A numerical model to investigate action of LIPUS on bone healing

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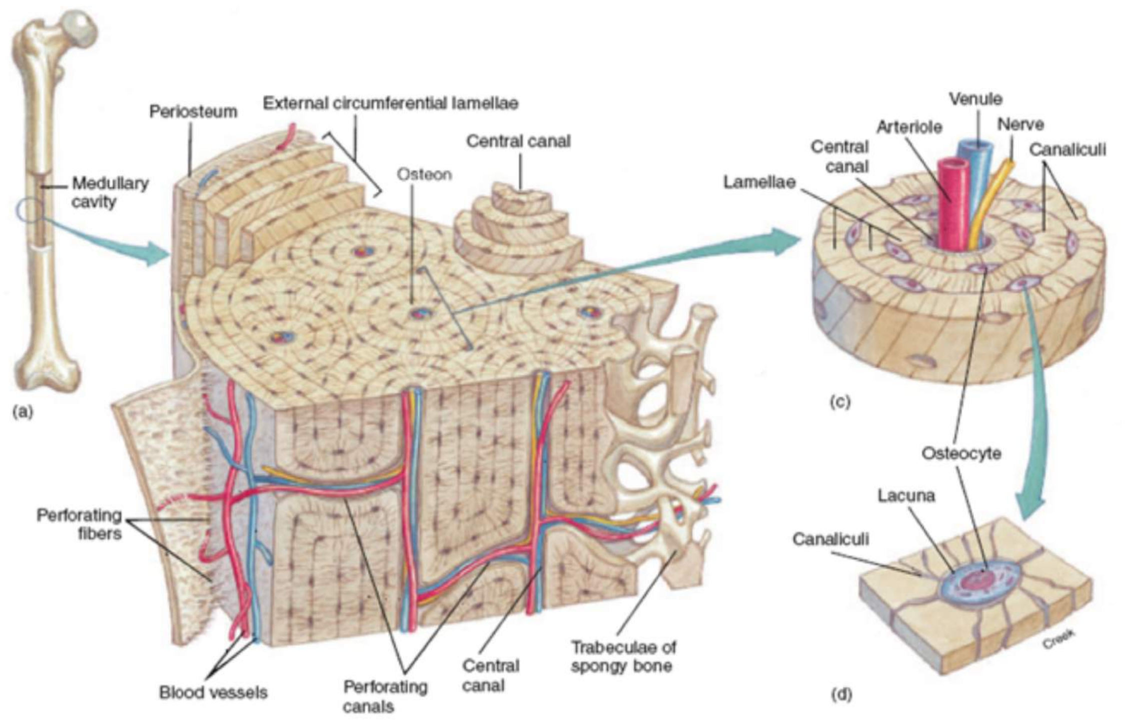
Background

Bone

- Living tissue able to adapt to mechanical environment
  => mechanosensors = osteocytes
- Double porosity = vascular and lacuno-canalicular porosities

Healing with Ultrasound (US) Stimulation

- LIPUS: Low Intensity Pulsed Ultrasound Stimulation
- US stimulation known since 1950's (Corradi & Cozzolino 1953)
- FDA approval for bone healing since 1994
- Mechanical and not thermal effects

