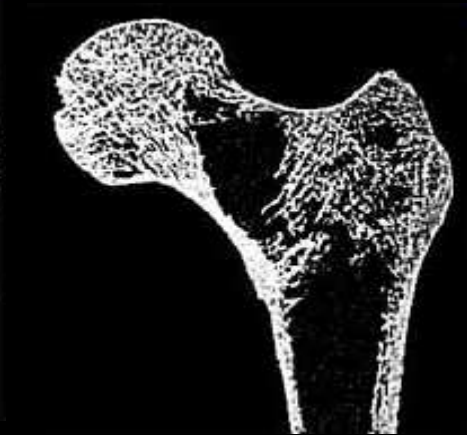


Caractérisation ultrasonore de l'os spongieux : analyse critique d'une modélisation de Biot

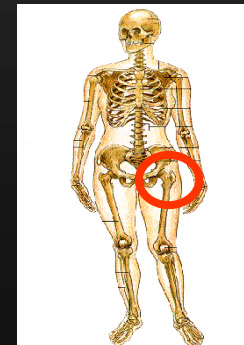
Laboratoire d'Imagerie Paramétrique
Université Pierre et Marie Curie – CNRS, Paris, France

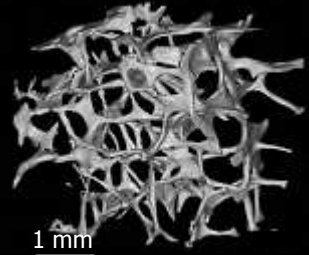
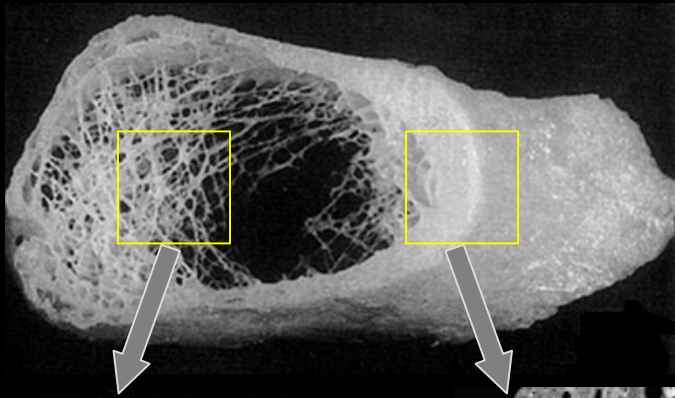
Outline

- Context
- The biot approach : pros
- The biot approach : cons
- Conclusion

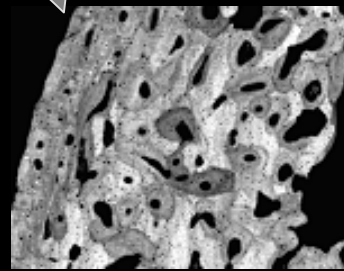


Osteoporosis



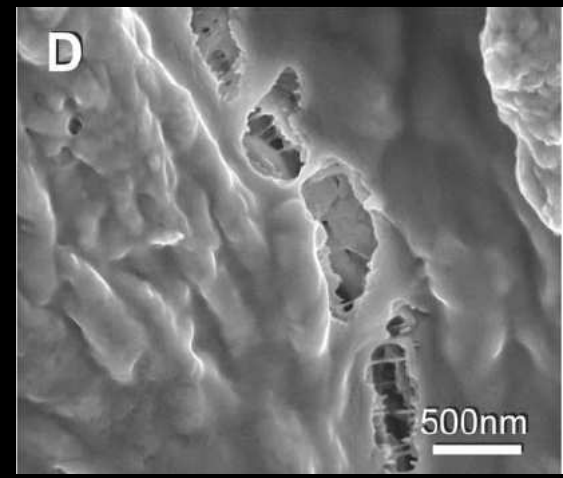


Os spongieux



Os cortical

Microfissures



Cancellous (spongy) bone: characteristics

Inner part of short bones and distal part of long bones

Heterogeneity & anisotropy

High porosity :

75-90%

Typical trabecular thickness :

50-150 μm

Pores size:

