Multidisciplinary Biomechanics Journal

Balance disorders in the inner ear during a head trauma

Daniel Baumgartner[a*], Manon Blaise[a], Anne Charpiot[a, b]

a University of Strasbourg, CNRS, ICUBE UMR 7357, Strasbourg, France
b University Hospital, ENT Department, Strasbourg, France
* Corresponding author: daniel.baumgartner@unistra.fr

Received date: 01/04/2025
Accepted date: 27/06/2025
Publication date: 27/10/2025

Keywords: balance system, inner ear, vertigo, head trauma, finite element method

1. Introduction

Human balance corresponds to a state of stability of the body and the gaze. It requires the mobilization of a set of peripheral and central mechanisms. In particular, the inner ear vestibule embeds sensors that measure the head kinematics. That peripheral information is processed in the central nervous system (CNS) to modulate muscle tone in order to allow postural adaptations and eye motion. Impairment of these peripheral sensors leads up to a state of instability commonly known as vertigo.

This study tries to establish why vertigo and instabilities are usually observed and diagnosed after a head trauma that may occur in traffic accidents, sport activities impacts or domestic life falls (Elzière et al., 2017). In particular, this work uses a finite element (FE) model of the lateral semi-circular canal (LSCC) of the human inner ear to identify what happens to the cupula during an extended range of head rotational decelerations in the axial plane.

2. Methods

A previously developed and validated 2.5D FE model of a 50-µm slice of the LSCC is used here (Blaise et al., 2022; Baumgartner et al., 2025). Six continuously meshed parts describe the two fluids – endolymph and perilymph – and the four tissue structures – labyrinth membrane, cupula, crista and petrous bone – of a human LSCC, resulting in a whole model made of 10,339 hexahedral elements and 21,201 nodes. The membranous labyrinth, forming biologically a small tube with an enlarged part called the utricule, contains the endolymph and bathes in the perilymph, itself embedded in the petrous bone of the skull base. As partially shown in Tab. 1 mechanical properties of water are assigned to both fluids. Besides, structures (membranes, crista and skull bone) are assumed to be linear elastic, following Hooke's law and are also assumed to be quasi-incompressible (with a Poisson ratio set at a value of 0.48). Eventually, the cupula is modeled as a Zener viscoelastic material because it is mainly composed of water and soft gelatinous glycoproteins. The value of the different variables of this behavior are taken from the literature (Selva et al., 2009).

This model is validated against data stemming from clinical observations. In fact, during a Sudden Stop Test (Van de Berg et al., 2018), which is used in clinical routine, a state of vertigo sets in and lasts more or less 15 seconds. This duration corresponds to the relaxation time of the cupula – to recover its initial position – used here as the main target parameter.

All nodes are constrained in the normal direction of the LSCC. That constraint is supposed to represent the boundary condition of the modeled slice, i.e. the presence of medium on both sides of the slice, thus containing the slice motion in its plane. The model is subjected to five levels of the Sudden Stop Test (Van de Berg et al., 2018), i.e. decelerations (axial rotation of the head) in 100 ms from velocities ranging from 180°/s (V1 – clinical test) to 900°/s (V5 – common

To cite this article: Daniel Baumgartner, Manon Blaise, Anne Charpiot, Balance disorders in the inner ear during a head trauma, *Multidisciplinary Biomechanics Journal*, 2025, vol. 2, p. 293–295, DOI: 10.46298/mbj.16178.

rotation level in a mild, "long lasting" and/or high damped head trauma).

For the five scenarios, two variables are computed: the angle between the kinocilium and the normal vector of the crista top, and the cupula von Mises stress, with a focus on the cupula base.

Biologically, each sensory ciliated cell takes birth in the crista. These cells have one predominant cilium measuring 100 µm in length – the kinocilium – which plunges into the cupula. Deflection of this kinocilium, due to cupula deformation, initiates the mechanotransduction cascade, generating an electrical signal that is processed by the CNS. The kinocilium itself is not directly represented in the model, but, a local coordinate system is positioned within the crista which can be considered as rigid compared to the cupula. The goal is to extract the local transverse nodal displacement representative of the bending of a kinocilium, thus of its angle with the normal vector of the top of the crista.

Table 1. Partial mechanical properties for the different components of the FE model of the LSCC.

Components	Density [kg.m-3]	Kinematic viscosity [Pa.s]	Young's modulus [Pa]
Endolymph	1,000	8.5E-4	/
Perilymph	1,000	8.5E-4	/
Membranes	1,000	/	100
Cupula	1,000	/	5
Crista	1,000	/	1E6
Skull bone	1,500	/	20E9

Credit: Daniel Baumgartner

3. Results

Significant variations are observed for both variables in these five rotational impact scenarios. Namely, increasing the deceleration level of the head in the axial plane from V1 to V5 leads to:

- a higher angle between the kinocilium and the normal vector of the crista top at time 200 ms, ranging from 121° for V1, 141° for V2, 153° for V3, 160° for V4 to 165° for V5.
- a higher level of cupula von Mises stress at time 200 ms, ranging from 0.122 Pa for V1, 0.232 Pa for V2, 0.327 Pa for V3, 0.410 Pa for V4 to 0.477 Pa for V5 (Fig. 1).