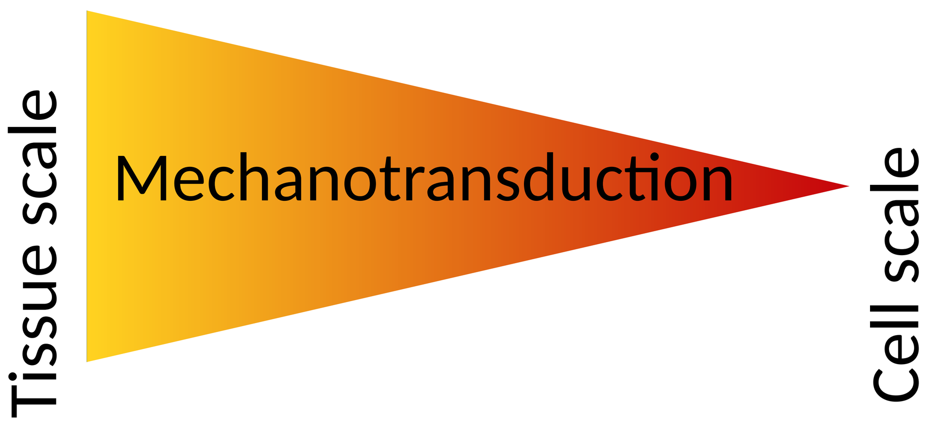


HOW can US heal bone? Still an open question

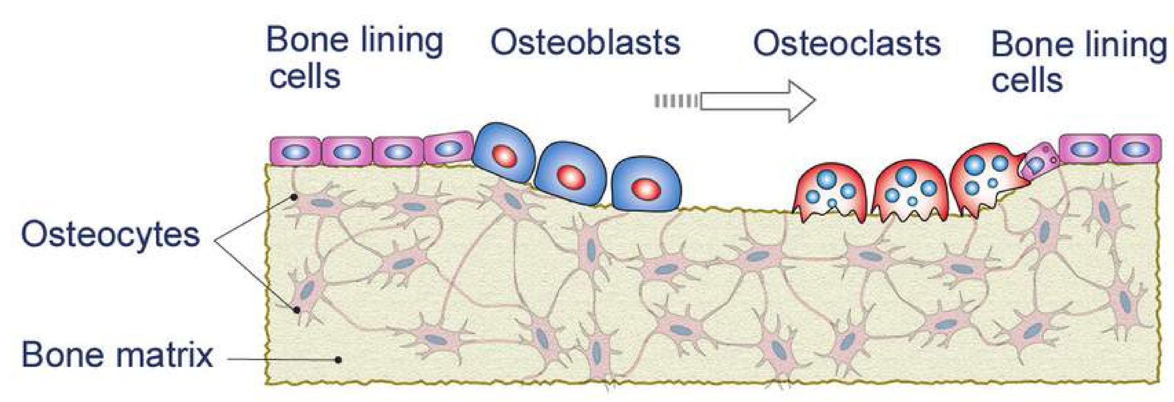
(Padilla et al. 2016)

Osteocytes immersed in lacuno-canalicular network

US Stimulation



Bone remodeling



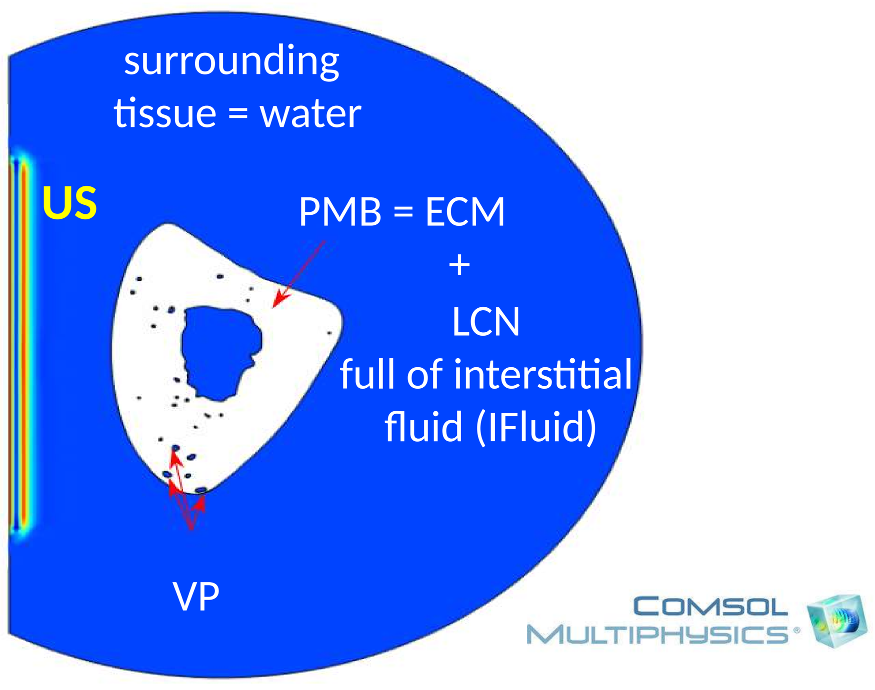
Multiphysics numerical model to understand