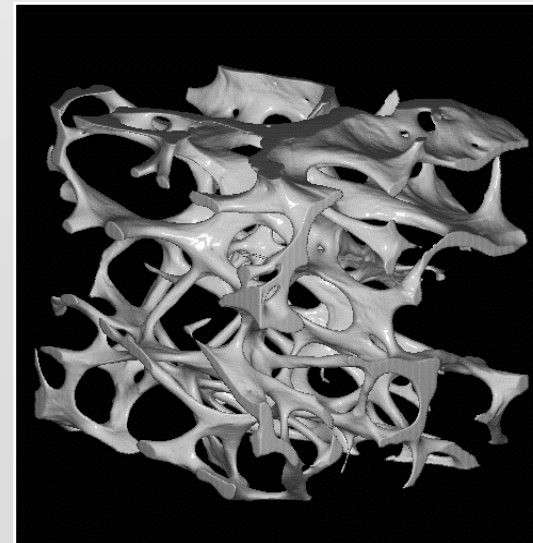
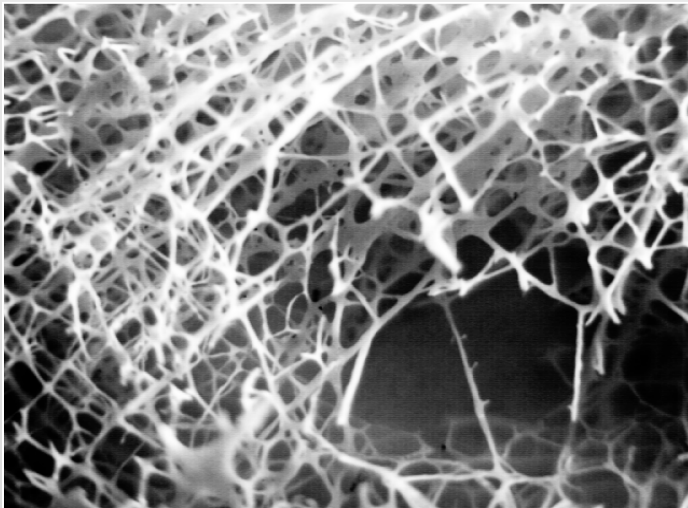
0.2-1.5 mm

Ultrasonic frequency

0.5 – 1.0 MHz

Wavelength

1.5 – 3.0 mm



6 mm

Biot's theory

- Biot proposed a phenomenological theory for wave propagation in fluid-saturated porous material which are macroscopically homogeneous and isotropic.
- Biot's theory predicts two bulk compressional waves and one shear wave
- However, the validity of Biot approach for bone is questioned by recent experimental and numerical results

Biot's approach : poroelastic medium, inertial, elastic and viscous coupling

Dispersion equations

longitudinal waves: $k^4 A_1 - k^2 \omega^2 A_2 + \omega^4 A_3 = 0$

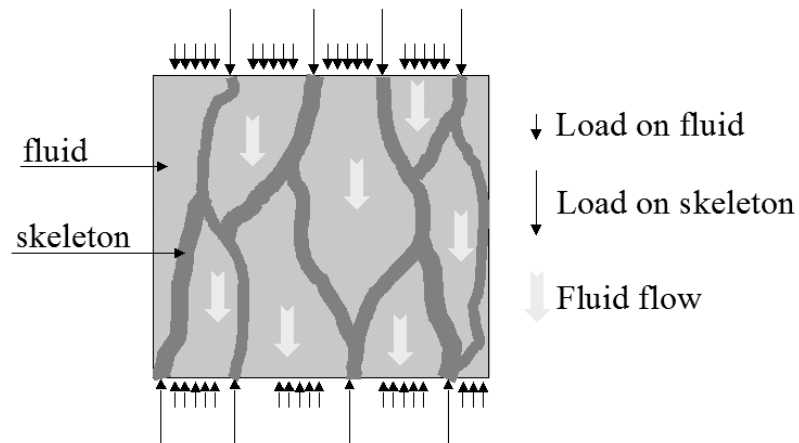
shear waves: $k^2 A_4 - \omega^2 A_3 = 0$

$$A_1 = (2N + A)R - Q^2 ,$$

$$A_2 = (2N + A + R + 2Q)(c - \frac{i}{\omega}b) + \rho^s R + \rho^f (2N + A)$$

$$A_3 = \rho^s \rho^f + (\rho^s + \rho^f)(c - \frac{i}{\omega}b)$$

$$A_4 = N[\rho^f + c - \frac{i}{\omega}(\rho^s + \rho^f)b]$$



Biot's approach : poroelastic medium, inertial, elastic and viscous coupling

Dispersion equations

longitudinal waves: $k^4 A_1 - k^2 \omega^2 A_2 + \omega^4 A_3 = 0$

shear waves: $k^2 A_4 - \omega^2 A_3 = 0$

$$A_1 = (2N + A)R - Q^2$$

$$A_2 = (2N + A + R + 2Q)(c - \frac{i}{\omega}b) + \rho^s R + \rho^f (2N + A)$$

$$A_3 = \rho^s \rho^f + (\rho^s + \rho^f)(c - \frac{i}{\omega}b)$$

$$A_4 = N[\rho^f + c - \frac{i}{\omega}(\rho^s + \rho^f)b]$$

A, Q, R generalized elastic Biot-Willis constants
 N shear modulus of the skeletal frame

$$A = \frac{(1-\phi)(1-\phi - \frac{K_b}{K_s})K_s + \phi \frac{K_s}{K_f} K_b}{1-\phi - \frac{K_b}{K_s} + \phi \frac{K_s}{K_f}} - \frac{2}{3}N$$

$$Q = \frac{\phi(1-\phi - \frac{K_b}{K_s})K_s}{1-\phi - \frac{K_b}{K_s} + \phi \frac{K_s}{K_f}}, \quad R = \frac{\phi^2 K_s}{1-\phi - \frac{K_b}{K_s} + \phi \frac{K_s}{K_f}}$$

