Wave Transmission in a Three-dimensional Nonhomogeneous Viscoelastic Brain Model

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Introduction

Bone conduction refers to the response of the skull bones against audio and higher frequency mechanical stimuli: it is the process by which a signal vibrates the skull bones and stimulates the cochlea in the inner ear, where mechanical vibrations are converted into neural impulses through the receptor cells[1]. Skull vibration can be caused by both acoustic and mechanical head stimulation as investigated in acoustics and biomechanics. Compared to air conduction, bone conduction becomes the first way of sound transmission in case of problems with outer or middle ear and deafness in one side[1]. Both bone and air conduction sound thresholds are evaluated performing audiometric tests, with the purpose to establish an individual's range of hearing. Air conduction audiometry detects middle-ear or conduction deafness, while bone conduction gives evidence of neurosensory hearing loss[2]. In addition, bone conduction implantable hearing aids could improve deaf people quality of life, partly solving aesthetic and functional problems caused by common hearing aids, in which electronic components (microphone and speech processor) are put on the skin surface. In order to better understand this phenomenon it is important to characterize the biomechanical properties and responses of the whole head system (skull bones, brain tissue and all others anatomical structures) in a variety of loading conditions. To appreciate the effects of bone-brain coupling, in this study we put our attention on the longitudinal propagation of mechanical waves (e.g. sound and ultrasound) in a cylindrical layered geometry mimicking isotropic, heterogeneous and viscoelastic bone and brain tissues. The aim of our study is an investigation of the dynamics of head vibrations frequencies according to the position of the vibrator and the signal amplitude, finalized to the study of implantable hearing devices.

Materials and methods

In this study both skull bones and brain were modeled as composite media, the former made up of cortical and cancellous bones[3], the latter made up of grey matter (GM), white matter (WM) and cerebrospinal fluid (CSF)[4]. Isotropic but heterogeneous properties have been considered, other than viscoelastic behavior, responsible for energy dissipation during wave transmission. Assuming small displacement and small strain, a correct approximation in acoustics, the equations of motion read as:

$$\rho(x_i)\frac{\partial^2 u_i(x_i,t)}{\partial t^2} = [\sigma_{ij}(x_i,t)]_{,j} + F_i \tag{1}$$

where $i,j=1,2,3$, σ_{ij} is the stress tensor, $[\sigma_{ij}]_{,j}$ its divergence, F_i is the vector of volume forces acting on the body, ρ the tissue density, u the displacement vector and "," indicates partial differentiation. In the gravitational field $F_i=\rho g_i$, where g_i is the gravity vector pointing along the z axis. More in general the stress tensor is the sum of an elastic and a viscous term[5], in our study assumed as:

$$\begin{gathered}\sigma_{ij} = \sigma^e_{ij} + \sigma^v_{ij}\\ \sigma^e_{ij} = (\lambda+\mu)\,u_{j,ij} + \mu u_{i,jj} + \lambda_{,i} u_{k,k} + \mu_{,j}(u_{i,j}+u_{j,i})\\ \sigma^v_{ij} = 2\eta\left(\frac{\partial \varepsilon_{ij}}{\partial t} - \frac{1}{3}\delta_{ij}\frac{\partial \varepsilon_{kk}}{\partial t}\right) + \zeta\frac{\partial \varepsilon_{kk}}{\partial t}\delta_{ij}.\end{gathered} \tag{2}$$

where δ_{ij} is the Kronecker delta while λ and μ are the Lamè coefficients, η and ζ are the viscosity coefficients (all dependent on the position) and ε_{ik} is the strain tensor defined as:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{3}$$

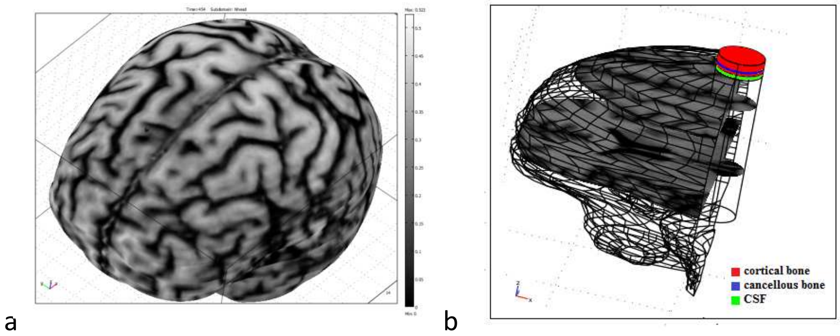

Fig1. a. Human brain tissue reconstructed from NMR images; b. Viscoelastic layered cylinder "plunged" into the human brain.

