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Finite element modeling and simulation of benign paroxysmal positional vertigo

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1. Introduction

This work aims to use an existing finite element (FE) model of one part of the vestibule of the human inner ear, namely the lateral semicircular canal (SCC), to improve the knowledge of the physiology of one common pathology: the benign paroxysmal positional vertigo (BPPV) (Fath *et al.* 2020). In this pathology, patients suffer for sudden and acute rotational vertigo when changing their position slowly. It is usually admitted that this type of vertigo derives from unexpected earstone movements in the fluid that is embedded in the SCCs, thus leading to altered fluid flow and modified cupula deformation.

This work explores two BPPV situations that are tested in clinical routine (sudden stop), *i.e.* the influence of either a single "big" earstone or a similar "small" earstones mud, on the cupula base, compared to a "healthy" reference state. In fact, the focus on the cupula base is linked to the sensory cells location. Shearing stress and transverse motion in this area trigger a signal to the central nervous system (CNS), and this signal funds the initial condition for the vestibular ocular reflex (VOR).

2. Methods and material

A previously developed and validated 2.5D FE model of a 50-µm slice of a lateral SCC has been used here (Baumgartner *et al.* 2020; Blaise *et al.* 2022). The software used to build the model and to run the various simulations is Altair® Hyperworks®, a commercial FE tool in its explicit version here. A Lagrangian approach has been set here for the entire model.

Six continuously meshed parts describe the two fluids — endolymph and perilymph — and four tissue structures — labyrinth membrane, cupula, crista and bone — of a human lateral SCC, resulting in a whole model of 10,338 hexahedral elements (Table 1). The membranous labyrinth, forming biologically a small tube with an enlarged part called the utricle, contains the endolymph and bathes in the perilymph, itself embedded in the petrous bone of the skull base. Mechanical properties of water were assigned to both fluids. An innovative feature of the current model was that solid tissues were assumed to be quasi-incompressible, linear elastic following Hooke's law, with a Poisson ratio close to 0.5.

Besides, and because it is mainly composed of water and soft gelatinous glycoproteins, the cupula is assumed to behave as a hydrogel thus as a viscoelastic material. Therefore, a generalized Kelvin-Voigt model, also known as Zener model, was used for that component. Concerning mechanical and physical properties of the cupula, very few direct experiments on animals have been performed and no one on humans, due to the consistency, smallness and fragility of this small anatomical structure. (Selva *et al.* 2009) computed from both mathematical and FE model an estimation of the cupula's Young's modulus at 5.4 Pa, a value that has been adopted by most of FE models in the literature. In our model, the long-term Young's modulus was set to 5.0 Pa, in accordance to this literature.

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Table 1. Basic mechanical properties of the various parts of the FE models.

	Density [kg.m-3]	Kinematic viscosity [Pa.s]	Young's modulus [Pa]
Fluids	1,000	0.00085	/
Membranes	1,000	/	100
Cupula	1,000	/	5
Crista	1,000	/	1.10^6
Earstones	2,000	/	1.10^6
Skull bone	1,500	/	20.10^9

All nodes of the model were constrained in the normal direction (to prevent from fluid leakage and to represent somehow the boundary condition of the modelled slice) and the bony part received boundary conditions to prevent its deformation. In this way, the SCC was controlled by the bony part as a rigid body. The outer solicitation imposed to this rigid body consists in a rapid deceleration in a time range of 100 ms, thus mimicking the clinical routine sudden stop test. In this test, the rotary chair on which the patient is seated vertically is quickly decelerated after a relatively long lasting and physiological rotation in the axial plane, at a velocity of more or less 360 °/s.

This reference model has been modified and enhanced by the addition of a single 200 µm earstone (earstone model) on the one hand, and by the introduction of an earstones mud made of 26 20 µm earstones (mud model) covering the same volume as the single earstone. The density of the earstones is set on 2,000 kg/m^3, while its linear elastic behavior is similar of the crista's one.

For the three models, two variables are computed:

- Transversal displacement of the cupula base
- Von Mises stress at the cupula base

3. Results and discussion

Starting the clockwise angular movement towards the right, the cupula always first deflected towards the SCC, *i.e.* to the corresponding movement direction. Then it relaxed towards its initial position due to its viscoelastic behavior and moved, after a recorded delay, to the utricle side.