ϕ : Porosity

K_b, K_s, K_f : bulk moduli of the frame, solid and fluid

$$b = \frac{\eta}{\kappa} \phi^2, \quad c = \rho^f (\alpha - 1)$$

η : fluid viscosity

κ : permeability

α : tortuosity

$$\rho^s, \rho^f \quad \text{solid and fluid density}$$

The Biot model applied to US propagation through cancellous bone

- Williams JASA, 1991
- Hosokawa and Otani JASA 1997, 1998
- Luppe et al. JASA 2002;
- Lee et al. JASA 2003;
- Fella, JASA 2004
- Otani, Jap J Applied Phys 2009

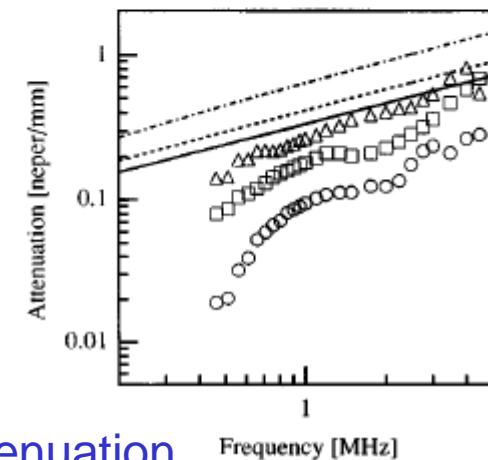
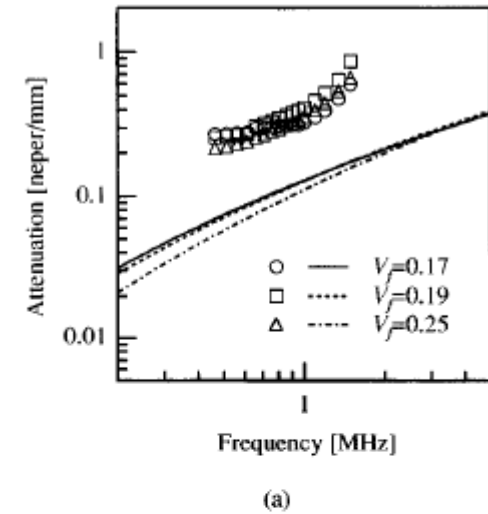
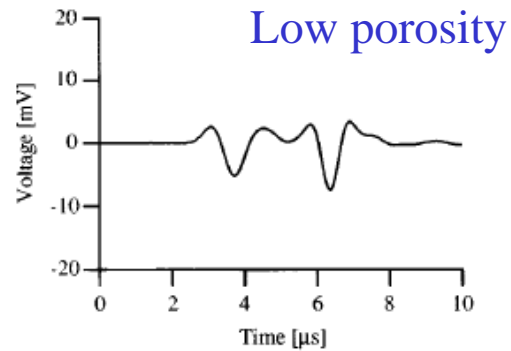
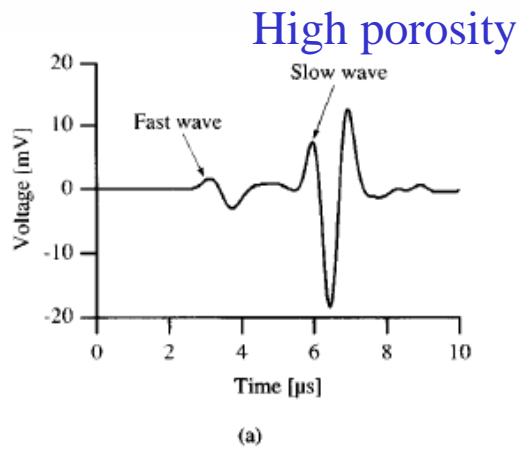
Two compression waves are
observed as predicted by Biot
theory of poroelasticity

Ultrasonic wave propagation in bovine cancellous bone

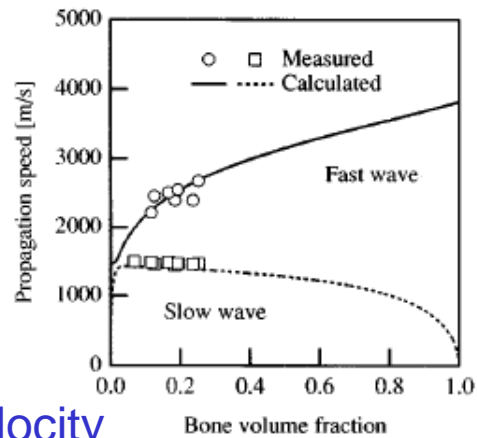
A. Hosokawa and T. Otani

Department of Electrical Engineering, Faculty of Engineering, Doshisha University, Tanabe-cho, 610-03 Kyoto-fu, Japan

(Received 1 September 1995; accepted for publication 29 August 1996)



