Chapter 6

GENERAL DISCUSSION

1 RESEARCH PROBLEM AND APPROACH

Accurate models of the implanted cochlea are required to gain a better understanding of the functioning of cochlear implants and to be used as tools during the development of new generation cochlear implants (Briaire & Frijns, 2000). Such models could focus on the nerve-implant interface or on processing of auditory information by the higher auditory system. In this thesis the focus was on modelling of the nerve fibre-implant interface. The objective was to introduce an accurate model of the implanted cochlea with which potential distributions and neural excitation patterns around cochlear implant electrodes could be determined.

To gain an appreciation of the effects of the 3-D structure of the implanted cochlea and of array and model variations, a 3-D model was required. Although a number of 3-D volume conduction models of the cochlea exist, a model that could effortlessly facilitate simulation of array variations and could therefore also be used to experiment with new arrays has not yet been constructed. The definition and construction of a detailed 3-D spiralling FE model of the implanted cochlea have been discussed. The model was extruded from a 2-D geometry representing a section through one turn of the cochlea into three dimensions around a central axis. The model incorporates the effect of neighbouring canals and conduction along the fluid-filled scalae of the cochlea. To create different array locations, electrode geometries and electrode configurations without remeshing the volume containing the electrode array, two electrode arrays were included in the original model. To activate or deactivate a specific array the resistivities of its elements were changed to those of an insulator or a conductor while the resistivity of the other array's elements was set to that of perilymph. Model generation, choice of model parameters and model verification methods have been discussed in detail in Chapter 2. Potential distributions generated with the FE model have been coupled to a nerve fibre model to facilitate the investigation of auditory nerve fibre excitation patterns around intracochlear electrode arrays. The GSEF nerve fibre model was used to calculate the neural response to excitation. The nerve fibre model is coupled to the FE model by defining the location of an array of nerve fibre models as a curved plane in the FE model. The nerve fibre model and also the FE-nerve fibre model interface have been discussed in full in Chapter 2.

2 RESULTS AND CONCLUSIONS

This study mainly endeavoured to explain four aspects influencing neural excitation patterns as a result of intracochlear stimulation: (1) the effect of array variations and nerve fibre degeneration (Chapter 3), (2) the effect of model variations (Chapter 3), (3) the effect of scar tissue around implanted electrodes (Chapter 4), and (4) focussing and shaping of excitation profiles with nonstandard electrode configurations (Chapter 5). In all cases the 3-D FE model described in Chapter 2 was used to calculate potential distributions as a result of current injection from different array variations with and without variations in the model structure. Activating function contours were frequently used to obtain a preliminary estimate of excitation profiles that can be expected as a result of a specific potential distribution. A nerve fibre model was used to translate potential distributions into excitation profiles that could be interpreted in terms of data measured in animals and humans.

In general it was found that the spiralling geometry of the cochlea causes asymmetry in potential distributions and that the location of electrodes along the length of the basilar membrane has a stronger influence on the location of excitation along the basilar membrane than the polarity of the leading phase of the stimulus.

Variation in array location indicated that threshold currents and the effect of postsurgical neural degeneration (and also ongoing loss of peripheral dendrites) on threshold currents can be limited by placing arrays close to the modiolus. It was also shown that array location is the primary parameter that controls excitation spread, although electrode separation can be used to a lesser extent to do the same. Subsequent variations in electrode geometry showed that point electrode geometries are recommended above banded electrode geometries only when the array can be placed close to the modiolus.

The critical focussing intensity of an electrode configuration was defined as the lowest stimulus intensity relative to the minimum threshold current where the excitation profile displays a discontinuity in slope. This discontinuity in the excitation profile indicates the point where spread of excitation becomes unfocussed. It was shown that CFI is a function of electrode separation.

The existence of bimodal excitation patterns at comfortable stimulus intensities for longitudinal bipolar electrode configurations were confirmed. The threshold minimum around the electrode that should act as the return electrode (and not as stimulating electrode) is regarded as an ectopic region of excitation. It was shown that NBP electrode configuration can be used besides radial, offset radial and monopolar electrode configurations to create unimodal excitation patterns. The CFI indicated that the focussing ability of monopolar stimulation is approximately the same as that of widely spaced bipolar electrode configurations. This finding is significant since widely spaced electrode configurations are frequently used to excite nerve fibres when closely spaced electrode configurations fail to do so. Given the advantage of unimodal excitation patterns when using monopolar electrode configurations, monopolar electrode configurations should be favoured above widely spaced bipolar configurations if the option is available. Based on current spread versus electrode configuration curves, and CFI values, it is believed that monopolar stimulation could be advantageous when BP+2 stimulation is required.

