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An Analysis of the Conduction of Electric Charges along the Fluid in the Canals of the Human Bone Haversian system.

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ABSTRACT

In diagnostic electrical stimulation methods, one cannot isolate conduction of bone from that of the soft tissue around it. In conduction studies in bone, charge passing through collagen and trabeculae of bone microstructure is negligible. The present paper theoretically analyse the charge conduction through the pores filled with fluid in live cortical bone. In cortical bone, the longitudinal fluid channels (Haversian canals) have lateral branching (Volkmann's canals) which accounts for 10 percent of fluid flow. Thus fluid movement occurs not only unidirectional in one longitudinal direction but in different directions. To explain this special mathematical applications like tensors are used. Further focused research is needed in this aspect as conduction in the fluid of canals of the cortex branching differently in bone is complicated by the movement of the fluid is such a bone is loaded.

Keywords: electric chanes, human bone, fluid, canal

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INTRODUCTION

Globally bone fracture represents a major public health burden. Proper recognition of the stage of healing is vital to direct the physician to correctly identify the end point of treatment in a particular case. Recently diagnostic electrical stimulation method is tried as a method to identify healing of human bone fractures [1-5]. The problem is currently no effective methods isolate electric charge conduction of bone from that of the soft tissue around it. This included conduction in tissues like the nerve, muscle, skin and blood vessels [6]. In an earlier paper [7], I have analysed in detail about electrical charge conduction through the microstructure of bone i.e. collagen and trabeculae without the fluid component mainly citing Sierpowska et al [8] in that article. However such transmission is negligible,

This review article a continuation of my previous paper [7], is intended to gain further insight in the field of bone conduction. It reviews scientific work providing insight on the distribution of the main conducting element of the bone, its fluid. In addition, modelling strategies are reviewed and potential areas of research are discussed. Successful use of these principles into bone conduction studies in intact bone and specifically on fractured bone will significantly chip in to the clinical success of bone fracture treatment in the future.

Bone has a unique dielectric property, that is not seen in any other animal tissue, i.e. it's dielectric properties change with aging and thus is dynamic. If this electric variation can be connected to a alteration in normal or diseased tissue, then it will be helpful in correctly identifying disease conditions. As the trabecular bone is heterogeneous, the probes are kept on their surface will not give significant measurement. In experimental bone sample preparation also there may be changes occurring on its surface. The overall tissue conductivity is primarily by ionic flow less than 2 Ghz, and it varies linearly with temperatures. The main variation in the dielectric property is decided by fat and water content. In a study fresh animal bone specimen obtained, demarrowed, acid treated to remove hydroxyl apatite and then subjected to microwave and micro CT. Minute irregularly shaped and spatially defined volumes beforehand are analysed. Plain washing of marrow will not show the direct response of the dielectric. Though the interior aspects may be more complex but still the measurements still are vital. It was found that with less mineral content, there was low dielectric and more saline high conduction. The bulk dielectric properties of saline saturated bone sample increase like that reported by Chakkalakal. This is mainly determined by the fluids in holes of the bone. There is a heavy reliance of the tissue dielectric on the water content. In life, these pores are filled with blood vessels and marrow and not water [9].

Gururaja S *et al* proposed a basic 2D model of fluid flow in bone. It consisted of an intermittent arrangement of lacunae and their surrounding systems of canaliculi to quantify local fluid flow characteristics near a single lacuna. micromechanics was used to standardize the peri-canalicular bone matrix, which is a system of straight circular cylinders in the bone matrix through which bone fluids can flow, as a locally anisotropic poro-elastic medium. When this cortical bone model was loaded, a micro-scale stress, and strain concentrations occur near each lacunae and create micro-scale spatial variations in the pore fluid pressure field. This sort of loading of the bone matrix and their containing canaliculi causes fluid pressures in the contained fluids themselves. This causes fluid flow in the canaliculi and exchange of fluid between canaliculi and lacunae. It was found that deformation-induced fluid pressures in the lacunar–canalicular system have relaxation times on the order of milliseconds opposed to the much shorter times ($1/100^{th}$ of milliseconds) associated with deformation induced pressures in the Haversian system [10].

As described in the above deliberation, the microstructure of bone decides its electrical properties. The main actors that conduct are electrolytes and conductive tissue like blood and nerve tissue filling the micro pores. Chakkalakal found that in saline saturated bone samples, the fluid filled pores determine the dielectric property. Kosterich observed that the longitudinal samples conducted more than the transverse because of abruption of the fluid filled longitudinal pores in later. Also fresh bone samples conducted three times more than the stored formalised bone [11] possibly due to reduction in the water content as there is drying up of the tissues by formalin.

The microstructure and branching of the canals

The microstructure of bone has a central feeding canal called Haversian canal. The lamella of bone are ingrained in extra cellular matrix that surround this Haversian canal These lamella are oblate spheres with

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have an empty space called lacuna of 5 µm diameter where osteocyte reside and canaliculi of 1 µm diameter carry blood from the Haversian canal to osteocyte in lacuna [11].