Attenuation



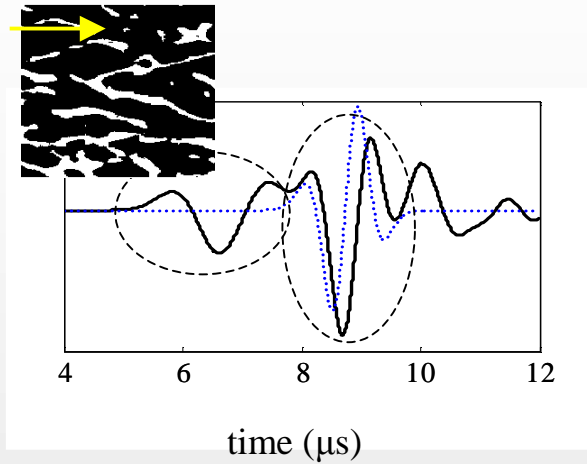
Velocity

Assumption

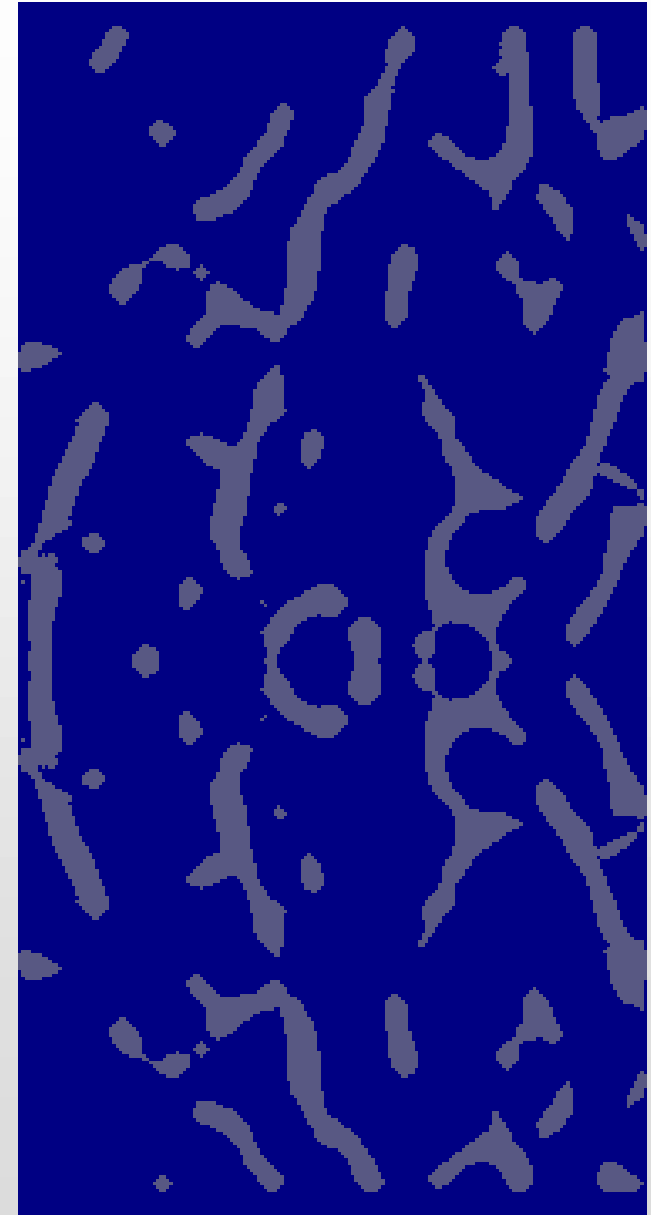
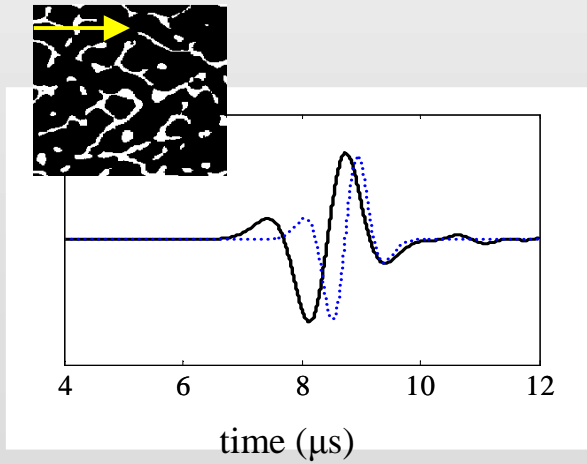
$$K_b = \frac{E_s}{3(1-2\nu_b)} (1-\phi)^n$$

$$N = \frac{E_s}{2(1+2\nu_b)} (1-\phi)^n$$

Numerical Simulation (FDTD)



