# SIFEM Project: Semantic Infostructure interlinking an open source Finite Element tool and libraries with a model repository for the multi-scale Modelling of the inner-ear

Christos Bellos, Athanasios Bibas, Dimitrios Kikidis, Steve Elliott, Stefan Stenfelt, Ratnesh Sahay, Konstantina Nikita, Dimitrios Koutsouris, *Senior Member, IEEE* and Dimitrios I. Fotiadis, *Senior Member, IEEE*

***Abstract*— The SIFEM project targets the development of an infrastructure in order to semantically link open source tools and libraries with existing data as well as new knowledge towards the multi-scale finite element modelling of the inner-ear. The SIFEM system is designed based on an open architecture schema that consists of a set of tools and subsystems in order to develop robust multi-scale models. The project mainly delivers: (i) tools for finite elements modelling, (ii) cochlea reconstruction tool and (iii) 3D inner ear models visualization tool. The main scientific results contribute to the knowledge of alterations associated to diverse cochlear disorders and could lead, in long-term, to personalized healthcare. The overview of the SIFEM platform and its architecture is presented in this paper.**

## INTRODUCTION

The clinical facts indicate that there is an increase in the number of people suffering from hearing impairment and hearing loss, mainly due to longer life expectancies [1], [2]. In order to understand the exact pathophysiological consequences and risk factors of hearing impairment in humans, there is required a deep understanding of the cochlear normal function. Despite significant progress, more work is needed to develop novel approaches to restore hearing.

There are three major parts to the ear, with distinct functions [4]; The Outer ear collects sound waves and funnels them towards the middle ear. The Middle ear ossicular chain oscillates in response to the airborne pressure waves, generating pressure waves in the inner ear fluid chambers. The Inner ear turns pressure waves into electrical signals that our brain can understand. The hearing impairments, which could lead to hearing loss, are mainly caused by cochlear and cochlear nerve pathology and are classified as sensorineural hearing loss [3]. This is by far the commonest, and may be caused by the normal aging process (presbyacusis), noise (noise-induced hearing loss), medications, or genetic causes [5].

The inner ear is inaccessible during life, which leads to unique difficulties in studying its normal function and pathology. Thus, biopsy, surgical excision and other conventional techniques of pathologic studies are not feasible, without further impairing function [6]. Therefore, insight into the pathologic basis of inner ear disease can be obtained only by post-mortem studies of the cochlea and by developing credible animal models. Mathematical modelling is therefore particularly attractive as a tool in researching the cochlea and its pathology.

Mathematical models were introduced into the study of cochlear pathology and physiology, providing a useful tool in order to observe the system's behaviour, which was impossible in previous human *in vivo* studies [7], [8]. In addition, finite elements (FE) could assist researchers to study the structure-function relationship in normal and pathological cochlear. Also, FE could assist the rehabilitation of sensorineural hearing loss by providing insights into the planning of novel surgical procedures.

With a few exceptions, the majority of human cochlea modelling focuses on efforts to accurately simulate basilar membrane vibratory characteristics and travelling wave development [9], [10]. The usual approach is the use of 2-chamber, uncoiled, passive mechanical models, not accounting for the contribution of micro-mechanical elements [11], [12]. There are only a few attempts to model the active cochlear mechanism, by accounting by coupling the vibratory characteristics of the outer hair cell [13], [14], [15]. There is also recently an effort to individually model other cochlear structures like tectorial or Reissner's membrane [16], to account for the renewed interest on their physiological importance in the physiology of hearing. However, coupling to basilar membrane vibration has yet to reach computational sophistication and thus, true multi-scale

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C. Bellos, D. Koutsouris and K. Nikita are with the Institute of Communications and Computer Systems (ICCS)-National Technical University of Athens (NTUA), Greece. (e-mail: cbellos@biosim.ntua.gr, dkoutsou@biomed.ntua.gr, knikita@ece.ntua.gr).

A. Bibas and D. Kikidis are with the 1st Department of Otolaryngology – Head & Neck Surgery, University of Athens, Greece. (e-mail: thanosbibas@hotmail.com, dimitriskikidis@yahoo.com).