Methods: 2D finite element model

Cortical bone = Biphasic medium:

Fluid in VP (water) | PBM = ECM+LCN

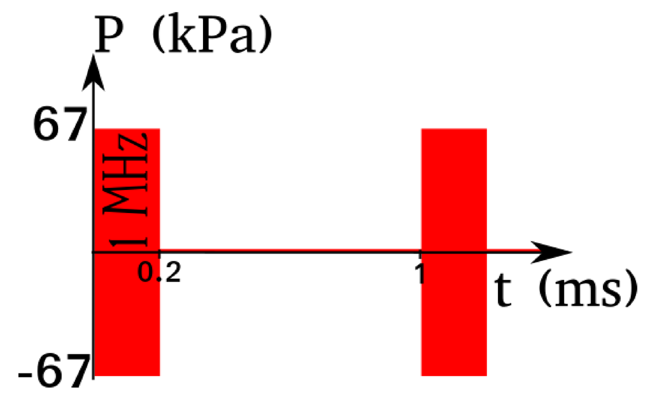
VP: Vascular porosity
PBM: Poroelastic bone matrix
ECM: Extra cellular matrix (ECM)
LCN: Lacuno-canalicular network



Acoustics, fluid and solid mechanics

US stimulation

frequency = 1MHz,
pressure = 67kPa,
duty cycle = 20%,
pulse duration = 1ms
∅transducer = 20mm