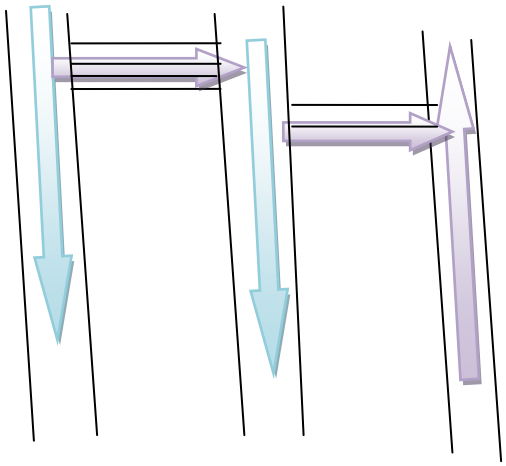

Figure 1: The arrows show that direction of the fluid flow and hence current flow in the Haversian canal. The transverse canals are the Volkmann's canal.

The central Haversian canal is the main canal from where the canaliculi and Volkmann's canal starts at right angle and proceeds. Like the lamella, the lacuna is also an oblate sphere. Length of the canaliculi is calculated by subtracting from the radius of the osteons, the radius of the Haversian canal as seen in the figure 2 [11].

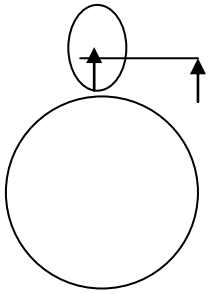

Figure 2: Central circle represents the Haversian canal. The outer circle denotes the approximate site of the osteocyte .

The average height of the osteons which is assumed as 4mm, R=radius of the Haversian Canal 25µm. Casas et al accept the pores in the Haversian system are of different sizes. They adopted certain simplification regarding pores distribution i.e. $1mm^3$ of the bone tissue has 25000 osteocyte lacunae, with a total surface area of $5mm^2 x mm^3$. The same amount of tissue will have 106 canaliculi with a total surface area 160 mm^2/mm^3 and 20 Haversian canals with a total surface area of 30 mm^2/mm^3. Since the electric conductivity of the bone - matrix is negligible, it is considered by Casas as an isotropic background. Different types of inhomogeneities like Haversian canal, Volkmann canal, canaliculi and osteocyte lacunae are embedded in the isotropic background of the bone matrix. Anisotropic property of collagen and Hydroxy-Apatite can be ignored as their electric conductivity is insignificant when weighed against the soft tissue (blood vessels and fluid) that filled the pores. They felt that dry bones are having piezo- electric effect when contracts when external current is applied [11]. However it was found that in wet bone and in life conditions the piezo- electric currents are too weak that they are washed away by the tissue fluid [6, 12].

Other assumptions by Casas et al that cannot be fully accepted are pointed by Newton et al in their work intended to identify the current limit above which tissue will be damaged i.e. to find safe limit [13]. According to Newton et al, bones are dielectric or semiconductors. As they conduct differently in different directions they are considered as anisotropic. The basic structure of bone has three parts, viz. the Haversian canal, Volkmann's canal and the extra cellular matrix. The aspect ratio is the ratio of the length to the diameter is calculated for Haversian canal, Volkmann's canals both are calculated to be 100 i.e if the diameter is 50 µm, the length is 0.5mm. The pores being filled with blood vessels conduct more and are considered metallic [13].

Casas et al assumed the total conductivity of bone matrix is independent of the direction. But in their assumption, Casas proposed that there are no intersecting canals between Haversian canals(Volkmann's Canals) and Haversian canal (Volkmann's Canal) considered as a long ellipsoid. Conductivity of one Haversian canal was calculated and then total conductivity of all canals was arrived. This sum total of conductivity of the entire bone is of Bone matrix -Haversian Canal- Volkmann's canal. When one assumes there is no Volkmann's Canal and there are no connecting channels between the Haversian canals, if such a bone is injured, then no repair can occur and the bone will not survive. Thus Newton felt that when a current is applied at one end of the bone, it branches out in different directions from each Haversian canal by the connecting lateral channels the Volkmann's Canal. In any model this must be clarified. Newton applied a method called tensors to explain this. Tensors are multi dimensional arrays to describe a physical property. Also the anisotropic nature of the bone must also be preferably included in a model and hence electric conduction of bone in unidirectional direction is not acceptable [13].

