Chapter 1
INTRODUCTION

It is generally accepted that cochlear prostheses can be successfully used to treat profound deafness (National Institutes of Health, 1995). In a study performed by Kou, Shipp and Nedzelski (1994) it was found that the majority of the cochlear implant subjects in the group studied, experienced a substantial improvement in independence and communication confidence after cochlear implantation. This finding was ascribed to an increased ability of implant wearers to communicate via hearing and an increased awareness of environmental sounds. However, much interperson variation in performance still exists and subjects do not all experience the same benefits from their cochlear implants.

The functioning of cochlear implants is still not well understood despite much research that has been done on the interaction between the implant and the target nerve fibres. To improve and ultimately guarantee subject benefits from cochlear implants, the mechanisms underlying the functioning of these devices have to be studied so that improvements can be based on a detailed understanding of the system as a whole.

Chapter 1 serves to place the research described in this thesis concerning the physical interaction between the implant and the target nerve fibres in context with research to date. Specific emphasis is placed on the distribution of electrical potentials in the cochlea and the neural excitation patterns following electrical stimulation. Factors that have an influence on these distributions are also discussed.

1 CONTEXT OF THE PROBLEM

1.1 Basic operation of cochlear implants

The peripheral auditory system consists of three primary parts: the outer ear, the middle ear and the inner ear or cochlea. The cause of profound deafness is in many cases located in the cochlea, where pressure waves caused by sounds have to be transduced to neural signals travelling to the higher auditory centres of the brain. The transducing mechanism between pressure waves and the electrical nerve impulses are hair cells which are located inside the cochlea. Profound deafness is in many cases associated with the loss of hair cells. If the hair cells are damaged or destroyed, no neural information can reach the higher auditory centres in the brain even though the neural pathways from the cochlea to the brain are intact. Deafness caused by hair cell loss can mostly be rehabilitated with a cochlear implant by directly activating the auditory nerve fibres through electrical stimulation (Black & Clark, 1980; Clark, 1996; Clark et al., 1990; Girzon, 1987; Rebscher et al., 1996).

Cochlear implants normally consist of three primary parts: an external signal processing unit, a telemetry system and an implanted stimulator-electrode system. The external signal processing unit detects sounds with a microphone and converts these sounds to an electrical code. This code is transmitted through the skin via a telemetry system to the implanted stimulator. The stimulator circuit uses the code to generate electrical signals that drive the electrode (in the case of single channel devices) or electrode array[1] (in the case of multi-channel devices) which is usually placed close to the residual nerve fibres inside the cochlea. The objective of intracochlear stimulation is to replicate the neural activity produced in the normal ear during acoustic stimulation (Girzon, 1987; Suesserman & Spelman, 1993). When a

[1]In this thesis the term "electrode" is used when reference is made to a single electrode contact. The electrode array, consisting of a silastic electrode carrier, electrode contacts and wires connecting the electrode contacts to the implanted electronics, is referred to as the "electrode array" or simply the "array".

cochlear implant is used, the entire peripheral auditory system up to the nerve fibres is essentially bypassed - the cochlea merely serves as a convenient mounting space for the electrode array since it contains the terminals of the auditory nerve fibres as well as an electrolyte (perilymph) to serve as conduction pathway between the electrodes and the nerve fibres.

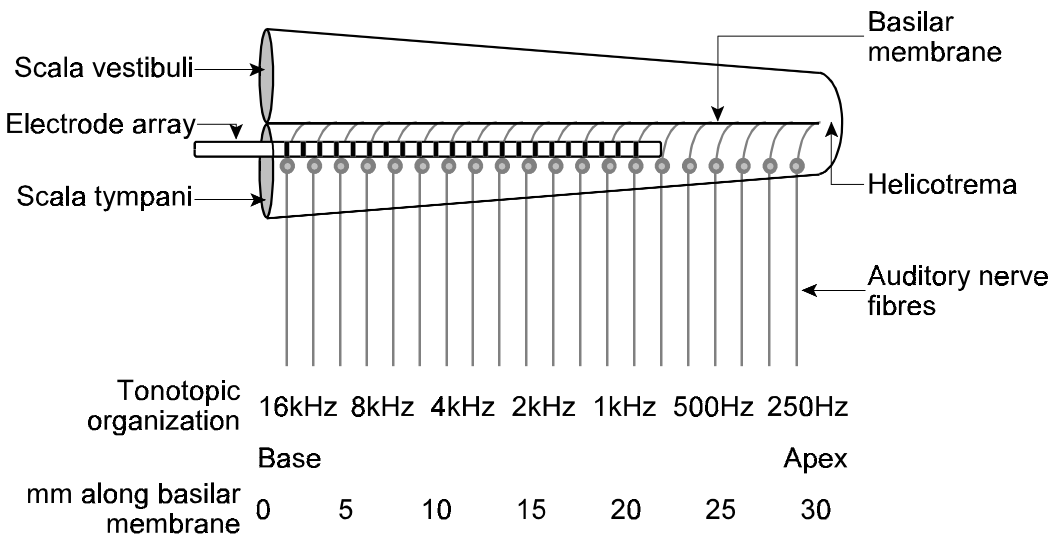

Figure 1.1. A simplified unrolled representation of the cochlea showing the auditory nerve fibres, the tonotopic organization of these nerve fibres and an intracochlear electrode array in the scala tympani.

