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► **To cite this version:**

Lucille Allegre, Corinne Mahfouz, Rémy Gauthier, Elsa Vennat, Sophie Le Cann, et al.. Ultrasound stimulation of bone cells: 3D finite-element model of acoustic streaming around osteocytes. 12th European Solid Mechanics Conference, Jul 2025, Lyon, France. <hal-05345982>

HAL Id: hal-05345982

<https://hal.science/hal-05345982v1>

Submitted on 4 Nov 2025

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Ultrasound stimulation of bone cells: 3D finite-element model of acoustic streaming around osteocytes.

Lucille Allegre^{*1}, Corinne Mahfouz^{2,3}, Rémy Gauthier⁴, Elsa Vennat⁵, Sophie Le Cann⁶,
Carine Guivier⁷, and Cécile Baron^{*8}

¹Institut de Recherche sur les Phénomènes Hors Equilibre – Aix-Marseille Université - AMU, CNRS,
Centrale Méditerranée – France

²Laboratoire Modélisation et Simulation Multi-Echelle – CNRS, Université Paris-Est Créteil (UPEC),
Université Gustave Eiffel – France

³Laboratoire de Mécanique Paris-Saclay – Université Paris Saclay, ENS Paris Saclay, Centrale Supélec,
CNRS – France

⁴Matériaux, ingénierie et science [Villeurbanne] – Université de Lyon, INSA de Lyon, Laboratoire
MATEIS CNRS UMR 5510 – France

⁵Laboratoire de Mécanique Paris-Saclay – Université Paris-Saclay, ENS Paris-Saclay, CNRS, Centrale
Supélec – France

⁶Modélisation et Simulation Multi Echelle – CNRS : UMR8208, Université Paris-Est Créteil (UPEC),
Université Gustave Eiffel – France

⁷Institut de Recherche sur les Phénomènes Hors Equilibre – Aix-Marseille Université - AMU, CNRS,
Centrale Méditerranée – France

⁸Institut de Recherche sur les Phénomènes Hors Equilibre – Aix-Marseille Université - AMU, CNRS,
Centrale Méditerranée – France

Abstract

Introduction

Ultrasound (US) stimulation of bone remodeling remains an open question as the underlying mechanisms involved are still poorly understood. Among the possible hypotheses, the propagation of ultrasonic waves (US) in bone tissue could generate acoustic streaming (AS) resulting in fluid shear stress exerted on the wall of osteocytes known as the mechanosensitive conductors of bone remodeling. Osteocytes are dendritic cells surrounded by a viscous pericellular fluid (PCF), ubiquitous in the bone extra-cellular matrix (ECM) forming a complex micrometric 3D network called the lacuno-canalicular network (LCN).

This paper investigates the interaction of US with the osteocyte dendrite (OD) confined in a canaliculus, as it is considered as the most mechanosensitive part of the cell. The aim is to explore the relevance of taking into account the irregular 3D shapes of the canaliculus and dendrite in terms of mechanical solicitations induced by US stimulation.

Material & Methods

*Speaker

From images (FIB-SEM imaging "slice and view" in BSE mode (Gianuzzi 2004), FEI Helios NanoLab 660, pixel size $16.78 \times 16.78 \times 20$ nm³), a realistic 3D geometry of a canaliculus of rabbit cortical bone is reconstructed and implemented in the Finite-Element software Comsol Multiphysics (v. 6.2). The geometry of the dendrite inside the canaliculus (not accessible by imaging) is deduced from the canaliculus wall geometry.

The acoustic properties of the cell dendrite and of the PCF are similar to those of water, except that the viscosity of the PCF is supposed to be 10 times higher than water dynamic viscosity ($\mu_{\text{water}}=0.65 \cdot 10^{-3}$ Pa.s).

To mimic the US stimulation of bone cells inside the LCN, a first order oscillating velocity \mathbf{U}_1 is imposed along the ECM/PCF interface under the form of a harmonic acoustic wave at frequency f of 1 MHz with an amplitude of displacement d_0 propagating in the US propagation direction: $\mathbf{U}_1(f) = i2\pi f d_0 \mathbf{e}_x$.

The acoustic streaming is a second-order (non-linear) acoustic effect which results in a steady flow. In order to investigate the acoustic streaming induced by US stimulation inside the PCF, we need to solve the second-order Navier-Stokes equations obtained by the perturbation method.

In Comsol Multiphysics, the Thermoviscous Acoustics module (in frequency domain) is used to resolve the first order acoustic field which provides the source term for the second order equation implemented in the Laminar Flow module.

From the acoustic streaming velocity (time-averaged second-order term) thus obtained, the resulting wall shear stress (WSS) applied at the PCF/process interface is calculated.

Results & Discussion

The WSS is plotted along the interface PCF/OD. The values are compared to those obtained for idealized 3D-geometries (annular tube) deduced from the realistic one and to the results obtained in 2D cross-sections as previously presented in (Baron 2023).

We investigate how canaliculus and dendrite geometries could have an influence on the US-induced PCF flow. Finally, the quantification of the WSS induced by acoustic streaming is questioned in regard of stress levels that can trigger a biological response (Weinbaum 1994).

Keywords: acoustic streaming; wall shear stress, osteocyte; mechanotransduction; FE model; FIB-SEM.

Acknowledgements: This work was supported by the French National Research Agency, ANR-23-CE51-0018 and ANR-22-CE51-0038.

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