- Fast and slow waves



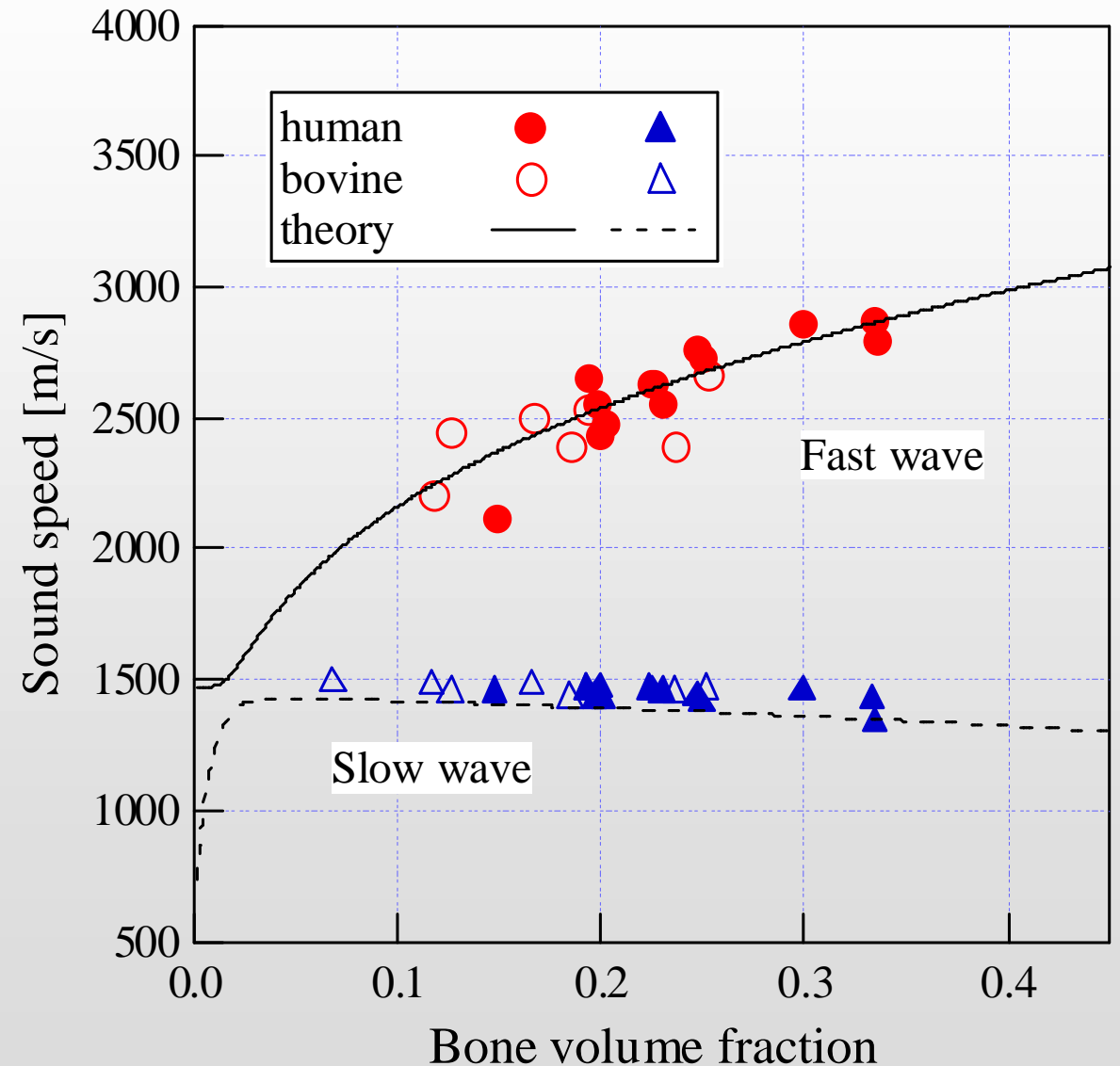
Outline

- Context
- **The biot approach : pros**
- The biot approach : cons
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The Biot approach : pros and cons

- Pros

Good agreement with Biot prediction of the wave speed



Building on this success, solutions
to the inverse problem have been
investigated