The auditory nerve fibres inside the cochlea are tonotopically arranged (Figure 1.1) so that those nearest to the base of the cochlea detect high frequencies and those nearest to the apex low frequencies (Eddington et al., 1988; Frijns, 1995). Multichannel implants currently make use of this tonotopic arrangement of the auditory nerve fibres to produce perceptions of changing pitch. By spacing the electrodes along the length of the cochlea (Figure 1.1), different populations of nerve fibres can be excited to produce different perceptions of pitch (Eddington et al., 1988; Frijns, 1995; Rebscher et al., 1996; Suesserman & Spelman, 1993).

1.2 Understanding and improving cochlear implants

Rubinstein (1988) identified three basic processes that have to be understood before a complete theory of the speech information transfer in cochlear implant subjects can be structured. These three processes include conversion of speech into electrical stimuli, the nerve fibre-electrode interface and information processing by the central auditory nervous system. Figure 1.2 shows a diagrammatic representation of the broad research areas concerned with each of the processes.

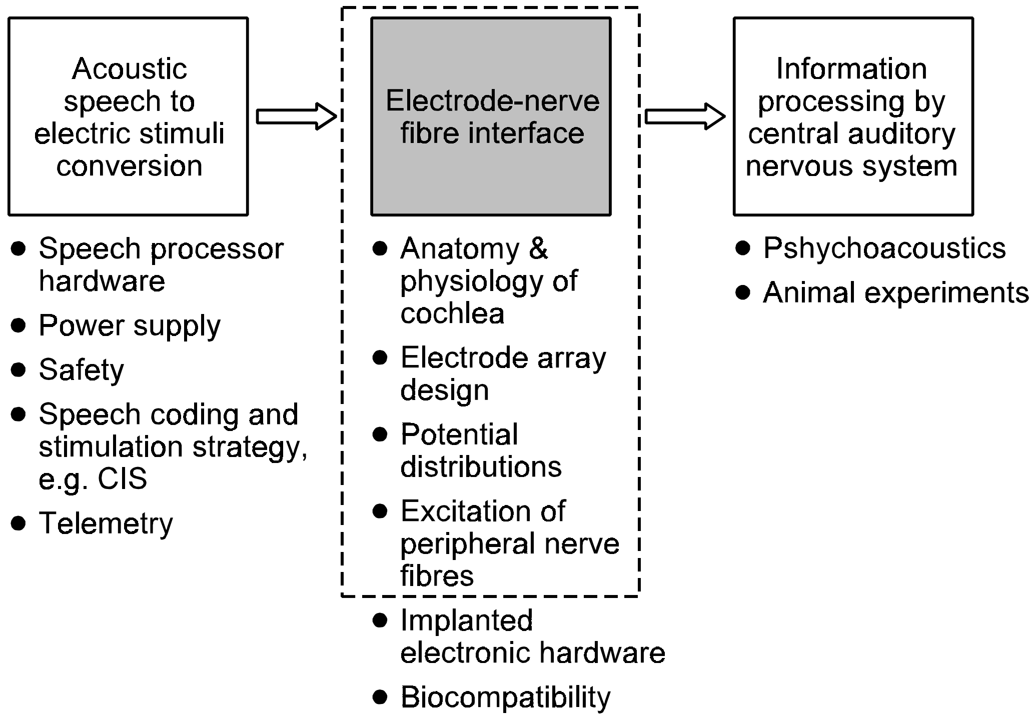

Figure 1.2. Diagrammatic representation of the broad areas in cochlear implant research. The research area addressed in this thesis is indicated with a dashed block.

Vast variations in the hearing sensations experienced by different users of cochlear implants bear witness to the fact that none of these processes is fully understood yet. Variations manifest in aspects such as the unpredictability of the performance of a cochlear implant subject preoperatively (Clark, 1996), the inability of most implant users to perceive music (Fujita & Ito, 1999), and the fact that many users cannot use a telephone or struggle to follow speech in noisy environments (Hirsch, 1993). Perceived auditory sensations vary as a result of complex interactions between several patient and device related factors, i.e. electrode placement, shape and size of the cochlea, number and distribution of surviving nerve fibres inside the cochlea and tissue reactions to the implanted electrode (Rebscher et al., 1996; Ruddy & Loeb, 1995).

