Characterization of shear wave propagation using Magnetic Resonance Elastography (MRE) and Finite Element Modelling (FEM)

[1]Gwladys E. Leclerc, [1]Laëtitia Debernard, [1]Sabine F. Bensamoun and [1]Marie-Christine Ho Ba Tho
[1]UMR CNRS 6600, Laboratoire BioMécanique et BioIngénierie, Université de Technologie de Compiègne, France

Introduction

Elastic [1] and viscoelastic [2] properties of phantoms (bovine gel, agarose gel) are characterized with MRE technique, allowing to achieve in vivo MRE experimental parameters.

Finite element models simulate MRE experiments in order to analyze the impact of the applied experimental parameters on the mechanical properties [1].

Combining experimental tests and numerical models allows for the identification of the mechanical behavior of the biological tissue.

Purpose

To develop a phantom mimicking mechanical properties of the biological soft tissues

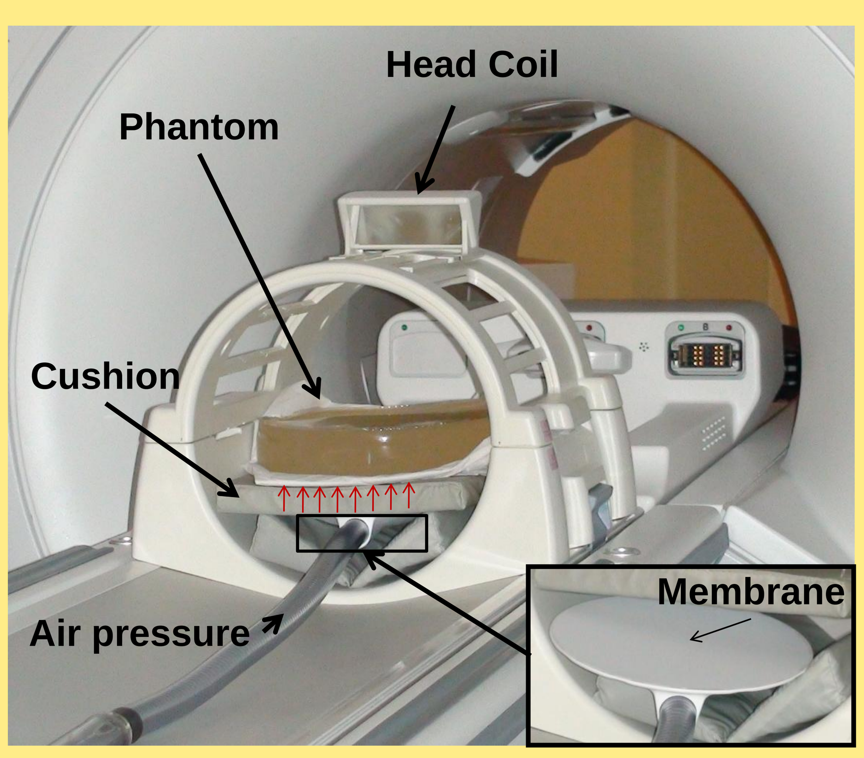
To simulate the propagation of the shear waves obtained experimentally with MRE technique

Materials & Methods

Magnetic Resonance Elastography (MRE)

A cylindrical phantom (D: 25cm, thickness : 5cm) composed of 55% liquid plastic and 45% softener solution

The phantom is placed inside a 1.5T MRI machine (GE, SignaHDx) :



- Gradient echo sequence
- FOV: 30 x 30 cm
- Matrix: 256 x 64
- Frequencies (f): 60 Hz, 70 Hz, 80 Hz
- TR: 50 ms, 43 ms, 38 ms
- TE: minimum full

MRE phase images show the shear wave propagation inside the phantom.

Elastic properties:

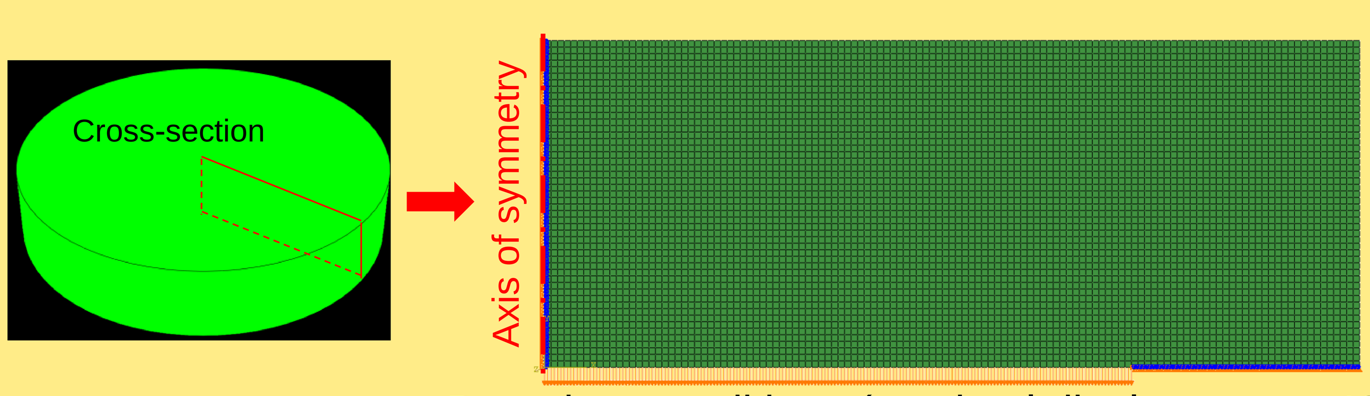
Shear stiffness: $\mu_{MRE} = \rho.(\lambda.f)^2$ (ρ=1000 kg/m³ and λ the wavelength)