Inverse problem based on Biot model

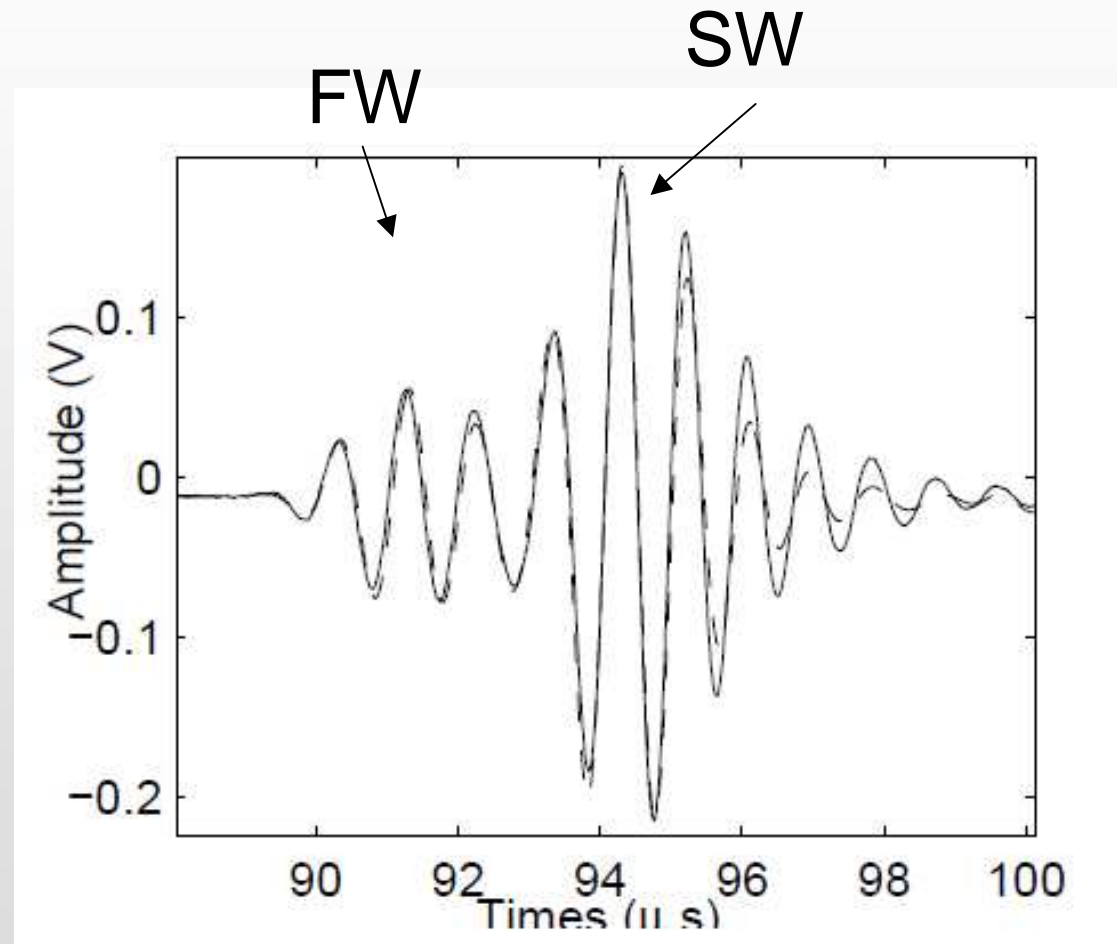
- Sebaa et al. (IEEE UFFC, 2008) proposed a solution to the inverse problem and retrieved 5 parameters using a classical minimization approach:
 - Modulus E_b and Poisson's ratio ν_b of the skeletal frame
 - Porosity ϕ , tortuosity α and viscous characteristic length Λ

(A priori knowledge of the characteristics of bone tissue and saturating fluid)

The Biot approach : pros and cons

- Pros : Good agreement with Biot prediction of the waveform

Porosity
permeability
Tortuosity
Viscous characteristic length
Young's modulus of tissue
Shear modulus
Tissue density
Young's modulus of skeletal frame
Poisson's ratio of skeletal frame
Fluid viscosity
Fluid density
Fluid bulk modulus



Outline

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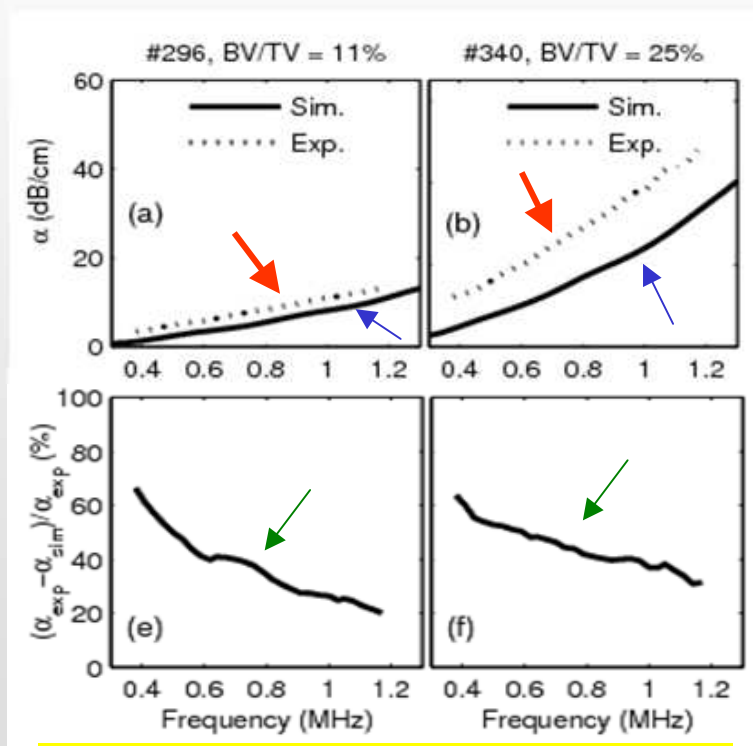
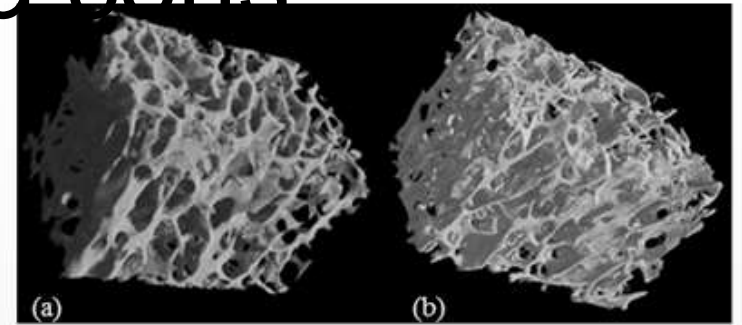
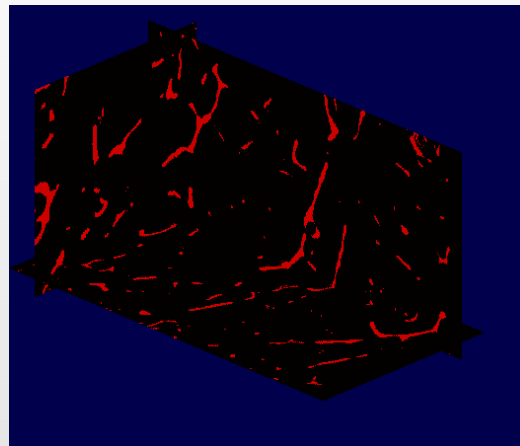
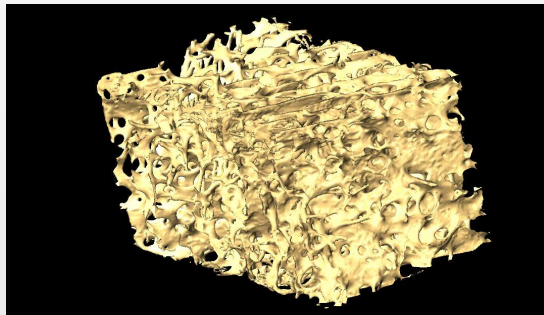
Biot theory does not succeed to
predict attenuation.