Like Newton et al, Swan et al they also applied tensors to explain the multidirectional fluid flow in bone tissue. According to them, Haversian bone can for most physiological loadings be modelled as a linearly elastic poro-elastic continuum. Usually for Haversian bone, the partitioned poro-elastic stiffness and compliance operators would be expected to feature transverse isotropy, due to the quasi-random arrangement of Haversian canals and osteons within the cross-section of a long bone specimen. The effective permeabilities in transverse directions are determined mainly by Volkmann canals and characteristically have about one tenth the values of that in the longitudinal direction possibly due to Volkmann canals and also randomly oriented canaliculi. These calculations match the measured conductivities of human cortical bone reported by Rouhana et al. At the bone specimen scale Haversian bone was modelled as an anisotropic poro-elastic medium. The dynamic equilibrium of the bulk porous medium both the bone matrix and Haversian fluid and that of the fluid relative to the rest of the medium are expressed and for generality, body forces per unit mass was also added. In general, the branches of osteons are aligned closely to the long axis of the bone, and as with the spiralling of osteons, would not likely have much effect as a result of orientation alone. Swan et al calculated transverse permeability roughly one tenth that in the longitudinal direction. Also branching of osteons is assumed to be < 5-10%. To allow structural analysis for Haversian bone, a displacement implementation is applied. The basic unknowns at each nodal point in the continuum with three components of solid displacements and three components of fluid displacement, relative to the solid. Totally there are six unknowns, or degrees of freedom at each node. In a fit human cortical bone, Haversian porosity is in the range of 1-5%, and the typical Haversian canals have diameters ranging from 10-70 mm [14].

Water content [9, 15] fat content [15] affected the electric properties of bone. Especially the water content of the tissue is also related to its dielectric properties. However as the exact composition of the tissue is unknown, any one single value cannot be chosen for conductivity, instead a range of values should be used [15].

Small endogenous currents in human body studied by Chiu et al with two models of bone marrow sub-structures being exposed to electric field are computed numerically. First one group of cancellous bone data acquired from computed tomography scan is calculated using both the finite element method (FEM) and scalar potential finite difference method. They found that there was a maximum electric field enhancement of 50%. On the second group of bone marrow stroma cells, FEM was applied using thin film approximation. They found that the trans-membrane potential (TMP) change across the gap junctions ranged from several to over 200 microV. These results suggest that even hardly noticeable contact currents can create biologically considerable change in trans-membrane potential in a few bone marrow stroma cells in any case [16].

Loading of the limbs

During loading of the limbs there is continuous pressure on fluids in the canaliculi. This stress induced flow is supposed to affect transport mechanism operating between cells and blood [17]. Load -induced fluid flow in bone is proposed as a mechano-transduction mechanism in bone adaptation. A unit cell micro-mechanical method is used to link the microstructure of Haversian cortical bone to its poro-elastic properties. The flow in the Haversian and Volkmann canals are studied and not canaliculi systems. Computational poro-elastic models applied to calculate in vitro Haversian fluid flows in a prismatic specimen of cortical bone during harmonic bending excitations over the frequency range of 100 to 106 Hz. At the higher frequencies, the breakdown of Poisueille flow in Haversian canals is modelled by introduction of a complex fluid viscosity [14].

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DISCUSSION

Understanding of the electrical parameters, method of conduction and the pathway of current path between the electrodes are vital, to fix an hypothesis at the cellular level and later to design relevant experimental protocols. Libolff et al did an in vivo demarcation of the current-voltage relationship in the medullary area between two platinum electrodes embedded in the human femur, by one of the techniques previously known to induce new bone formation. At potentials higher than 1 volt, electrolysis happened and there is increasing non-linearity. Below these potential differences of 1 volt, good ohmic dependence was seen, with an approximate specific resistance of 2 to 5 times 10-5 ohms/cm. Libolff felt that experimental methods that adjusts current through bone tissue assuming an ohmic dependence are valid [18].

Another worker calculated both in vivo and in vitro current flow using AC by four-electrodes inserted through all of the bone layers into the bone marrow space of the femora of rabbit. Bone electric resistance was first measured and later the animal was killed and then again the bone resistance was measured. There was three times increase in resistance. This scientific worker group ultimately felt that if electro conductivity of bone is determined by body fluids and more than bone tissue then measuring the "specific resistance" of bone in vivo is meaningless [19].

Tissue fluid and blood occupy the pores and canals in the cortical part of the live bone. The electric charge conduction in bone happens through these pores filled with fluid. When the bone is loaded this fluid should be disturbed and there should be an increase in or at least disturbance in the charge movement. If such a flow is in one direction that it would be synonymous to walking inside a running train. This is not as simple as this. In those literature discussed above it is clear that in the cortical bone fluid channels bones as there are different lateral branching (Volkmann's canals) of at least 10 percent of the longitudinal canals (Haversian canals) and so fluid movement occur in different directions.

SUMMARY

Though special mathematical applications like tensors are used to explain this unique feature, further focussed research is needed in this aspect. Thus currently the problem is of not only studying the conduction in the fluid that is contained in the fluid canals of the cortex which branch differently in bone but also that this fluid keeps moving with loading of the bone.

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