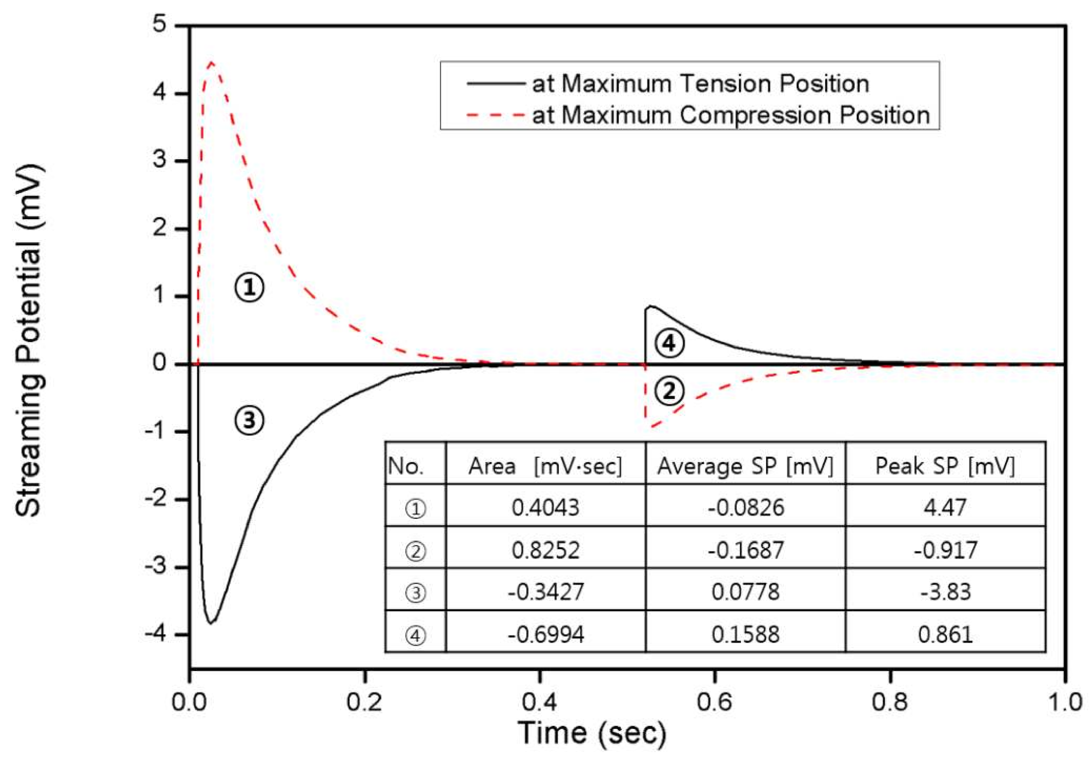

**Piezoelectric Potential Distribution**




**Porepressure Distributions**




**Streaming Potential Trends**




| No. | Area [mV·sec] | Average SP [mV] | Peak SP [mV] |
|---|---|---|---|
| ① | 0.4043 | -0.0826 | 4.47 |
| ② | 0.8252 | -0.1687 | -0.917 |
| ③ | -0.3427 | 0.0778 | -3.83 |
| ④ | -0.6994 | 0.1588 | 0.861 |

## Discussions

### The Generation Mechanism of Streaming Potential

- When a solid channel is filled with the ionic fluid(electrolyte), the polarity of the channel wall attract ions of opposite polarity toward near the channel wall intensively. If the fluid flows in a certain direction, the gathered opposite ions near the channel wall moves by the flows. Therefore, The concentration of opposite ions in the traveling direction becomes higher and this direction has relatively the same polarity with the ions on the channel.
- In this study, since the piezoelectric potential near the canaliculi(fluid channels)is positive and fluid flow toward the convex face in loading step, negative ions moves toward the convex face and the polarity of the face is negative, on the other hands, the polarity of the concave face is positive.
- When comparing streaming potential trends in loading and unloading step, the effect of piezoelectricity was four times larger than that of non-piezoelectricity.

