Subject-specific modelling of neural responses to electrical stimulation of the auditory system

by Ramana Govindasamy, Tiaan K Malherbe, Prof Tania Hanekom and Prof Johan J Hanekom

The cochlear implant has restored partial hearing to over 200 000 profoundly deaf people, making it the most widely distributed and successful neural prosthetic by several orders of magnitude. It has also proven useful as a research tool in expanding the understanding of neural plasticity in children and the mechanisms involved in auditory pattern recognition. Speech perception in certain users is incredible, considering that the low-resolution signal, presented through a limited number of channels, still provides enough information for speech recognition.

In the vicinity of the inner ear lies the cochlea (Latin for "snail"), which is responsible for the conversion of sound waves into neural impulses. This transduction is inclusive of displacements in the nanometre range and can occur at a rate that humbles other peripheral systems. Engineers are familiar with the Fourier transform, which enables the decomposition of complex signals into fundamental sinusoids.

This spectral discretisation is explanatory of the cochlea's ability to represent audible frequencies as a function of length along the cochlea (tonotopy). This organisational structure is preserved through to the inferior colliculus, a metabolically vibrant region in the midbrain involved in acoustic integration and linked to the cochlea via the auditory nerve.

Sensorineural hearing loss occurs when the hair cells required for transduction are damaged. The cochlear implant is an engineering feat enabling thousands of people to regain some perception of hearing by the controlled electrical stimulation of the auditory nerve fibres. Existing implants provide varying degrees of speech perception, enabling some users to engage in telephonic communication without associative lip reading. In addition, they have been clinically proven to enhance the implantees' quality of life.

Despite its widespread success, the level of hearing restoration, speech intelligibility and music perception provided by the cochlear implant varies greatly among subjects. Speech intelligibility is particularly difficult in noise, while music perception is generally poor, although quiet environments also lead to variance in speech perception, suggesting that there may be inherent subject-specific variables that influence this.

Members of the University of Pretoria's Bioengineering Group have been working in the field of cochlear implants for more than two decades. The research group specialises in computational modelling of the electrically stimulated hearing system. The models are used to probe and understand the underlying