Attenuation cannot simply be
explained by absorption.

The Biot approach : pros and cons

- cons

Importance of scattering



The relative contribution of scattering to total attenuation increases with frequency, becoming predominant (>50%) over absorption for frequencies above 500 kHz

$$\alpha_{total} = \alpha_{absorption} + \alpha_{scattering}$$

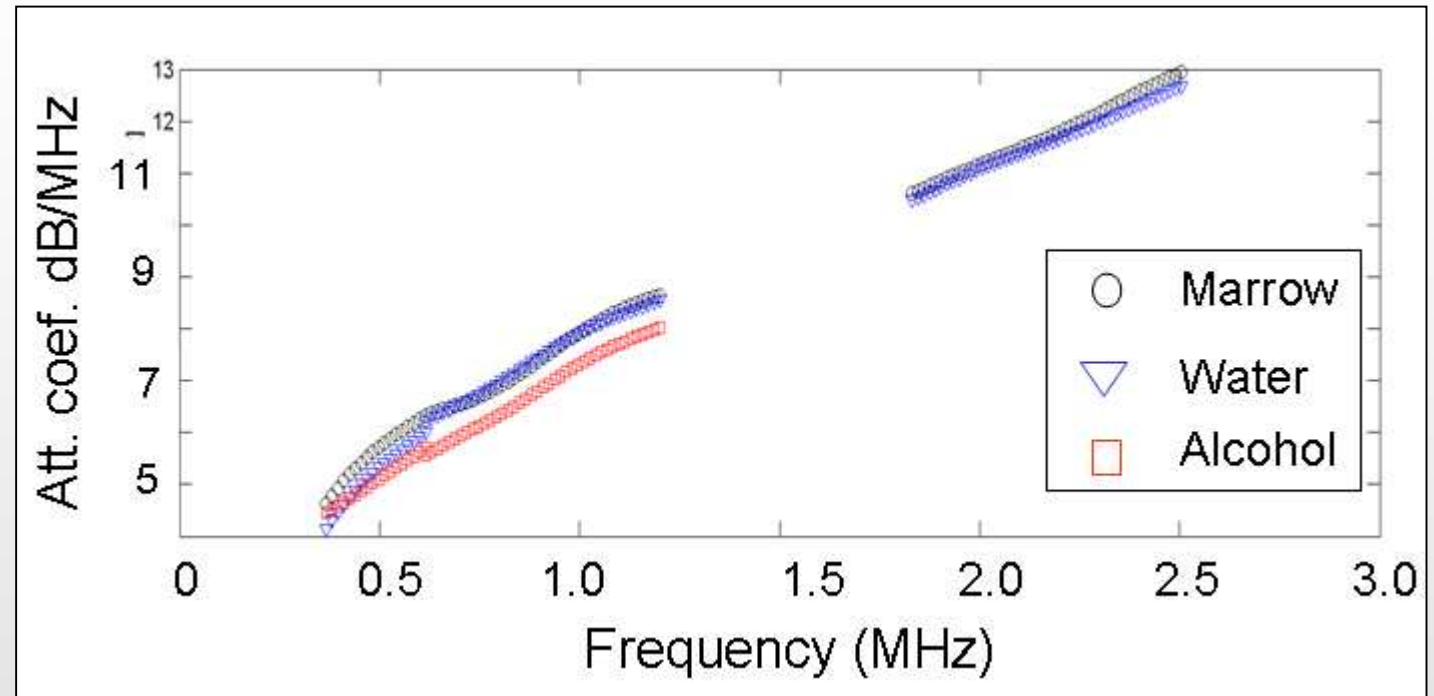
Experimental

Predicted by FDTD

Total attenuation is not influenced by the filling fluid

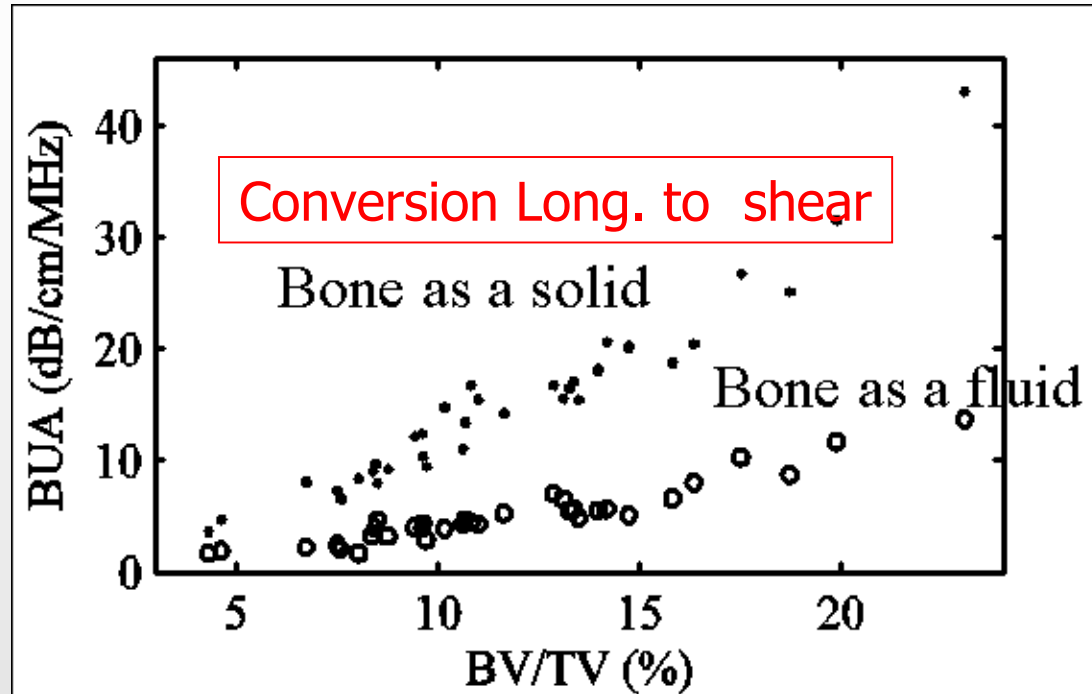
No influence of the viscosity of the fluid (marrow $\eta_{\text{marrow}}=1500$ vs. water $\eta_{\text{water}}=0.89$)

No influence of the bulk compression modulus of the fluid (alcohol 1.56GPa vs. water 2.25GPa)



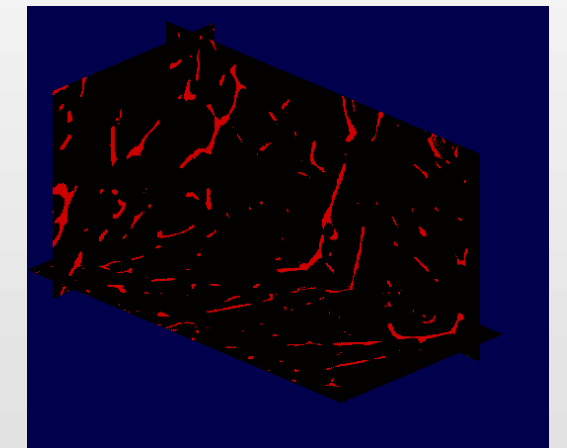
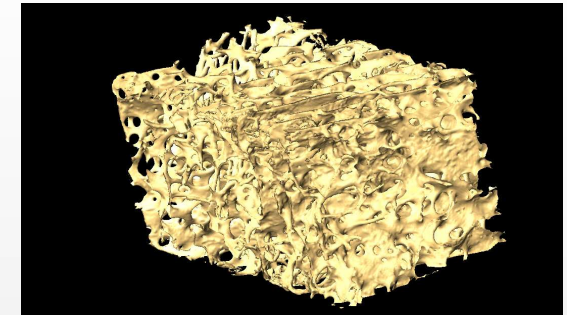
$$\alpha_{total} = \alpha_{fluid} + \alpha_{friction} + \alpha_{solid L} + \alpha_{solid S} + \alpha_{scattering L \rightarrow L} + \alpha_{conversion L \rightarrow S}$$

Importance of L-S scattering to explain total attenuation



No shear

FDTD simulation



$$\alpha_{total} = \alpha_{fluid} + \alpha_{friction\ f/s} + \alpha_{solid\ L} + \alpha_{solid\ S} + \alpha_{scattering\ L \rightarrow L} + \alpha_{scattering\ L \rightarrow S}$$

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Conclusion

Forward problem

- Existence of two waves as predicted by Biot theory
- Relative good agreement with wave speed
- Attenuation cannot be explained in the framework of Biot theory
- Compelling evidences that
 - fluid viscosity does not play a role
 - L-S conversion is an important mechanism for attenuation
- Is Biot theory accurate to model propagation in cancellous bone?
- Alternative approaches need to be developed, like, e.g.
 - scattering models taking into account LS scattering

Acknowledgement

- Frédéric Padilla
- Emmanuel Bossy
- Michal Pakula