S. Elliott is with the Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, United Kingdom (e-mail: S.J.Elliott@soton.ac.uk)

S. Stenfelt is with the Department of Clinical and Experimental Medicine, Technical Audiology, Linköping University, 58185 Linköping, Sweden (e-mail: stefan.stenfelt@liu.se).

R. Sahay is with the Digital Enterprise Research Institute, National University of Ireland, Galway, Ireland (e-mail: ratnesh.sahay@deri.org).

D. I. Fotiadis is with the Unit of Medical Technology and Intelligent Information Systems, Dept of Materials Science and Engineering, University of Ioannina, Ioannina, Greece. (e-mail: fotiadis@cc.uoi.gr).

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modelling approaches are largely missing.

Multi-scale modelling involves solving physical or mechanical problems which have distinct features at multiple (spatial or temporal) scales. The main aim of multi-scale modelling is the calculation or computation of mechanical properties or system behaviour at one level using information or models from higher or lower levels. Thus, it is possible to obtain information of a systems' behaviour that would not be possible if single scale techniques were utilized. To the best of our knowledge, there is no multi-scale FE model of the entire cochlea at the moment. There are currently either transduction models (just the organ of Corti) or 3-D model concentrating on the basilar membrane displacement properties. Steele et al [17] have published a multi-scale model of the organ of Corti. However their research was focused on the multi-scale differences in the mechanical properties (mainly stiffness related) at scales in the Organ of Corti (vibrating cochlear partition, the hair cells and stereocilia). Although modelling of other physiological systems have employed coupling of different modelling modalities [18], such efforts have not been identified as far as the cochlea is concerned. Some authors have coupled the outer and middle ear responses to the cochlea [11], [12].

## System Overview

The SIFEM project results to the delivery of an infrastructure, which will semantically interlink various tools and libraries (i.e. segmentation, reconstruction, visualization tools) with the clinical knowledge, which is represented by existing data, towards the delivery of a robust multi-scale model of the inner-ear. These tools, will facilitate stakeholders to interact and cooperate to a) dynamically discover interoperable inner ear models (i.e. cochlea geometry, fluid dynamics, cochlea micromechanics, electrical coupling, bone conduction vibration) for potential integrated simulation; b) have homogenized and standardized access to the shared, harmonised datasets (histological data, micro-CT images of the cochlea, pathological data) and inner ear models required to execute the simulations; c) accept the simulation results for feedback in future simulations; and d) enable interoperability with other simulation environments (i.e. ANSYS, OpenFOAM) by exposing models and other linked data in standard, published formats.

### A. *The SIFEM Semantic Infostructure*

The SIFEM solution proposes an innovative, open, generic approach (called the SIFEM Semantic Infostructure Conceptual Architecture), which introduces the concepts and tools for simulating the inner ear. The proposed SIFEM Semantic Infostructure Conceptual Architecture consists of three main (3) software components, facilitating researchers in collaborating, sharing data, creating common multi-scale models and conducting joint research, and a set of supporting Infostructure utilities:

*1) The Linked Knowledge Repository*, which comprises a knowledge base of semantically interconnected clinical rule sets, linked experimental data, inner-ear models, and linked data sources across the Web. The Linked Knowledge Repository will provide the mechanisms and tools required for the identification of interoperable models, interconnection of clinical, biological and provenance data, information and knowledge.

*2) The Intelligent Knowledge Services*, which provides an interface to the querying and processing of clinical, biological, and simulation research data with (i) Reasoning, Querying and processing interfaces through a Semantic Rule Engine, (ii) Model recommendation based on the semantic specification of models as black boxes to establish integration points; and (iii) Simulation Output Validation where the models can be examined for consistency and be validated against available data.

*3) The Semantic Infostructure Utilities* that provides researchers with advanced capabilities with regard to the management and version control of the inner ear -related models and multi-scale models (uploaded and/or generated by the researchers), the alignment and archiving of the available data provided by the researchers or generated by the simulations execution

### B. *Open Source FEM Tool and 3D Visualization*

Apart from simulating normal physiology, one of the most powerful uses of models is their ability to predict pathological conditions and to simulate surgical management. The SIFEM project will utilize PAK software [19], which is a well-known open source FEM set of software tools, utilized in previous research and modelling activities [20].