To address variations in perception, Loizou (1999) pointed out that (1) the factors that contribute to variability in performance among patients must be identified, (2) preoperative procedures that can predict how well a patient will perform with a particular type of cochlear implant have to be developed and (3) better electrodes capable of providing a high degree of specificity have to be designed. Activation of sensory nerve fibres by electrical stimulation with a high degree of specificity is regarded as one of the main problems in cochlear prostheses research (Girzon, 1987; Kral et al., 1998; Loizou, 1999; Miller & Spelman, 1990; Ruddy & Loeb, 1995). Researchers active in the field agree that better models of the three-dimensional structure of the cochlea are necessary, that better models of the current distribution are required, and that this knowledge can lead to better electrode designs (Miller & Spelman, 1990; Suesserman & Spelman, 1993).

1.3 Volume conduction models of the implanted cochlea[2]

Girzon (1987), Finley (1990), Frijns et al. (2000; 1995) and Rattay (2000) made important contributions in the field by creating volume conduction models to predict the potential distributions around intracochlear electrode arrays and developed neural models to predict nerve fibre excitation patterns around electrode pairs.

However, existing detailed volume conduction models are limited to spiralling models for either the guinea pig cochlea (much anatomical detail included) (Frijns, Briaire, & Schoonhoven, 2000) or a simplified human cochlea (Rattay, Leao, & Felix, 2000). The models also do not provide an easy method to test structural and geometrical

[2]The phrase "implanted cochlea" is used to refer to a cochlea that contains an implanted electrode array.

variations of the electrode array or variations in the anatomical structure of the cochlea. The degree of anatomical detail that is necessary to include in such models has not yet been established either.

1.4 Potential distributions and neural excitation patterns

1.4.1 Array location, electrode configuration and nerve fibre properties

Electrical potential distributions at the target nerve fibres are dependent on the material, size, shape and impedance of the electrodes, the amplitude and waveform of the electrical stimulus, the distance from the electrode to the nerve fibre and the characteristics of the tissues surrounding the implant (Marsh, Coker, & Jenkins, 1992; Ruddy & Loeb, 1995). Threshold currents at which a nerve fibre will be activated and spread of neural activation are functions of these electrical fields and of the electrical properties of the nerve fibres, their dimensions and survival patterns and higher order processing in the central nervous system. The closer an electrode is to the nerve fibres, the less current is required to elicit a threshold response (Shepherd, Hatsushika, & Clark, 1993), the larger the dynamic range of stimulation is and the more discrete the stimulated nerve populations are (Skinner et al., 1994; Wang et al., 1996).

Experimental data of Pfingst et al. (1995) showed that the intensity of the potential fields generated at a specific stimulation current changes if the electrode configuration is changed. It has been experimentally verified that lower currents are required to reach the psychophysical detection threshold if widely spaced bipolar[3] electrode pairs are used for stimulation than when more narrowly spaced pairs are

[3] The term *bipolar electrode pair* is normally used when referring to the Nucleus electrode array from Cochlear Corporation Ltd. A bipolar (BP) electrode configuration refers to an electrode pair consisting of two neighbouring electrode contacts which are both located inside the cochlea. A bipolar+1 (BP+1) electrode configuration refers to an electrode pair separated by one electrode contact, bipolar+2 (BP+2) by two electrode contacts, bipolar+3 (BP+3) by three electrode contacts, etc. A "widely spaced" bipolar pair refers to a BP+m electrode configuration where m>0.

used (Pfingst, Morris, & Miller, 1995; Shepherd, Hatsushika, & Clark, 1993). Some auditory prostheses make use of electrode spacing to control the loudness of electrical stimulation and to ensure that the device can deliver adequate current to effect stimulation (Pfingst, Morris, & Miller, 1995). The lowest threshold for electrical stimulation is usually obtained with monopolar[4] electrode configurations.

Research contributions in this area can potentially be made by quantification of the discussed observations in terms of parameter variations such as electrode separation, array location and survival patterns of auditory nerve fibres.

1.4.2 Postoperative changes

Changes to the electrode-nerve fibre interface that occur after implantation could influence neural excitation patterns. Such changes could include further degeneration of the nerve fibres and the formation of scar tissue and bone around the electrode array.

Implantation and direct stimulation of the nerve fibres in the cochlea do not cause degradation of these structures if no trauma is caused. Rather, electrical stimulation may preserve existing neural processes and decrease or eliminate the normal sequence of neural degeneration that follows deafness (Leake et al., 1992; Shepherd, Hatsushika, & Clark, 1993). However, it has been shown that trauma to the cochlea is not uncommon during insertion of an electrode array (Welling et al., 1993). It includes scraping or tearing of the endosteum lining the medial wall of the scala tympani, damage to the osseous spiral lamina including fracture, perforation of the basilar membrane, including deviation of the electrode into the scala media or scala vestibuli, and damage to the spiral ligament (Rebscher et al., 1996). Studies in cats have shown that even minimal damage to the spiral ligament, basilar

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[4]A monopolar electrode configuration refers to an electrode pair consisting of a stimulating electrode that is located inside the cochlea, normally the scala tympani, and a return electrode that is located outside the cochlea, for example in the temporalis muscle.

membrane or osseous spiral lamina results in direct rapid loss of peripheral dendrites and spiral ganglion cells (Leake et al., 1992).