Evidence of electrode discrimination ability by implant wearers for overlapping regions of excitation exists (Hanekom & Shannon, 1996). In addition, simulation results indicated that neighbouring, narrowly spaced electrode pairs create overlapping but different excitation patterns. These observations suggest that the stimulation resolution of cochlear implant electrode arrays can potentially be improved by increasing the number of electrode contacts in an array.

Model results indicated that there is a tradeoff between array location and the degree of ectopic stimulation caused by a specific array location. Perimodiolar arrays, which are the arrays of choice when focussed excitation is required, are more prone to cause ectopic excitation than arrays further away from the nerve fibres. A precautionary measure that could be taken to prevent ectopic excitation is to use the *narrowest* possible spaced electrode pair that would elicit a response and allow sufficient loudness growth. This could mean that several different electrode configurations should be used in one implant wearer to obtain the best results.

The effects of various cochlear structures in the model on excitation profiles were investigated. It was shown that, at least in this model, the effects of the helicotrema, stria vascularis and Organ of Corti were negligible. Structures that did have a noticeable effect and should consequently be included in future models, are the spiral lamina, Reissner's membrane and the basilar membrane. Simulated tapering of the perilymphatic spaces in the cochlear model also had a marked effect on mainly minimum threshold currents. Narrowing of the cochlear canals towards the apex causes an increase in the resistivity of the volume surrounding the electrodes which, in turn, causes threshold currents to decrease towards the apex. Evidence of more focussed excitation towards the apex as a result of tapering of the canals is vaguely displayed by the model and could be more pronounced in a real cochlea.

The effect of electrode encapsulation by fibrous scar tissue on electrical potential distributions and auditory nerve fibre excitation patterns was investigated by creating a thin layer of encapsulation tissue around the modelled electrodes in the FE model.

An LP model of the implanted cochlea incorporating encapsulation tissue around the electrode array was created to explain threshold changes predicted by the FE-nerve fibre model in the presence of encapsulation tissue. Both the LP and the FE models show that electrical potentials at the target nerve fibres and the electrode contacts increase in the presence of encapsulation tissue. This leads to a decrease in threshold currents and spread of excitation. Narrowly spaced electrode configurations and array locations close to the modiolus are influenced most by the presence of encapsulation tissue. It was concluded that the effect of electrode encapsulation on threshold currents and spread of excitation is a function of electrode configuration and array location. Although compliance problems could occur if the resistance of encapsulation tissue becomes very high, advantages of electrode encapsulation could be a decrease in threshold current and an increase in dynamic range.

In Chapter 4 it was observed that a local increase in the resistivity of the volume in contact with the electrodes can cause a decrease in threshold currents, as well as an increase in the focussing ability of an electrode configuration. Some evidence that the same effects are caused by tapering of the cochlear canals (i.e. an increase in the resistance of the cochlear volume surrounding the electrodes) was also found in Chapter 3. These observations suggest that the electrode carrier might also serve to lower threshold currents and could even focus excitation. This statement was verified with simulations where the electrode carrier was deactivated[1] (i.e. its resistivity was set equal to that of perilymph) and has also been proposed by Suesserman and Spelman (1993). It has been suggested that an electrode carrier that replaces much of the perilymph in the scala tympani could compensate for electrode to nerve fibre distance variations (Seldon et al., 1994; Zrunek et al., 1980). Such variations are known to cause threshold current variations and also variations in the focussing of neural excitation patterns around electrodes (Chapter 3, Shepherd et al., 1993). A variation on the scalar filling approach has recently been introduced

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[1] These results have not been presented elsewhere in this thesis.

by which a straight array (e.g. the electrode array of the Nucleus implant) is placed in a perimodiolar position (Tykocinski et al., 2000). This is done by an electrode positioner that is inserted into the scala tympani lateral to the electrode array and distal from the modiolus, forcing the array into a perimodiolar position. Based on model results this technique should reduce threshold currents and spread of excitation as hoped. However, whether sufficient flow of perilymph will be possible to assure minimal cochlear damage over the long term, e.g. survival of the hair cells (Leake, Kessler & Merzenich, 1990), is not clear.