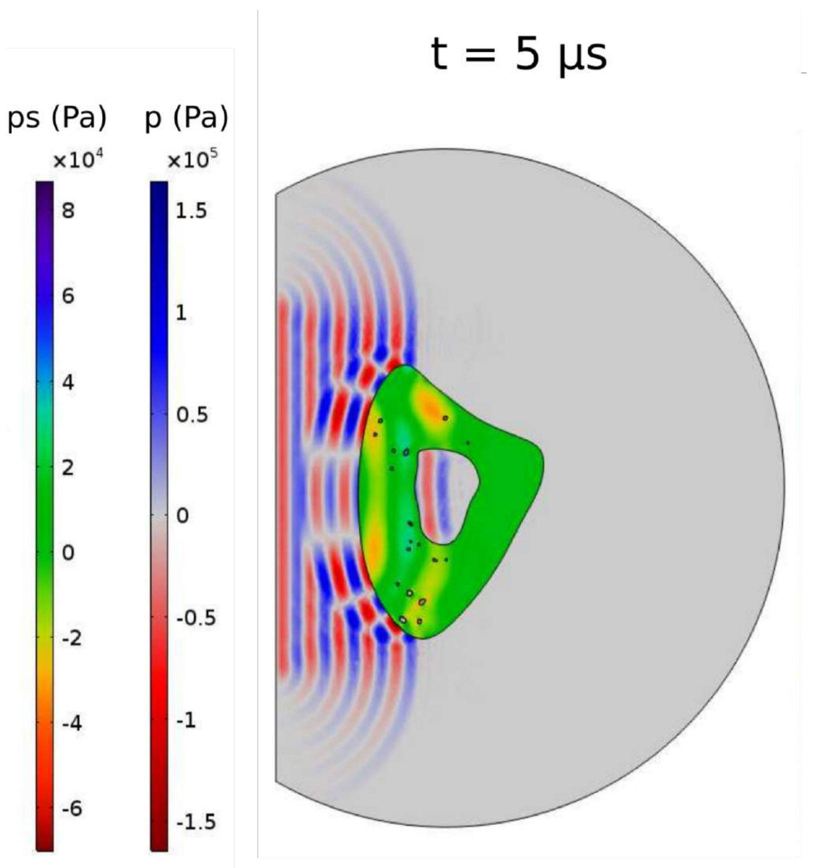


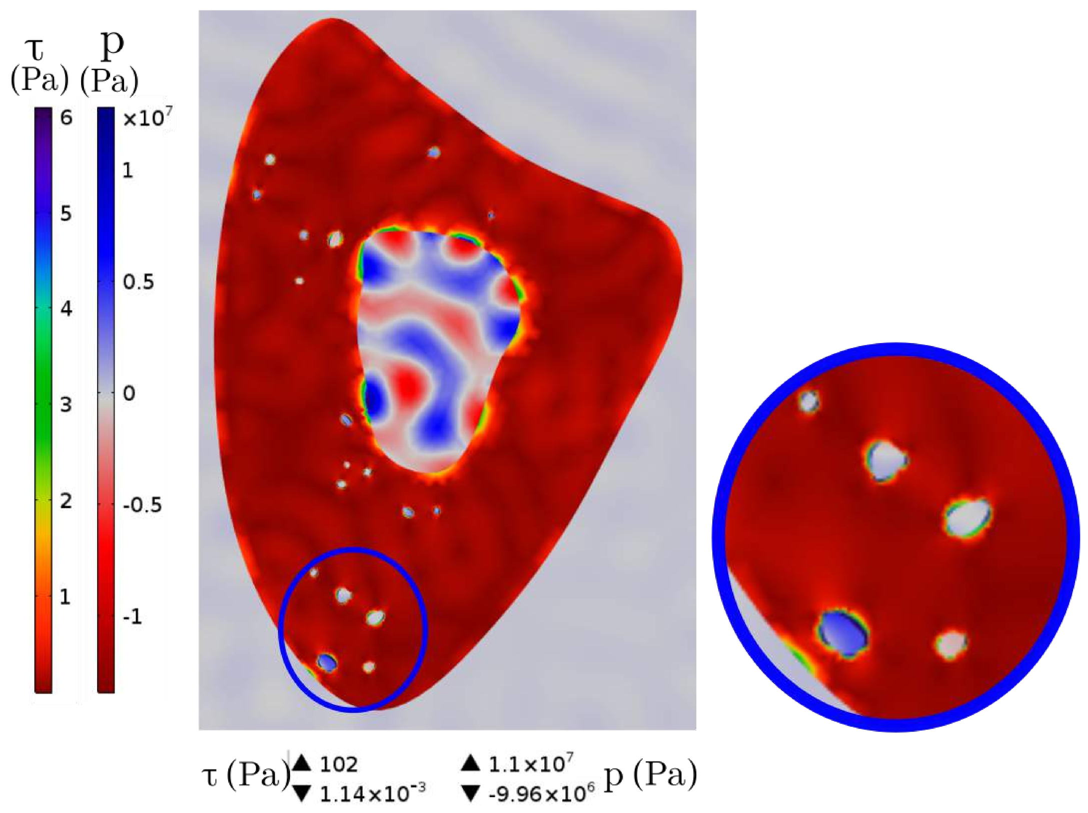
Simulation parameters

Time dependent problem: weak form of wave equation in poroelastic medium (Nguyen et al. 2010), $\Delta x=\lambda/5$, $\Delta t=0.1\mu s$