Trauma to the cochlea during electrode insertion could also cause tissue reactions such as the formation of scar tissue or new bone at the implant-tissue interface (Webb et al., 1988; Zappia et al., 1991). Grill and Mortimer (1994) reported that the resistivity of encapsulation tissue around implanted electrodes is sufficient to alter the shape and magnitude of the electric field generated by such electrodes. Postoperative changes to the cochlea and the implant-tissue interface could be responsible for threshold variations that are frequently observed in the months following implantation (de Sauvage et al., 1997; Pfingst, 1990).

The mechanisms responsible for postoperative changes in threshold currents are not clearly understood yet (Brown et al., 1995; Miller, Morris, & Pfingst, 2000) and require further investigation.

1.5 New electrode arrays

In an NIH report on the development of speech processors for cochlear prostheses Wilson, Lawson and Zerbi (1996) commented on existing cochlear electrode designs and proposed the development of an electrode array with a greater number of electrodes which are spaced closer to the medial wall of the scala tympani as a new generation solution to overcoming deficiencies in existing designs. The design of improved cochlear prostheses requires a better understanding of the factors that dictate the potential distributions and therefore the neural activation patterns inside the implanted cochlea (Girzon, 1987).

Knowledge of the exact location of the electrode array within the cochlea is important to improve electrical stimulation of the auditory nerve (Gstoettner et al., 1999). To control the location of the array, state of the art intracochlear electrode arrays assume a perimodiolar position inside the scala tympani (Schindler & Kessler, 1989; Tykocinski et al., 2000). This has the additional benefits of lowering threshold currents, limiting spread of excitation and increasing dynamic range (Tykocinski et al., 2000). However, the number of electrode contacts that are currently used is between 16 and 22 which is very few compared to the approximately 30 000 nerve fibres (Allen, 1985) that must be activated by these electrodes. Furthermore, stimuli are mostly delivered nonsimultaneously to electrode pairs to prevent crosstalk between electrode pairs, corrosion of the electrode metal and uncontrollable spread of excitation. Recent advances in the development of intracochlear electrode arrays include better focussing of excitation and limiting of lateral current spread, thus allowing simultaneous stimulation via all electrode pairs (Advanced Bionics Corporation, 2000). Research in this field is continuing and could be complemented by accurate models of the implanted cochlea.

2 RESEARCH GAP

From the deficiencies in the understanding of the functioning of cochlear implants with regard to the nerve fibre-implant interface, the following research gap has been identified:

1) The construction of a *detailed* three-dimensional volume conduction model of the implanted cochlea that can be adapted to investigate potential distributions and neural excitation patterns as a result of
   a) stimulation with existing electrode configurations;
   b) variations in electrode configuration, electrode geometry and array location;
   c) stimulation with new, improved electrode arrays; and
   d) variations in the model structure or current pathways such as the absence or presence of electrode encapsulation and cochlear structures, i.e. the helicotrema and the Organ of Corti.
2) Qualitative and quantitative characterization of the effects of the above-mentioned aspects on auditory nerve excitation patterns to contribute

towards the knowledge base on the implant-nerve fibre interface.

The area within cochlear implant research that is addressed in this thesis is indicated with a dashed block in Figure 1.2.

3 OBJECTIVE AND OVERVIEW OF THIS STUDY

The objective of this study is to provide additional insight into the functioning of current intracochlear electrode arrays and also to facilitate investigation of new electrode arrays. The focus is on potential distributions and excitation profiles generated by different electrode array types and factors that could have an influence on these distributions and profiles.

Chapter 2 deals with the generation of a three-dimensional finite element model of the implanted cochlea to calculate potential distributions on the nerve fibres as a result of electrical stimulation. The interface of the finite element model with an existing nerve fibre model and a modification of the nerve fibre model to represent degenerated nerve fibres are described. In Chapter 3 the effect of electrode geometry and configuration, array location, anatomical structure of the cochlea and peripheral dendrite degeneration are investigated. Chapter 4 illustrates and explains the effect of scar tissue around intracochlear electrodes on excitation patterns while Chapter 5 investigates multi-electrode configurations that could be used for focussing and continuous, simultaneous shaping of the excitation profile of the auditory nerve fibres. The thesis is concluded with a general discussion and a summary of results and findings in Chapter 6.