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Research paper

The effect of the resistive properties of bone on neural excitation and electric fields in cochlear implant models

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ABSTRACT

The resistivity of bone is the most variable of all the tissues in the human body, ranging from 312 Ω cm to 84,745 Ω cm. Volume conduction models of cochlear implants have generally used a resistivity value of 641 Ω cm for the bone surrounding the cochlea. This study investigated the effect that bone resistivity has on modelled neural thresholds and intracochlear potentials using user-specific volume conduction models of implanted cochleae applying monopolar stimulation. The complexity of the description of the head volume enveloping the cochlea was varied between a simple infinite bone volume and a detailed skull containing a brain volume, scalp and accurate return electrode position. It was found that, depending on the structure of the head model and implementation of the return electrode, different bone resistivity values are necessary to match model predictions to data from literature. Modelled forward-masked spatial tuning curve (fmSTC) widths and slopes and intracochlear electric field profile length constants were obtained for a range of bone resistivity values for the various head models. The predictions were compared to measurements found in literature. It was concluded that, depending on the head model, a bone resistivity value between 3500 Ω cm and 10,500 Ω cm allows prediction of neural and electrical responses that match measured data. A general recommendation is made to use a resistivity value of approximately 10,000 Ω cm for bone volumes in conduction models of the implanted cochlea when neural excitation is predicted and a value of approximately 6500 Ω cm when predicting electric fields inside the cochlear duct.

1. Introduction

Geddes and Baker reported in 1967 that the resistivity of bone is the most variable of all the tissues of the body because of the variation in its composition throughout the body (Geddes and Baker, 1967). This is supported by numerous studies over the years that reported values from 312 Ω cm (Gabriel et al., 1996) to 84,745 Ω cm (Akhtari et al., 2002), depending on the type of bone (cancellous vs. cortical), orientation of the bone sample during measurement, measurement frequency, species, state of the bone (e.g. live vs. dried and rehydrated) and the specific site, e.g. skull vs. tibial bone.

Volume conduction (VC) modelling studies of the distribution of currents as a result of intracochlear stimulation with cochlear implant electrodes have conventionally used a homogeneous, isotropic, purely resistive value to represent the electrical characteristics of bone. However, since the compact bone that envelops the human cochlea is mainly responsible for directing current through the cochlear structures instead of allowing dispersion of the currents throughout the surrounding head tissues, it is hypothesised that its electrical properties will have a significant effect on the excitation profiles of the auditory neurons. This effect is especially significant using monopolar stimulation where the return electrode is located outside the cochlea in the surrounding bone. The human cochlea is enveloped in what is regarded as some of the densest bone in the human body. Although bone density is not a good indicator of the absolute resistivity of cortical bone, it is reported to be less conducting than cancellous bone. Bone density is affected by many factors including age, chemical composition, gender and disease, e.g. otosclerosis (Bozorg Grayeli et al., 2004), and varies among individuals (Marshall et al., 1996).

Some VC models of the cochlea have thus far used a value of 641 Ω cm for the resistivity of the bone surrounding the vestibular duct (Frijns et al., 1995; Finley et al., 1990; Hanekom, 2001b;

Abbreviations: μ-CT, Micro Computed Tomography; CT, Computed Tomography; EFI, Electrical Field Imaging; FE, Finite Element; fmSTC, forward masked Spatial Tuning Curve; GSEF, Generalised Schwartz-Eikhof-Frijns; VC, Volume Conduction

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Malherbe et al., 2013). This value originated from a value reported in 1987 by Spelman and Clopton (cited in Finley et al. (1990)) and was derived from guinea pig experiments. However, absolute thresholds predicted for humans using this value are greatly overestimated (Hanekom, 2001a; Briaire and Frijns, 2006), while some animal models predict relatively accurate thresholds using this value, e.g. the guinea pig model of Govindasamy (2012). Other studies on neural excitation in and around the human cochlea have used values of 6400 Ω cm (Rattay et al., 2001a), 7143 Ω cm (Kalkman et al., 2014), 6250 Ω cm (Frijns et al., 2009) and a 100:1 bone to scalar fluid conductivity ratio (Mens et al., 1999; Whiten, 2007) which equates to around 7042 Ω cm in the present study. These values were mainly derived by comparing modelled results to objective data. These values are an order larger than the value used in the other studies mentioned. Such large variability of values complicates the selection of the resistivity value to use in a VC model.

The objective of this communication is to report the effect of bone resistivity variations on neural excitation spread and intracochlear potential spread predictions that use VC models as their premise and to propose a range of values that provide realistic predictions when all other tissue resistivities that are used in present VC models of the cochlea are assumed to be sufficiently accurate. The report also deals with various levels of complexity of the implementation of the head volume surrounding the cochlea to assist modellers in making an appropriate choice for the bone resistivity value based on the structure of their model. Forward-masked spatial tuning curve (fmSTC) widths and slopes and electric field profile length constants are compared to measured data found in literature to assess the validity of a predicted result for a bone resistivity value.