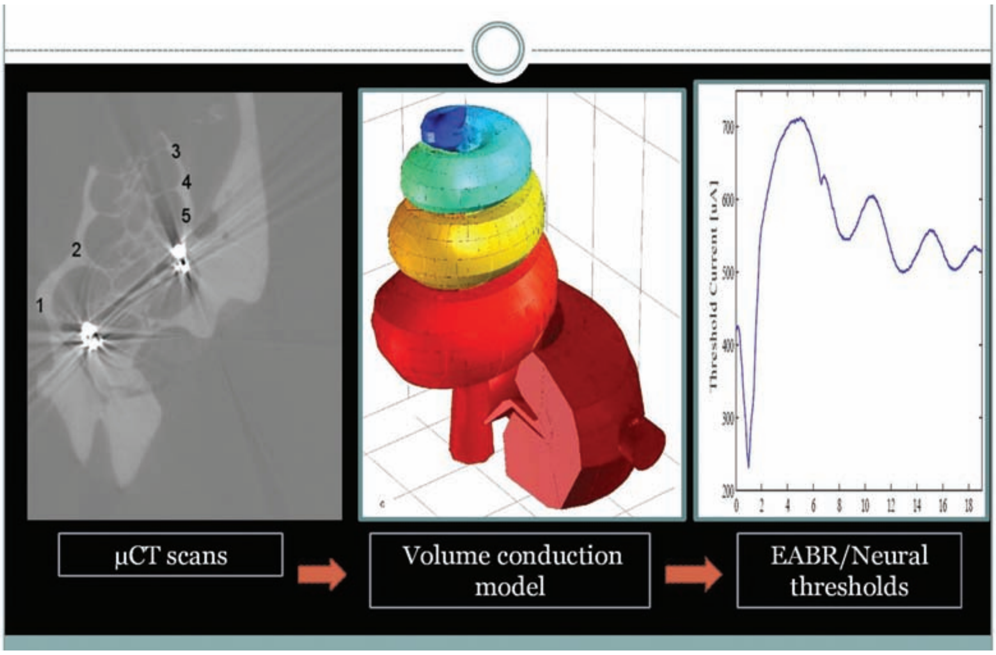


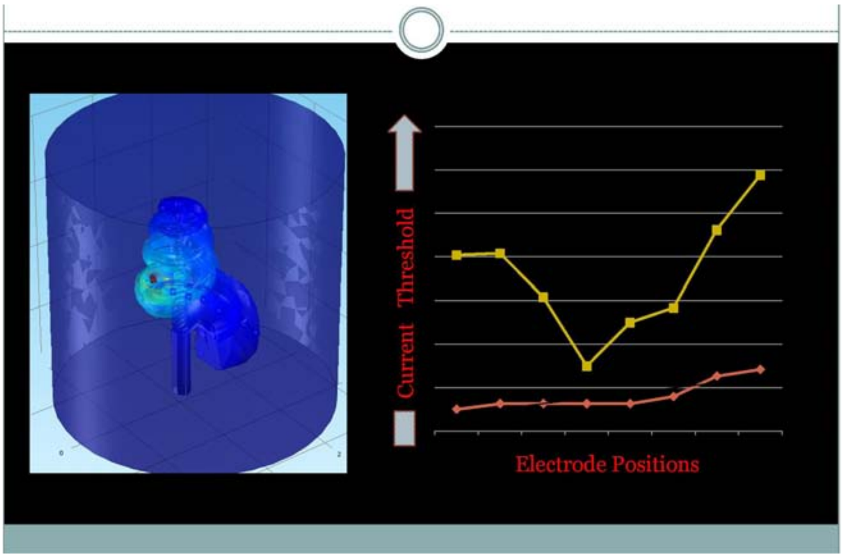
Figure 1. Modelling of a specific subject's auditory neural response.

processes that translate an electrical stimulus into the impaired auditory system to the hearing sensation perceived by the subject.

One of the group's key research areas is the development of models to study the influence of subject-specific variables on hearing performance. The first steps towards the development of a subject-specific model are the identification of the important parameters that govern the behaviour of the stimulated auditory neurons and the development of a technique to represent the anatomy of a subject's cochlea with a computational model using standard non-invasive measurements. Computer tomography (CT) images are used to extract anatomical parameters.

An animal model is a good starting point for the development of subject-specific models, since histological sections can be obtained and used to steer the development of the technique that is used to extract geometrical parameters from the CT scans. Another advantage of an animal model is that invasive measurements of neural responses can be made directly from single-nerve fibres to evaluate the model's accuracy on a neural level. For these reasons, a three-dimensional subject-specific computational model of a specific guinea pig cochlea was developed by the Bioengineering Group using micro-CT data and electro-physiological measurements provided by a partner research group in San Francisco, USA. The complete model incorporates a realistic volume conduction description of the subject's cochlea, constructed from the micro-CT scans, coupled with a neural model that describes the consequential neural excitation behaviour (see Figure 1).

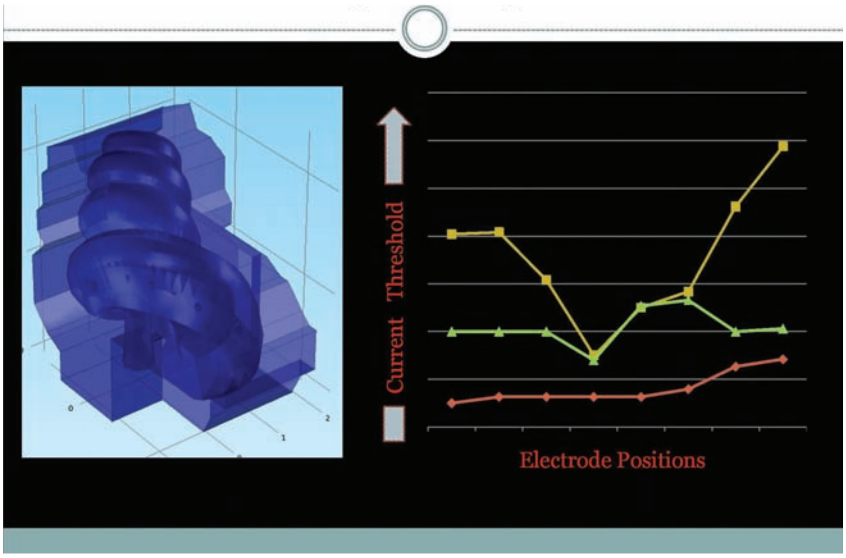
The neural excitation behaviour predicted by the model was



