

Development of a finite element model of a human lateral semicircular canal of the inner ear

D. Baumgartner , A. Charpiot , M. Lamy , H. Vuong-Chaney

I. INTRODUCTION

The human inner ear hosts a fundamental component of the mechanisms regulating balance and maintaining gaze: the vestibular system. It can detect motion thanks to three semicircular canals (SCC), which act as sensors of angular acceleration of the head, using deflections of the cupular diaphragm to generate neural information. This system is often damaged after a head trauma, as a consequence of a traffic accident, a domestic fall or a violent sport activity as well as from blast injury, and this damage causes significant difficulty and reduced quality of life for the accident victim. As the vestibular system is very small, complex to access surgically and breakable when extracted, an accurate understanding of its behaviour has not yet been achieved. One way to improve our knowledge on it is to develop and use analytical models such as Finite Element (FE) analysis tools.

Consequently, this study aims to investigate the mechanical behavior of that peripheral neural sensor to help surgeons in their diagnosis and treatment, and to develop better support for the victim after a head trauma.

II. METHODS

To this end, a 3D FE model of a lateral SCC was developed using the Altair™ Hyperworks™ Software.

The geometry of the model was extracted from anatomical measurements [1] of the human lateral SCC (Fig. 1). The FE model (Fig. 2 and Fig. 3) includes the following components: membranous structures on the outer surface of the model, divided between canal, ampulla and utricle; a cupular diaphragm, composed of a cupula and a crista, in the ampullar compartment; and an endolymphatic fluid filling the remainder of the enclosed volume. Membranous structures are represented by 4-nodes quadrilateral 2D elements (with a given implicit thickness of 0.01 mm), while the other structures are made of 8-nodes hexahedral 3D elements. The whole mesh consists of 17,112 nodes and 18,882 elements. The mesh is also perfectly continuous.

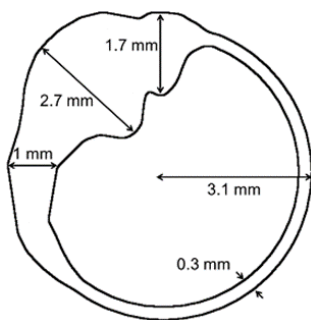


Fig. 1. Principal dimensions of the anatomical model [1].

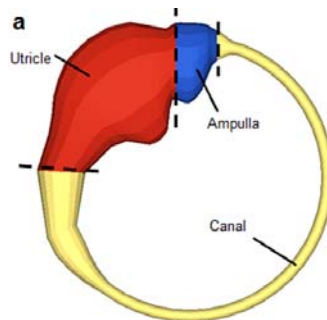


Fig. 2. Membranous walls of the FE model.

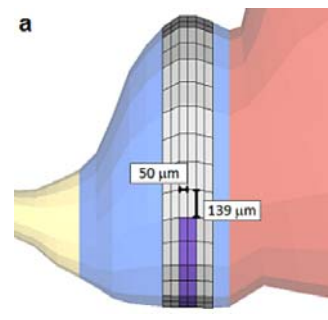


Fig. 3. Cupula and crista inside the ampulla of the FE model.

The fluid in the endolymphatic space is considered to be a Newtonian homogenous quasi-incompressible viscous fluid. It has been attributed a density of $1,020 \text{ kg.m}^{-3}$. For the kinematic viscosity, literature reports values in the order of magnitude of $10^{-4} \text{ m}^2.\text{s}^{-1}$ [2]. The solid structures of the model (the membranes and the cupular diaphragm) have been considered as being linear elastic materials. Literature values were taken into account for the choices of the Young moduli of cupula (1 Pa) and membranes (100 Pa) [3]. For the crista, Young modulus (1 MPa) was based on other known tissues of similar composition. The rigidity, i.e. the Young's

D. Baumgartner (e-mail: daniel.baumgartner@unistra.fr) is Associate Professor in Biomechanics and M. Lamy is Researcher, both at Strasbourg University, France.