2. Methods

Volume conduction models of the implanted cochlea in different configurations were used to assess the effect that the value of bone resistivity has on the spread of neural excitation and intracochlear electric fields. In all model configurations the bone resistivity value was varied while neural and electric spread was calculated. Spread was measured in the form of width (mm) and slope (dB/mm) of the neural excitation curves and in the form of length constant of the intracochlear electric field profiles. These neural and electric spread predictions were then compared to data from literature to determine appropriate bone resistivity values to be used in cochlear models.

The model predicted neural excitation spread from the present study was compared to data in a study from Nelson et al. (2008) in the form of fmSTCs. The average monopolar spread for six implanted Clarion HiFocus users was estimated. The fmSTC slope of 1.2 mm/dB which they obtained was used as the benchmark for the predictions in the present study. Their study also measured the average fmSTC width at 1 dB above threshold as 4.6 mm, which was used as the benchmark to which the results in the present study were compared to. Care was taken to mimic the methodology of the Nelson et al. experiments to ensure that the data is comparable.

The electric field data from literature came from a study by Tang et al. (2011) where electrical field imaging (EFI) data of five implanted cochleae are presented. An EFI curve represents the voltages measured on all the electrodes of an implanted array when a stimulus is presented through a single electrode. In that study EFI profiles were obtained for a basal, middle and apical stimulus electrode in each of five implanted ears. The averaged EFI profiles of these electrodes in all the ears were compared to the modelled data in the present study. All the ears in the Tang et al. (2011) study were implanted with Clarion HiFocus electrode arrays; subsequently the volume conduction models in the present study were also implemented with Clarion HiFocus electrode arrays.

2.1. Volume conduction models

Five finite element (FE) volume conduction (VC) models based on the morphologies of five individual implanted cochleae of live human implantees were used. All ears of the users have been implanted with the Nucleus 24 cochlear prosthesis from Cochlear Limited: four with contour electrode arrays and one with a straight electrode array. However, although the Nucleus device allows the recording of electrode potentials, a floating reference ground causes difficulties in obtaining absolute potential levels and thus electric field profiles cannot be measured for Nucleus users. To compare modelled results to the Nelson et al. data in the neural domain (fmSTCs) and to the Tang et al. (2011) data in the electrical domain (electric field profiles), it was thus necessary to convert the Nucleus electrode arrays in the VC models to Clarion HiFocus electrode arrays. This was done by changing the size and spacing of the modelled electrode contacts to those of a HiFocus array while maintaining the intra scalar location of the electrode carrier of each user. This conversion resulted in the electrode contacts having a slightly curved surface as opposed to a flat surface of a HiFocus array. The effect of this slight curvature on results was assumed to be minimal as the surface area of the HiFocus electrodes was maintained.

The geometry of each model was constructed from computed tomography (CT) data of each implanted ear using similar methodology as described for the construction of our guinea pig model (Malherbe et al., 2013). In that study, the bony geometry of the cochlea and location of the electrode contacts were estimated from μ-CT data and augmented with a model containing the finer inner structures of the cochlea. The same approach was followed in the present models, with the exception being that the bony cochlear geometry was estimated from relatively low resolution standard clinical CT images of which the image sharpness was increased using bicubic interpolation and application of a colour lookup table. Fig. 1 shows a mid-modiolar section through a single duct of a user's cochlear model with regions that have different material properties (electrical resistivity) indicated. The material that envelops the structures is bone and is indicated in grey. The spiral lamina is also represented by the same material property as that of

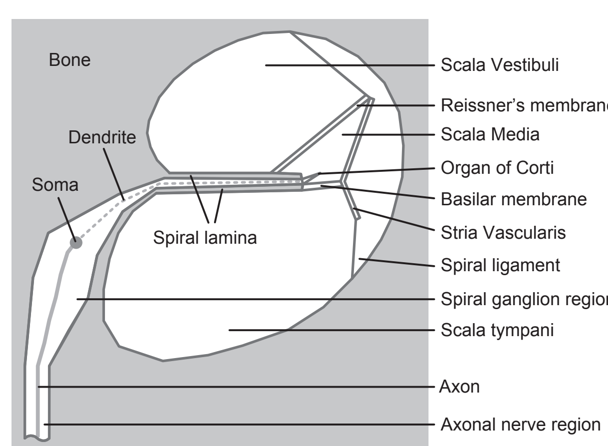

Fig. 1. Mid-modiolar section through a single duct of the cochlear part of the VC model indicating modelled structures that were assigned different material properties. Modelled structures are entirely encased in bone (grey area). The spiral lamina is also modelled with the same material as the surrounding bone. The position of the neuron is indicated with the soma in the spiral ganglion region.