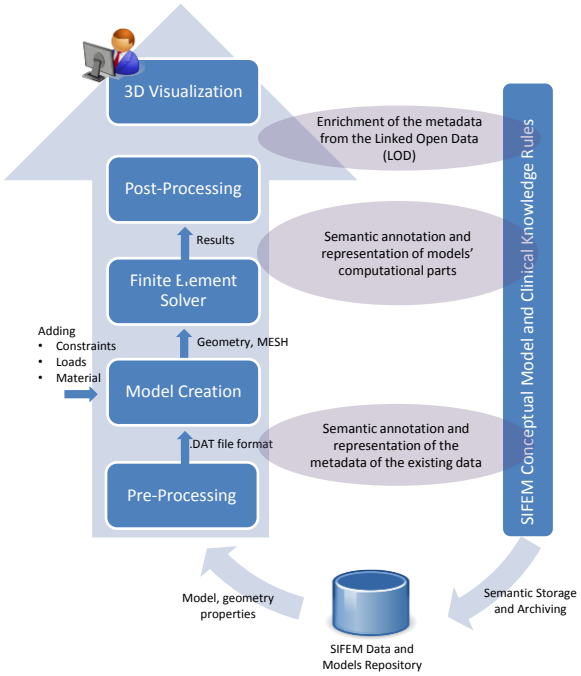


Fig. 1: Semantic annotation and representation of data and models imported and exported to SIFEM open source FE and visualization tools.

In Fig. 1 the generic architecture of the SIFEM system is depicted, presenting the connection between the modelling parameters with the FEM tool, the conceptual model and the knowledge rules. Geometry of the cochlea is defined in the "Pre-Processing" module. All geometrical parameters from images and user friendly web interfaces are incorporated into this module. The boundary conditions, material properties and load conditions are defined through the "Creating Model" module and after generating 3D eight-node mesh, the "PAK Solver" will solve the fluid coupling problem within the chambers of the cochlea. Also micromechanics effects are analysed within the organ of Corti at different positions along the cochlea as well as electrical coupling within the cochlea. A next step in further modelling will be the modelling of the cochlear microphonic signal observable from outside of the cochlea.

### *C. Multi-Scale Modelling*

There are three research directions in the project and a model validation and verification phase, which result to robust and validated inner ear models addressing various scales of modelling:

*1) Research Direction I*: addresses various scales of inner ear modelling like geometry of the cochlea, fluid coupling within the chambers of the cochlea, micromechanics within the organ of Corti at different positions along the cochlea and combines the fluid coupling and micromechanics to predict the coupled response of the cochlea. The current FE model of the fluid coupling [21] will be adapted to be more flexible. The current model uses ANSYS with fluid elements whose size and geometry are defined by a meshing program. In the new model the definition of the element size and shape need to be defined in PAK, in order to be meshed by openFOAM.

*2) Research Direction II*: addresses the scale of electrical coupling within the cochlea [22], which might be a significant aspect in accurately modelling the way the cochlea behaves. Almost all models of the cochlear include the geometry, fluid coupling and micromechanical aspects, but do not consider electrical aspects. The activities in this direction include: (i) electrical coupling in the cochlea may actually be a significant aspect in accurately modelling the way the cochlea behaves and (ii) modelling the cochlear microphonic (CM) signal observable from outside of the cochlea can facilitate a method of interpreting such observations, and hence providing valuable diagnostic information.

*3) Research Direction III*: addresses the scales of Bone Conduction (BC) stimuli [23] and modelling as well as the CM signal modelling providing valuable diagnostic information and extracting sound vibration patterns. The main difference between the air conduction (AC) and BC models is that while the AC model boundaries are rigid and still, the whole model framework moves in the BC model. Consequently, all masses in the model are assigned inertial forces. Moreover, due to the distributed forces, the compliances in the model become important and the cochlear boundary cannot be considered as infinitely stiff and the cochlear fluids is not incompressible and stiffness properties are assigned.

*4) Model Validation and Verification*: It validates the developed models and the coupled inner ear model according to already possessed clinical and experimental data (pathological and not). Clinical validation of cochlear models is difficult, since there is no direct non-invasive technique to measure the basilar membrane response. To the best of our knowledge, no cochlear models have used clinical validation. Hence, validation efforts will have to rely on indirect measurements of cochlear function, mainly otoacoustic emissions in the normal cochlea and possibly in Meniere's disease.