Viscoelastic properties:

Shear stiffness (μ) and **viscosity** (η) are determined using different rheological models: Voigt, Maxwell and Zener [2]. A mean squared method is used with MATLAB R2008b.

Finite Element Modelling (FEM)

To simulate the propagation of the shear waves, a 2D rectangular model (12.5 x 5 cm) is generated with the software ABAQUS 6.9-1 Standard, representing a cross section of the cylindrical phantom. Mesh is composed with elements (CPS4) of 1 mm.



Boundary conditions (maximal displacement: 40 µm)

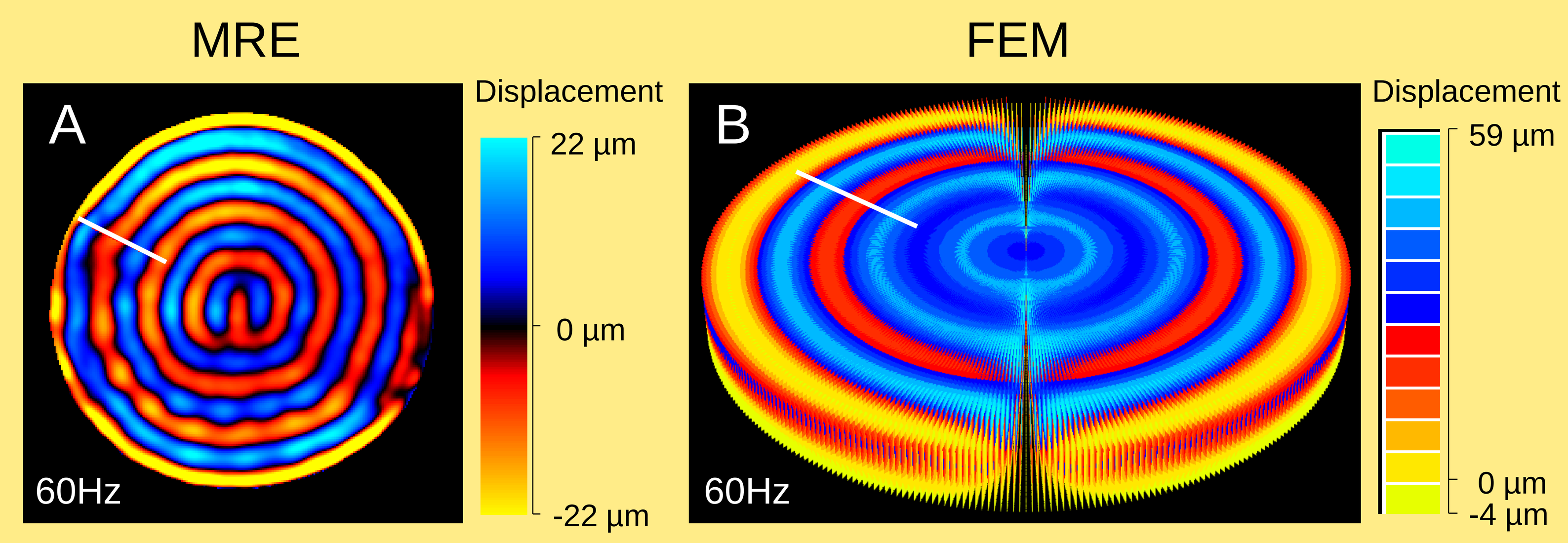
Sinusoidal motion is generated at the experimental frequency (60 Hz).

Elastic properties:

Shear stiffness (μ_{FEM}) is determined with an identification process used to determine the elastic properties by comparing the experimental (λ_{MRE}) and numerical (λ_{FEM}) wavelengths.