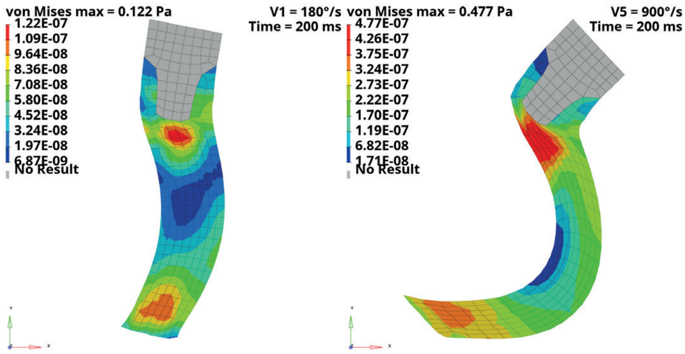

Figure 1. Cupula von Mises stress at time t = 200 ms for both extremal levels of head decelerations in 100 ms ranging from 180°/s (V1 – clinical test) to 900°/s (V5 – mild head trauma). Crista in grey, with kinocilium (not visible here) at its top.

Credit: Daniel Baumgartner.

4. Discussion and conclusions

The cupula von Mises stress is considered, and reaches its highest value, at the cupula base, i.e. at the top of the crista. It is in that area that the kinocilium is rooted in the crista. Besides, it can be observed that a secondary area of the cupula is also experiencing high levels of shearing stresses, namely where the cupula is attached to the membrane that separates the endolymphatic compartment from the perilymphatic compartment. That area is often subject to debate since the way the cupula is linked to the membrane is not fully clear. So, it is commonly admitted that the cupula is fixed (recessed) in the membrane (as it is implemented in the present model), even if some authors imagine rather a kind of sliding boundary condition. In fact, this minority hypothesis could be tested and would surely modify the global behavior of the cupula, and in particular both variables under study here: the von Mises stresses as well as the angle between the kinocilium and the normal vector of the crista top.

Shearing stress and transverse motion at the cupula base trigger a signal to the CNS, funding the vestibular ocular reflex, itself responsible for vertigo and instability when altered. Thus, the high levels of both angle between the kinocilium and the normal vector of the crista top, and cupula von Mises stress, explain well the clinical observation of instabilities and vertigo – among other types of injuries such as concussion, brain bleeding, skull fractures, subdural hematoma – for patients suffering from head trauma after an important rotation of the head in the axial plane.

In fact, a remaining challenge is to enhance this study with linear acceleration pulses (and not only pure single decelerations) at different levels and in various directions and also for both others SCC, as well as for the utricule and the saccule, to complete the knowledge on vertigo appearance consecutively to a head trauma. Besides, improvements of the FE model used here in order to refine the results should also be undertaken. Particular enhancements should be led on more accurate mechanical variables identification. Moreover, various mesh types should also be implemented to check mesh convergence. Nevertheless, these first and particular results show how promising the use of FE method is to understand what may happen in the inner ear during and after a head trauma.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Contributor Roles

Daniel Baumgartner and Manon Blaise developed the finite element models and the methodology, achieved the simulations and produced the results.

Anne Charpiot provided the initial clinical expertise and analyzed the results from a medical and surgical point of view

Funding

This work, as part of the ITI 2021-2028 program of the University of Strasbourg, CNRS and INSERM, was supported by IdEx UNISTRA (ANR-10-IDEX-0002) and SFRI (STRAT'US project, ANR-20-SFRI-0012) under the framework of the French Investments for the Future Program.

Data, software, code availability

The software used in the present study is the Altair Hyperworks 2022.3 suite.

www.altair.com

References

Elzière, M., Devèze, A., Bartoli, C., & Levy, G. (2017). Post-traumatic balance disorder. *Eur Ann Otorhinolaryngol Head Neck Dis, 134*(3), 171–175. https://doi.org/10.1016/j.anorl.2016.10.005

Blaise, M., Baumgartner & D., Charpiot, A. (2022). Rotary chair testing in otology: biomechanical modelling and numerical simulation. In *Actes du 25e Congrès Français de Mécanique*. Nantes, France. Retrieved from https://hal.science/hal-04219693v1

Baumgartner, D., Blaise, & M., Charpiot, A. (2025). Finite element modeling and simulation of benign paroxysmal positional vertigo. *Multidisciplinary Biomechanics Journal, 1*, 311–313. https://doi.org/10.46298/mbj.14531

Selva, P., Oman, C.M., & Stone, H.A. (2009). Mechanical properties and motion of the cupula of the human semicircular canal. *J Vestib Res Equilib Orientat, 19*(3-4), 95–110. https://doi.org/10.3233/VES-2009-0359

Van de Berg, R., Rosengren, S., & Kingma, H. (2018). Laboratory examinations for the vestibular system. *Curr Opin Neurol, 31*(1), 111–116. https://doi.org/10.1097/WCO.0000000000000526