## DISCUSSION

The development of accurate geometric 3-D FE cochlear models will provide a unique opportunity to simulate both normal physiology as well as cochlear pathology and correlate it to histopathological findings in a wide variety of ear diseases. Additionally it may be used in innovation of novel therapeutic approaches in managing sensorineural hearing loss.

*1) Physiology of cochlear function*: A FE model can be used to test hypothesis on poorly understood aspects of cochlear function such as the exact mechanism of Bone Conduction excitation of the cochlea, or on the effect of various anatomical features [24] as for example the effect of the size of the helicotrema on the traveling wave in various input frequencies.

*2) Pathology of cochlear function*: A FE model may be useful in testing different pathophysiological hypotheses of mechanisms of disease, by introducing "defects" in the model and observing its behaviour. For example there are known pathologies with reduced coiling of the cochlea (1 ½ turns instead of 2 ½), where a model would be able to predict its behaviour and correlate it to the clinical data. There are also other cochlear pathologies with poorly understood pathophysiology such as the raise in bone conduction thresholds in cases of additional openings in the cochlea chambers (collectively called 3rd window lesions). Finally there are pathologies, like Meniere's disease (hearing loss, vertigo and tinnitus), where there is increased fluid volume in one of the cochlear chambers (scala media), which the current FEMs are not able to model, as they include 2 cochlear chambers rather than 3.

*3) Patient specific modeling* may prove useful in predicting outcome following medical or surgical intervention and it has been employed in various medical and biological domains. In orthopedics for example it may provide surgeons with data regarding bone stress distribution or implant micro-displacements [25]. It may also be used to provide enhanced information from imaging data regarding risk fracture prediction. In interventional Cardiology it has been recently been used to investigate the use of FE analysis on the impact of carotid stent placement by using data from

individual patients (Fig. 2). To date, there are no patient-specific models of the cochlea or the ear.

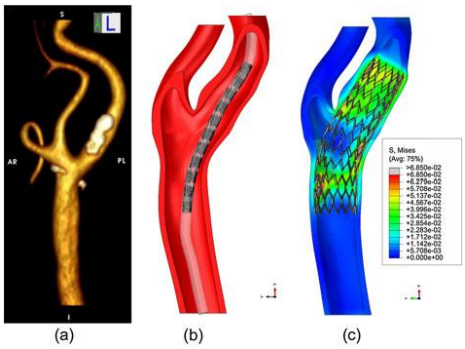


Fig. 2: Patient-specific FE modelling of carotid artery stenting [26]

## CONCLUSIONS

The SIFEM project could eventually assist the management of hearing loss. Perhaps one of the most promising and useful aspects of using FEM is the planning of surgical procedures and their predicted effects by employing what-if scenarios. Such scenarios may help both in innovation of surgical techniques as well as the better design of auditory implants. As an example, the research modeling activities of SIFEM may be used in the following scenarios:

*1) Study and predict the effect of cochlear implant* on vibration patterns of cochlear implants. This can be done by simulating short vs. long and hard vs. soft electrodes. Recent studies have shown that the residual acoustic hearing at low frequency may be preserved after cochlear implantation. The relationship between the residual hearing level and the depth, mechanical properties, and surgical procedure of cochlear implant could be studied with FEMs.

*2) Study and predict the effect of newer auditory implants*. A relatively new kind of implant (Floating Mass Transducer) can be attached to the round window, thus reverse driving the cochlea (rather than the forward-driving through the ossicular chain and the oval window), for some specific types of ear disease. However, the reverse driving versus forward driving needs further study on its mechanism, which can be executed by the appropriate FE model.

*3) Modelling drug delivery to the cochlea*. Inner ear disorders could be treated by local drug deliveries to the round window membrane. The knowledge of drug distribution in the inner ear utilizing variant delivery methods could be crucial to the development of safe therapies. Moreover, application protocols and drug delivery systems could be evaluated by utilizing computer simulations, which could, also, lead to the extrapolation of animal studies to the larger cochlea of the human.

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