Results and Discussion

Hypothesis: mechanical stimulus at cell scale = fluid shear stress τ

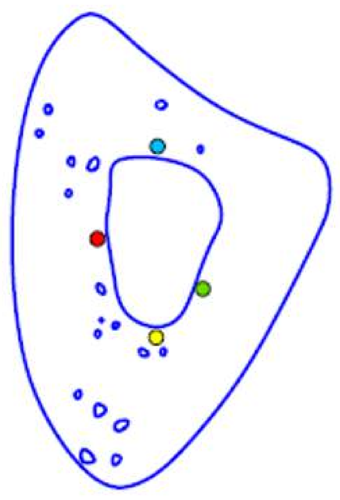


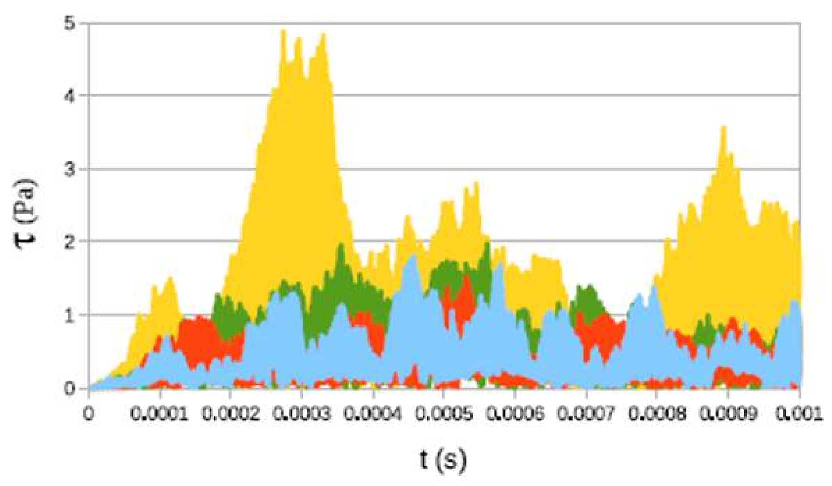


$$\tau = \frac{\mu \|\dot{w}\|}{\sqrt{k}}$$

τ : wall shear stress (Pa)
μ : dynamic IFluid viscosity (Pa.s)
$\dot{w}$: IFluid velocity relative to the solid (m/s)
k : LCN permeability (m^2)

(Goulet et al. 2008)



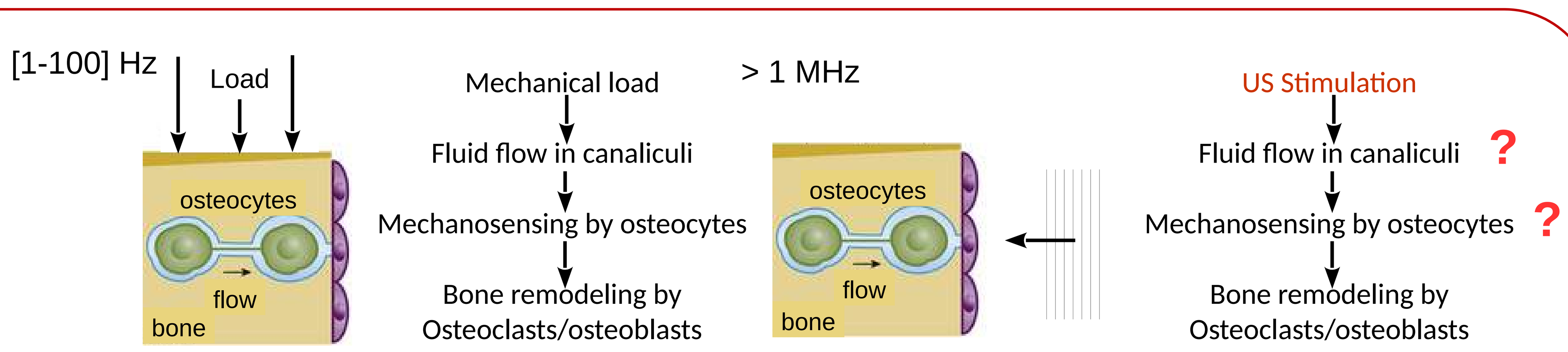


Average IFluid shear stress : [] Pa
Prediction interval for osteocytes response to τ : [0.3 – 8] Pa
BUT for physiological loading

(Weinbaum et al. 1994)

Conclusion and Perspectives

- Appropriate shear threshold ?
  → physiological loading ≠ US stimulation
- VP = water or poroelastic medium
- Influence of healing tissues
- Relaxation time LCN (1 ms) vs VP (1 µs)
- Combined phenomena: piezoelectricity, microstreaming, drag forces, strain amplification



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Weinbaum et al. (1994) Journal of Biomechanics, 27, 339-360

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