After a preliminary study on a realistic viscoelastic human brain reconstructed from NMR images, adopting ad hoc image segmentation routines in order to obtain the full interpolating function of the brain tissue and to identify the three different tissue levels (Fig.1a), we decided to focus on the effects of the bone-brain tissue coupling. Due to the complexity of the geometry and the computational load, we left the reconstruction of the whole head geometry for future work and performed preliminary simulations on a small cylindrical layered geometry (radius 10mm). The brain interpolating function was used in the part of the cylinder "plunged" into the human brain for 65mm. This was covered by a CSF layer (thickness 2mm) and an external skull layer (thickness 5mm) modeled as cancellous bone placed between two cortical bone areas (Fig.1b). Both skull and CSF layers were artificially added. Mechanical parameters are reported in Tab.1. The stimulation signal was generated in a simulation environment set up in MathWork Simulink, filtered through Matlab routines and then exported to COMSOL Multiphysics 3.5a, where the full viscoelastic FEM problem was solved. According to the experiments performed by Cai et al.[6], the stimulation was imposed as a gaussian random signal, filtered by a bandpass filter in the range 2-50kHz. Although hearing by air conduction is limited to about 20kHz, hearing by bone conduction extends to at least 100kHz: it was demonstrated, in fact, that speech modulating an ultrasonic carrier could be understood to some degree[6].

Results

The gaussian random displacement signal was applied on the upper surface of the cylinder for a limited time interval (5ms) of the whole simulation (25ms) (Fig.2a). The domain consisted of about 7000 tetrahedral mesh elements, corresponding to about 35000 degrees of freedom, requiring about 6 Gb and about 1 hour of computational time on a multiprocessor machine. Dirichlet boundary conditions were applied on the perturbed surface of the cylinder, while the Neumann condition $\sigma_{ik} \cdot n_k = 0$, where n is the normal vector pointing along the z axis, was set on the free boundary. During the imposed external stimulation the system starts oscillating and it continues to vibrate even after the stimulation was interrupted.

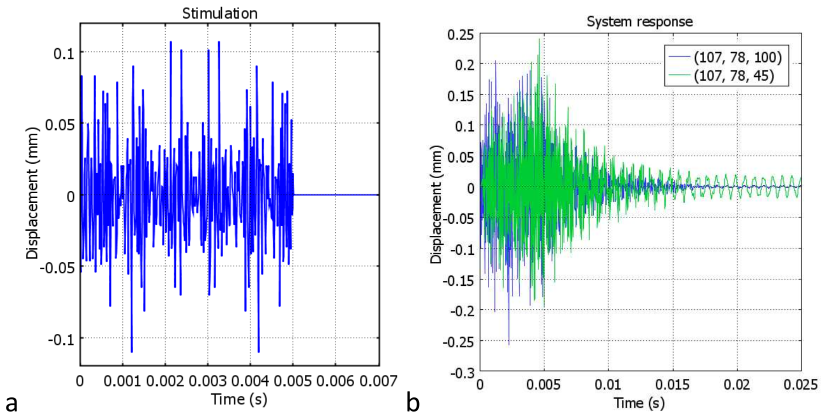

Fig 2:a. Gaussian random stimulation signal; b. System displacement response recorded at two different points along the stimulation axis. Note that the point (107,78,100) is nearer the stimulation site.

Due to the viscoelastic effect, the system's response magnitude decreases until it disappears after a transient time, reaching the initial steady state (Fig.2b). This behavior is caused by the quasi-normal mode frequencies of vibration, in which the real part represents the temporal oscillations, and the imaginary part is the temporal, exponential decay[7]. Such a behavior resembles other physical systems: as an example a ringing bell, a glass perturbed with a knife or a black hole with a gaussian wave packet[7].

	Density ρ[Kg/m3]	**Young modulus E [GPa]**	**Poisson ratio ν**	**Porosity φ**	**Shear viscosity η [Pa·s]**
Cortical bone	1900	10	0.3	7.5%	$3.7 \cdot 10^4$
Cancellous bone	1000	1	0.3	85%	10^5
GM	1040	0.1422	0.49	0.2%	6.7
WM	1040	0.1422	0.49	0.2%	6.7
CSF	1000	0.1176	0.49	100%	10^{-3}

TABLE I. Mechanical parameters of the 3D isotropic heterogeneous head model. In the case of CSF bulk viscosity has been neglected due to its small value and to its incompressible nature.

Discussion

In this work bone and brain tissues mechanical responses were characterized in relation to localized imposed displacements. After a preliminary study on a realistic isotropic, heterogeneous and viscoelastic human brain reconstructed from NMR images, the effects of the bone-brain tissue coupling were investigated. Due to the complexity of the geometry and the computational cost, the reconstruction of the whole head geometry will be pursued in future work, while preliminary simulations on a cylindrical portion of the reconstructed geometry have been conducted. The system, stimulated by a random gaussian signal for a fixed amount of time, showed quasi-normal mode frequencies of vibrations, characteristic behaviors detect also in the case of other physical systems. After the stimulation is delivered, the response magnitude decreases until the system reaches a steady state. These results can be considered into a more general approach devoted to the study of implantable hearing devices, in which both bone conduction phenomena and brain tissue architecture have to be considered in order to correctly design stimulation, filtering and recording[8]. The final target of this work is the implementation of the proposed theoretical formulation on a complete head geometry, coupling the bone-brain system, thus introducing white matter anisotropy and cerebrospinal fluid. This approach would allow researchers to test mechanical responses in silico before performing audiometric tests and to investigate effects due both to position/shape of the vibrator and frequency/amplitude of the stimulation.

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