### The Role of Interstitial Fluid Transport

- It is well known that the canaliculae open to the extracellular fluid and bone surfaces for the nutrients and metabolic activities of the OS. Thus, the TB PLC SP could affect the red marrow in the intertrabecular pore space (PIT).
- In this study, the TB has the mean positive and negative EP values on the concave and convex faces during the loading cycle, respectively. These indicate that the PLC fluid is spouted into the PIT through the concave face of the TB during the loading cycle. In contrast, the extracellular fluid in the PIT is flown into the TB through the convex face of the TB during the loading cycle.

### The Signals of Bone Modeling and Remodeling

- Because of the positive EP, the OB and MSC in the PIT could migrate toward the concave face of the TB[2]. For the MD, the PLC fluid flow through the concave face could provide signaling proteins and genes (produced by the OS) to the migrated OB and MSC. The migrated OB and MSC near and on the concave face of the TB with the signaling substances result in the new bone formation.
- The role of EP on the OC is not known in humans. Since the convex side of the TB undergoes a tensile stress profile, the lacunae in the side have the negative fluid pressure. Since an excessive negative fluid pressure causes apoptosis of the MSC[7], apoptosis of the OS in the convex side of the TB would occur. In addition, the apoptosis could activate the OC formation on the convex side. With assistive mechanisms of the PLC SP, therefore, the formation and resorption of bone could occur in the concave and convex faces of the TB, respectively. More biological study is required to understand roles of the negative PLC EP in the MD process.

## Conclusions

### Conclusions

- From the simulation, porepressure distributions and streaming potential trends in trabecular bone were obtained to confirm the interstitial fluid flow and possibility of electric stimulation for bone modeling.
- The EP has shown clinical efficacy for the healing of bone fracture. However, detailed mechanisms of the EP for bone healing process is unknown. This study could provide a combined mechanism of the EP with the fluid communication between the PLC and PIT for the MD. In addition, this could be used for studying the bone remodeling process.

## Future Plan

### Future Study

- Since little studies have been done on the piezoelectric properties of trabecular bone, the experimental studies have to be done on these properties to fulfill re-simulation.
- In addition, many studies are need to apply the real shape of canaliculae and lacunae
- Finally, a study should be conducted to confirm the effect of exogenous electric potential on trabecular bone.


References

1. CRESSWELL, Erin N., et al. Mechanically induced bone formation is not sensitive to local osteocyte density in rat vertebral cancellous bone. Journal of Orthopaedic Research®, 2018, 36.2: 672-681.
2. ZHAO, Zhiqiang, et al. Directed migration of human bone marrow mesenchymal stem cells in a physiological direct current electric field. Eur Cell Mater, 2011, 22: 344-358.
3. ERCAN, Batur; WEBSTER, Thomas J. Greater osteoblast proliferation on anodized nanotubular titanium upon electrical stimulation. International journal of nanomedicine, 2008, 3.4: 477.
4. FERNANDEZ, J. R.; GARCIA-AZNAR, J. M.; MARTÍNEZ, R. Piezoelectricity could predict sites of formation/resorption in bone remodelling and modelling. Journal of theoretical biology, 2012, 292: 86-92.
5. MIN, Sungki, et al. Theoretical study of the effect of piezoelectric bone matrix on transient fluid flow in the osteonal lacunocanaliculae. Journal of Orthopaedic Research®, 2018.
6. ASHMAN R. B., ; RHO J. Y. Elastic Modulus of Trabecular Bone Material. Journal of Biomechanics®, 1988, 21.3:177–181.1
7. ZHANG, Yin-Gang, et al. Effect of negative pressure on human bone marrow mesenchymal stem cells in vitro. Connective tissue research, 2010, 51.1: 14-21.