A. Charpiot is Professor in ENT and H. Vuong-Chaney is Medical Doctor, both at the Medical Hospital of Strasbourg University, France.

modulus, of the cupula, which is the most deformable part of the model, has to be lower than that of the membranes, while the crista rigidity has to be much higher. Also, the density of the cupula ($1,020 \text{ kg.m}^{-3}$) must be equal to that of the surrounding endolymphatic fluid to avoid mass and inertia effects, while the density of the other materials is that of water ($1,000 \text{ kg.m}^{-3}$), of which they are mostly made. The fluid/structural coupling followed an Arbitrary Lagrangian Eulerian approach.

III. RESULTS AND DISCUSSION

The FE model of the lateral SCC is validated against measures from clinical practice. The test used is a case of sudden stop of the head, in 100 ms, following rotation, namely the Head Impulse Test of Halmagyi [4].

Results (Fig. 4) of the reference simulation, concerning the cupula displacements and relaxation durations, were in agreement with known data from literature [5]. In fact, a $17 \mu\text{m}$ transversal deflection of the cupula is calculated in the simulation, and is comparable to the $21 \mu\text{m}$ transversal deflection measured in the experiments [5]. Moreover, a 1.23 s relaxation duration of the cupula is obtained in the simulation, and is comparable to the 1.8-5 s relaxation duration that is measured in the experimental tests [5].

Pressures (Fig. 5) and Von Mises stresses (Fig. 6) in the cupula were also calculated in order to estimate the levels such variables may reach in that kind of anatomical structure. Nevertheless, these maximal values, i.e. a pressure of 0.48 Pa and a Von Mises of 0.70 Pa, could not be compared to experimentally measured values because of lack of such data in literature.

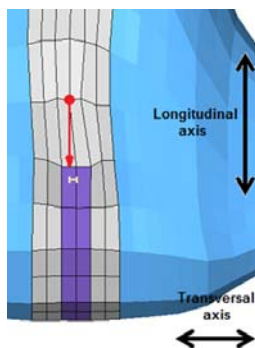


Fig. 4. Transversal displacement of a node above the crista ($t=100 \text{ ms}$).

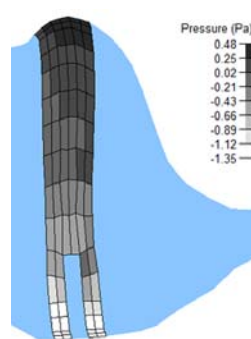


Fig. 5. Pressures in the cupula at the end of the deceleration ($t=100 \text{ ms}$).

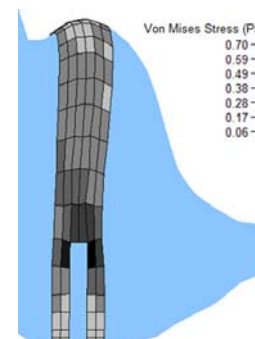


Fig. 6. Von Mises stresses in the cupula at the end of the deceleration ($t=100 \text{ ms}$).

IV. CONCLUSION

This study describes the development and the validation against experimental data and clinical observations of a FE model of a human lateral SCC of the inner ear. This model is of particular interest for the understanding of vestibular physiology, in order to help ENT practitioners in their positional diagnostic and therapeutic manoeuvres after a head trauma. In addition, this model could also prove useful for clinical purpose, in cases of atypical pathologies of the inner ear. In fact, there is no other way to obtain such knowledge of this very small and fragile system.

V. REFERENCES

- [1] Curthoys I.S., Oman C.M., Dimensions of the horizontal semicircular duct, ampulla and utricle in the human. *Acta Otolaryngol* 103: 254-261, 1987.
- [2] Rajguru S.M., Ifediba M.A., Rabbitt R.D., Three-dimensional biomechanical model of benign paroxysmal positional vertigo. *Ann Biomed Eng* 32(6): 831-846, 2004.
- [3] Kassemi M., Deserranno D., Oas J.G., Fluid-structural interactions in the inner ear. *Comput Struct* 83: 181-189, 2005.
- [4] Halmagyi G.M., Curthoys I.S., A clinical sign of canal paresis. *Arch Neurol* 45(7): 737-739, 1988.
- [5] Njeugna E., Eichhorn J.L., Kopp C., Harlicot P., Mechanics of the cupula: effects of its thickness. *J Vestib Res* 2: 227-234, 1992.