Finally, the focussing and shaping ability of various multi-electrode configurations was investigated. Electrode configurations modelled included enhanced tripolar, quadrupolar, tetrapolar and pseudo-continuous configurations. It was confirmed that focussing of excitation around intracochlear electrodes could be improved by using overlapping quadrupolar electrode configurations. Side-lobes in the excitation profile, which occur at relatively higher stimulus intensities relative to the stimulus intensity required to excite the target nerve fibres, can be further suppressed if the currents that are returned to the lateral electrodes are spread over multiple electrodes. The ultimate lateral spread would occur for a common ground return electrode. Simulation results suggest that a tradeoff could exist between focussing ability of electrode configurations and suppression of side-lobes in the excitation profile.

It has been shown that it could be possible to shape the excitation profile continuously with enhanced tripolar electrode configurations, multipolar banded electrode configurations and pseudo-continuous electrode configurations. Model results obtained with shaping electrode configurations suggest that the SAS strategy implemented in the Clarion processor could effectively deliver auditory information in a simultaneous fashion to different nerve fibre populations in the cochlea.

Results from Chapter 3 suggest that electrode pairs might be discriminable even though their respective regions of excitation might overlap. Furthermore, results from Chapter 5 that show that continuous shaping of the excitation profile might be possible with an array with high lateral electrode density and that the focussing ability of multipolar electrode configurations is improved if electrode separation is decreased. These results provide some evidence in favour of increasing the lateral electrode density of intracochlear electrode arrays. An array with high lateral electrode density could also facilitate customization of the array for individual implant users by selecting subsets of electrodes based on surviving nerve fibre patterns.

3 RESEARCH CONTRIBUTION

The most important research contributions made by this study are the following:

1) The creation of a detailed 3-D model of the implanted cochlea that accurately predicts measurable effects in cochlear implant wearers and facilitates effortless implementation of existing and new array variations.
2) The establishment of the important fine anatomical structures required in a 3-D representation of the implanted cochlea.
3) Establishment of evidence that array location is the primary parameter that controls spread of excitation.
4) Confirmation that monopolar stimulation could deliver focussed stimulation to approximately the same degree than that delivered by widely spaced electrode configurations and that the use of monopolar configurations over bipolar configurations is advantageous under certain conditions.
5) Explanation of the effect that encapsulation tissue around cochlear implant electrodes could have on neural excitation profiles.
6) Extension on the information available on the focussing ability of multipolar electrode configurations.
7) Establishment of evidence that excitation profiles could be shaped in a continuous fashion using multiple radially oriented electrode pairs and also longitudinally oriented electrode sets operating in a non-bipolar fashion.
8) Confirmation that the SAS strategy could effectively deliver auditory information to different neural populations along the length of the cochlea.

9) Establishment of evidence that a higher lateral electrode density could facilitate better focussing of excitation, continuous shaping of excitation profiles and postoperative customization of electrode arrays for individual implant wearers.

4 FUTURE RESEARCH DIRECTIVES

Much valuable information has been gathered from the representation of an implanted cochlea has been presented in this thesis. Although the model does not incorporate the tapering of the cochlea toward the apex, simulations that were performed in a restricted region of the cochlea (e.g. simulation of NBP to BP+3 electrode configurations confined to the region halfway through the first half-turn of the modelled cochlea) are not significantly influenced by the untapered geometry. The present model lies the foundation for development of a tapered, high resolution, detailed model of the human cochlea and the use of a more accurate human nerve fibre model that includes fine details such as the soma region of the fibre (Rattay, 1999).

However, although the information gained by the above-mentioned improvements could provide some additional insights into the nerve fibre-implant interface, results are nonspecific, i.e. only general trends in cochlear implant patients can be predicted. It is proposed that the next quantum step in modelling of the auditory nerve-implant interface would be to model individual cochleas. This could facilitate preoperative evaluation of potential cochlear implant candidates, estimation of the potential benefits of implantation for an individual and ultimately, estimation of what a person could expect to hear with his or her implant. To facilitate modelling of individual cochleas, research presented in this thesis should be extended to include the development of high resolution imaging techniques whereby an accurate numerical representation of the shape of an individual's cochlea can be obtained. Automatic model generation software and atraumatic techniques to estimate nerve survival patterns inside the deaf cochlea should also be developed. The model presented in this thesis can provide a basic geometry which could be adapted according to the additional information gained from imaging, e.g. by scaling each model segment according to the dimensions provided by the imaging technique.

The model provided evidence that a high density electrode array could increase the amount of auditory information that can be transferred to the auditory nerve fibres. Research required to complement the findings in this thesis regarding high density electrode arrays should include *in vitro* characterization of the potential fields generated by such an array in an electrode tank and also measurements in cadaver cochleas and animals to assess the functionality and effectiveness of such an array.