→ *Figure 2. Original subject-specific guinea pig model (left) and threshold current predictions (right).*

compared to measured electrically evoked auditory brainstem response (EABR) data captured from the guinea pig. In Figure 2, the yellow line shows the threshold currents (currents required to elicit a neural response) that were predicted by the model for different electrodes inside the cochlea. The orange line represents the threshold currents that were measured in the guinea pig subject for the same electrodes. The ideal result would be if the predicted threshold currents approach the measured values.

Although the model did not predict the EABR responses with a high degree of accuracy, it was validated as a scientific research tool with significant potential. Initial results also suggested that the model had the potential to perform better than a generic model when predicting EABR data. In retrospect, it was revealed that increasing the



→ *Figure 3. Thin bone enveloping the cochlea (left) and threshold current prediction (right).*

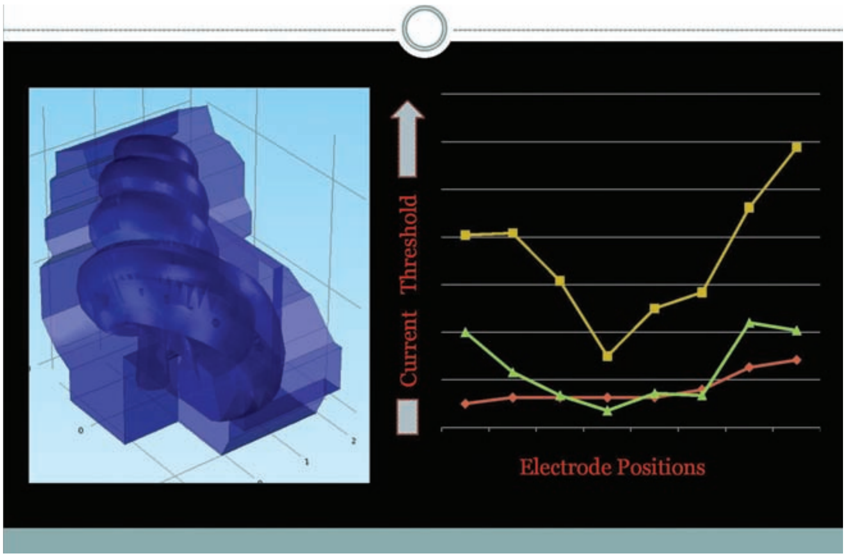


Figure 4. Thin bone enveloping the cochlea in combination with increased model resistivities (left) and threshold current predictions (right).