The maximal transverse displacements plotted in (Figure 1) show that the expansion of the cupula, *i.e.* the amplitude of the motion, is in the range of 24 µm

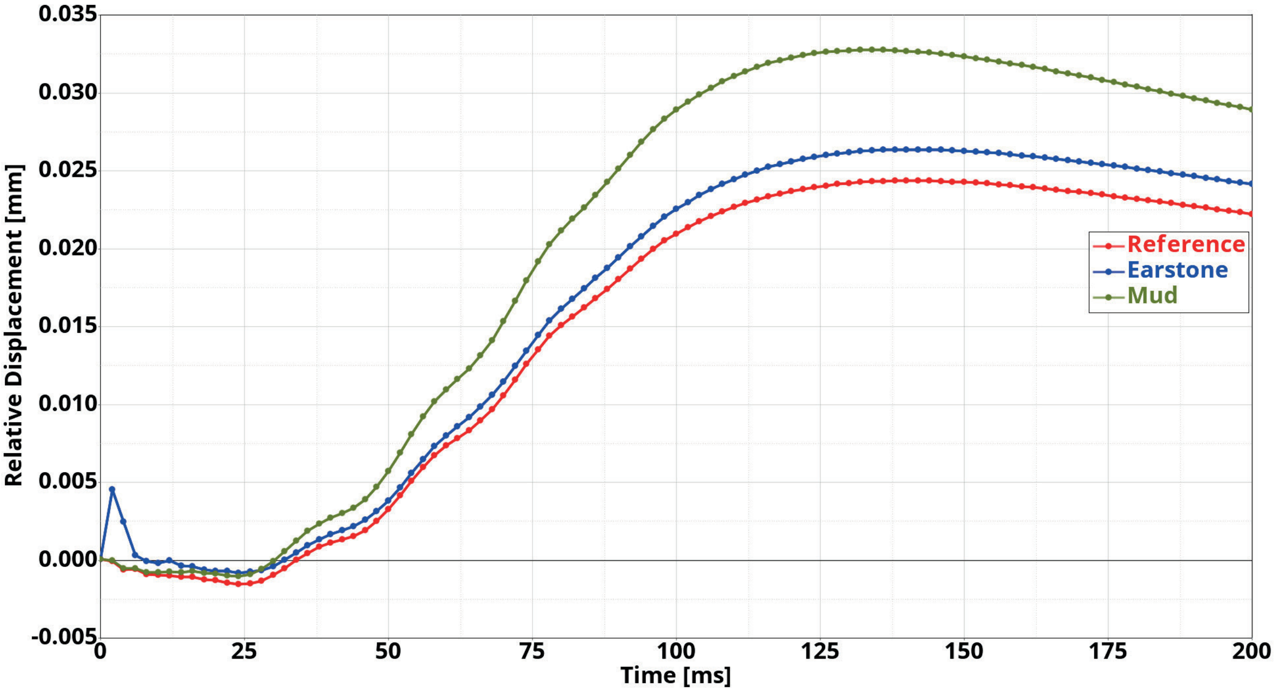

Figure 1. Transversal displacement of cupula base in the reference model (red), in the earstone model (blue) and in the mud model (green).

and 33 µm. These values are reached at time 125 ms, *i.e.* 25 ms after the motion stops. Thus, a delay is observed between the motion itself and its consequence in terms of cupula deformation.

The Von Mises shear stresses were in all three configurations maximal at the top of the crista, where the cilia from the cell layer are embedded into the cupula. The maximal values that are reached rely between 1.50.10^{-6} Pa (for the reference and the earstone models) and 2.1.10^{-6} Pa (for the mud model). These peak values are reached at time 75 ms, *i.e.* during the head deceleration that ends at time 100 ms.

Besides, significant variations are observed for both variables, thus revealing different responses of the VOR and the perception by the CNS of an overestimated head rotation in the horizontal plane. This overestimation is far higher in case of an earstones mud compared to a single earstone. Eventually, it can be underlined that a single earstone generates a peak value for both variables at the very beginning of the stimulation, in particular on the sides of the crista.

4. Conclusions

The presence of a single big earstone or of a small earstones mud in the vestibule of the inner ear modifies the cupula deformation, namely on its base, sending an altered signal to the CNS. Thus, head rotation is overestimated and patients may perceive sudden and acute vertigo. In fact, this is what is experienced in real life by patients suffering from BPPV. Nevertheless, this conclusion should be enhanced by increasing the accuracy of the FE model used here, namely by varying the nature and the location of the earstones, as well as by implementing an Arbitrary Lagrangian Eulerian formulation to mimic the fluid/structure interactions more accurately.

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Conflict of interest statement

The authors have no conflicts of interest to declare.

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