Assumptions: isotropic, homogeneous, linear elastic and quasi incompressible (ν = 0.499) media

Results



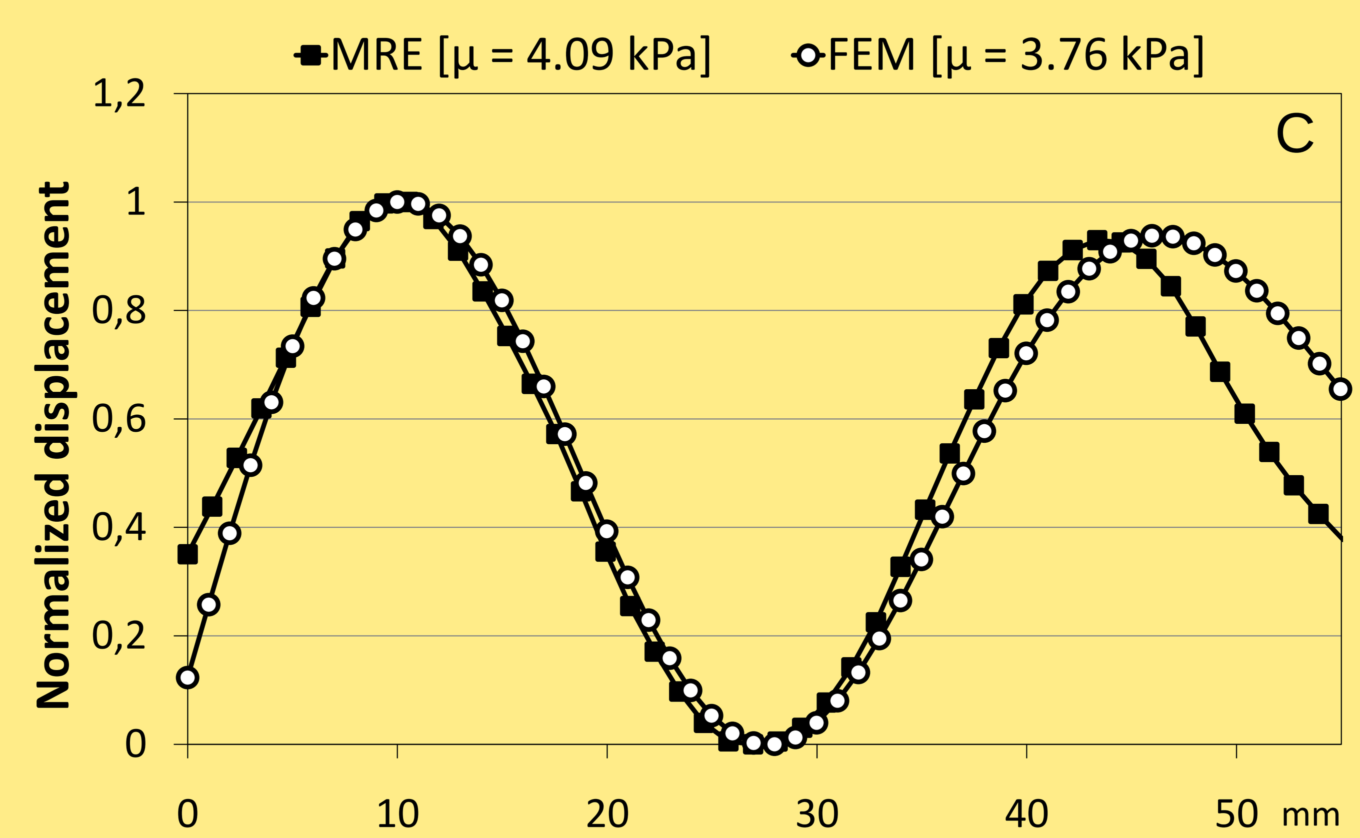
MRE tests show a clear propagation of the shear waves inside the phantom (A) with an increase of the shear stiffness in function of the frequency, reflecting the viscoelastic behavior of the phantom (Table).

At 60 Hz the experimental shear stiffness value (4.09 kPa) is similar as in vivo MRE study performed on soft tissue (liver) [3].

Shear stiffness (μ) and viscosity (η) are obtained with rheological and FE models performed on the phantom:

MRE Elastic case	Voigt	Maxwell	Zener	FEM Elastic case
μ_{60Hz} = 4.09 kPa μ_{70Hz} = 4.14 kPa μ_{80Hz} = 4.27 kPa	μ = 3.85 kPa η = 2.84 Pa.s	μ = 4.48 kPa η = 17.79 Pa.s	μ_1 = 3.82 kPa μ_2 = 3.38 kPa η = 1.97 Pa.s	μ_{60Hz} = 3.76 kPa

Maxwell model showed a higher viscosity (about 15 Pa.s) and shear stiffness (about 1 kPa) compared to Voigt and Zener models, due to its property to reflect the fluid component.



The comparison between the experimental and numerical wavelengths (B,C) reveals similar shear stiffness at 60 Hz (μ_{MRE} = 4.09 kPa vs. μ_{FEM} = 3.76 kPa). The identification method showed a 3.86% of error between both wavelengths.

Conclusion

The Finite Element model, composed of realistic MRE boundary conditions, simulates the elastic behavior of the phantom developed to mimic the mechanical properties of the biological soft tissues.

Acknowledgments

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References

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