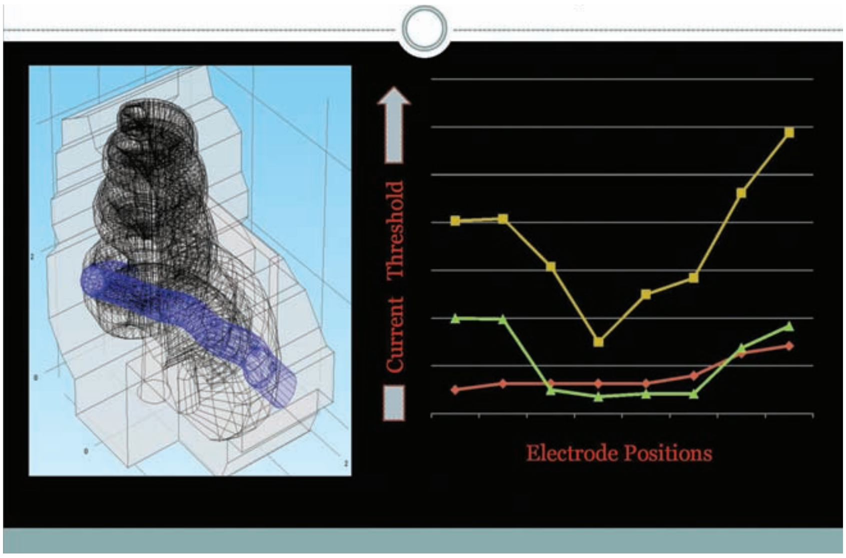


Figure 5. Location of electrode carrier in model mesh (left) and threshold current predictions (right).

complexity of the subject-specific representation may improve the model's predictions.

A follow-up study was thus targeted at the improvement of the model's accuracy, with encouraging results. This research showed that significant improvements to the model's predictions could be achieved with specific alterations to the original model.

Figure 3 illustrates an improvement of the model's prediction when the bone enveloping the guinea pig cochlea is described with greater accuracy. In the original model, the cochlea was embedded in a bone volume extending to infinity in all three dimensions (see Figure 2), but the guinea pig cochlea actually protrudes into an air-filled space with only a thin bone layer surrounding the cochlear structure.

The green line shows the threshold currents predicted by the model with the improved representation of the bone envelope relative to the predictions from the original model (yellow) and the measured data (orange).

Another important factor that influences the threshold current predictions of the model is the impedance values that are used to represent the different tissues. A recent study showed significant intersubject variation in impedances of the same cochlear structure. Figure 4 shows that an even greater improvement can be obtained in the model's predictions through the use of refined impedance values. Increased impedances of the fluids in the cochlear ducts lower the threshold currents by increasing the current density at the target nerve fibres.

Finally, the silicon electrode carrier onto which the electrode contacts are mounted and which fills a significant portion of the cochlear duct into which the electrode array is implanted was also included in the model. The original model excluded the carrier to simplify generation of the model geometry. The most accurate prediction is provided when the thin bone envelope, insulative electrode carrier and refined impedances are integrated, as shown in Figure 5.

These findings provide insight into the various parameters that affect neural excitation behaviour in the electrically stimulated auditory system and also lay the foundation for the development of subject-specific human models. Development of the first human models commenced following the encouraging results from the initial animal model and is well advanced. It is expected that these models could potentially provide a tool to individualise implant parameters, so that a subject can benefit optimally from his or her implant.

Sources

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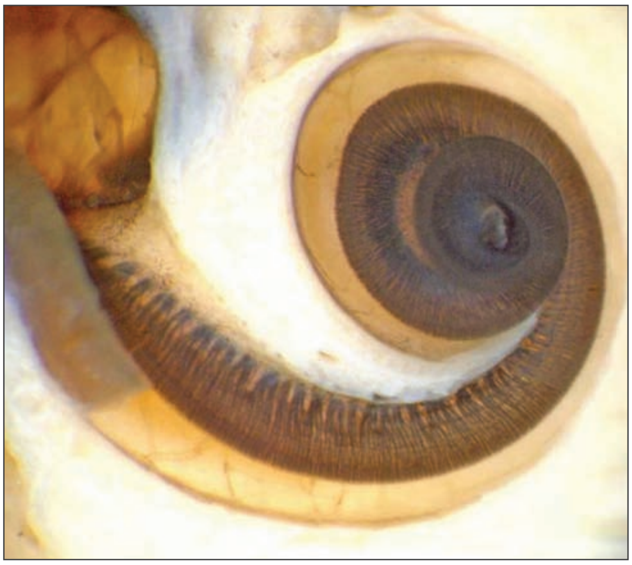

→ *Osseous lamina with its nerve fibres in a specimen oriented in a nearly horizontal plane.*

→ *A preparation in which the modiolus and osseous lamina are seen in profile after removal of the otic capsule bone covering the human cochlea.*