A Lesson in Cartilage Therapy: Do Chondrocytes Utilize Mechanical Energy From Exercise for Cell Maintenance and Growth?

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Abstract

Physical exercise has been shown to improve the mechanical properties of cartilage, increasing the proteoglycan content and subsequently the stiffness [1, 2, 3, 4]. As damaged cartilage has limited capacity for self-repair, strategies to enhance in-vivo cartilage repair and function are of medical interest [5]. Low-intensity ultrasound (US) is often used as an alternative therapy to facilitate cartilage repair and restoration[6].

COMSOL Multiphysics® Acoustics Module was used to analyze the US effects on cells over a range of frequencies centered on resonance to identify the most effective US regime. The model was set up, as shown in Figure 1, with a cell attached to a plane angled at 45° with respect to the propagation direction of the US field. The US source is positioned below the plane and a water/air interface is present above the plane.

Figure 2 (left), a cell located at a pressure anti-node in a 5MHz US field, shows the cell expands and contracts primarily in the radial direction, this 'breathing' action creates an alternating tensile/compressive force on the adhesion points normal to the plane. The cell on the right is located at a pressure node in an 8 MHz US field. At a pressure node the water velocity oscillates with maximum amplitude. The alternating flow exerts a rolling action on the cell, thence the adhesion points experience stronger forces parallel to the plane (shear). At 8 MHz the nucleus exhibits notable displacement relative to the cytoplasm - note the acentric location of the nucleus in Figure 2 (right). At lower frequencies (<6MHz) the nucleus and cytoplasm do not exhibit inertia with respect to each other and the motions of their centers of mass are synchronized.

Chondrocytes' primary resonance is around 5 MHz and only in a narrow band around the resonance value does mechanical energy couple effectively in all parts of the cell. At this frequency, the mechanical energy density in the nucleus is approximately two times higher than in the cytoplasm (Figure 3). The practical implication is that cells can still couple significant amounts of mechanical energy between 4 MHz and 6 MHz, provided the cell lies at an anti-node, but cells at pressure nodes will capture very little mechanical energy unless it is delivered at a frequency that lies in a narrow band around the resonance frequency. These results show that the most effective US regime is to use the resonance frequency as one cannot guarantee all cells will lie at an anti-node.

Reference

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Figures used in the abstract

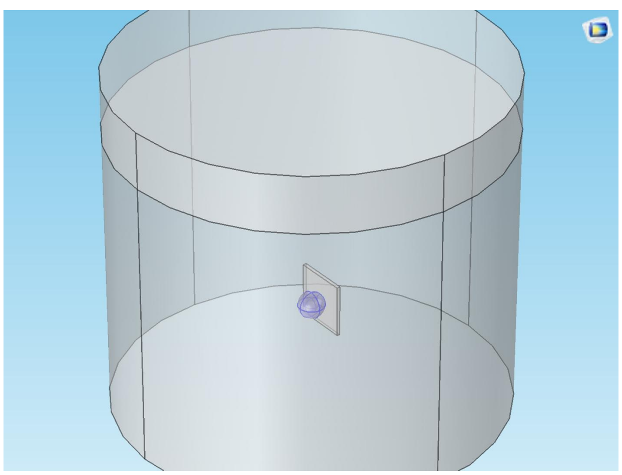

Figure 1: Model Setup

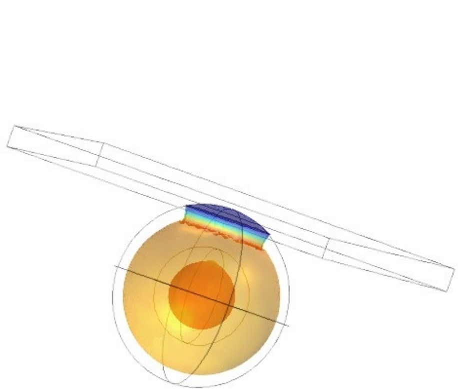

Figure 2: Model of cell attached to an oblique plane (45°). (Left) Cell at anti-node in 5 MHz field.

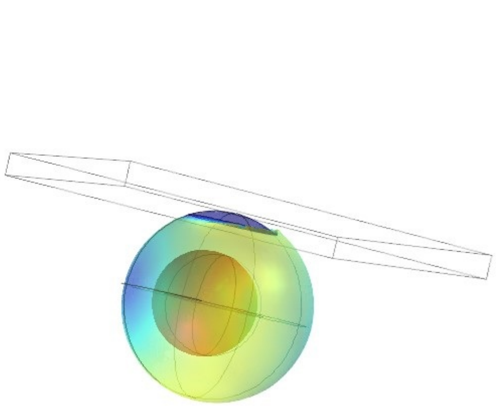

Figure 3: Model of cell attached to an oblique plane (45°). (Right) Cell at node in 8 MHz field

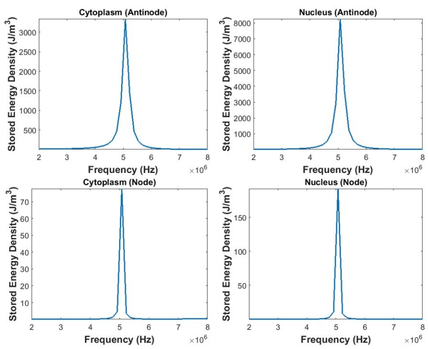

Figure 4: Total mechanical energy density in the cytoplasm (left) and nucleus (right) for cells attached to a vertical plane. The top panels present cells located at a pressure anti-node; results for cells at a pressure node are shown in the bottom panels.