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Chapter 5

MULTIPOLAR ELECTRODE CONFIGURATIONS AND SIMULTANEOUS STIMULATION

1 INTRODUCTION

Electrode configuration influences aspects such as phoneme recognition in the speech recognition ability (Fu & Shannon, 1999a;1999b) and pitch perception (Busby et al., 1994) of implant users. This could be because dissimilar neural populations are activated by different electrode configurations (Busby et al., 1994; McKay, O'Brien, & James, 1999). Besides the potential distributions around cochlear implant electrodes, the stimulation strategy also has an influence on the sound sensation perceived by implant wearers because it controls the place and temporal information that are provided to the nerve fibres in the cochlea (Loizou, 1999). Cochlear implant stimulation strategies either transmit place information (vocoder type strategies, e.g. SPEAK (Loizou, 1999)) or mimic the temporal structure of auditory signals in addition to providing place information (i.e., the CIS strategy (Loizou, 1999) and the SAS strategy (Kessler, 1999)).

It has been proposed that improvement of the focussing ability of intracochlear electrodes could improve the performance of cochlear implants (Loizou, 1999; van den Honert & Stypulkowski, 1987). Moreover, research in cochlear implants has increasingly been focussed on ways to manipulate the excitation patterns of the cochlear nerve mainly by improving the electrode design, manipulating the electrode

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configuration and varying the stimulus distribution[1] on the electrodes (Jolly, Spelman, & Clopton, 1996; Liang, Lusted, & White, 1999; Rodenhiser & Spelman, 1995; Ruddy & Loeb, 1995). The Clarion electrode array is designed to create focussed stimulation based on the requirement that spectral content must be preserved during transmission of the auditory signals to the nerve fibres (Kessler, 1999).

Traditionally, stimulation is not applied to more than one electrode pair at a time to ensure that the charges that are injected through the electrodes are balanced during the anodic and cathodic cycles (Brummer & Turner, 1975). Balanced charge injection prevents the occurrence of irreversible electrochemical reactions at the electrode-tissue interface (Donaldson & Donaldson, 1986; Huang et al., 1999). This is ultimately also the reason for current rather than voltage stimulation in cochlear implants (Robblee & Rose, 1990). However, it has been shown that bipolar type stimulation causes bimodal excitation patterns (Chapter 3; Frijns, de Snoo, & ten Kate, 1995; Jolly, Spelman, & Clopton, 1996) and that the focussing ability of monopolar stimulation with an electrode pair is limited although it has the advantage of activating only one region of nerve fibres (Chapter 3). Electrode configurations that focus stimulation and have unimodal excitation properties are required to augment excitation of independent neural populations.

Tripolar and quadrupolar electrode configurations have been investigated both with animal experiments and models (Kral et al., 1998; Miyoshi et al., 1999; Suesserman & Spelman, 1993). These stimulation modes proved to focus the excitation profile and eliminate bimodal excitation patterns that occur during stimulation with bipolar electrode configurations. Rodenhiser and Spelman (1995) used an inverse technique to determine the driving currents required for focussed stimulation in the cochlea.

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[1] In this chapter the term "stimulus distribution" will be used in the context of the allocation of different stimulation currents for different electrodes, i.e one stimulus distribution could entail application of stimulation currents of -100, 200 and -100 A on the three electrodes in a tripolar electrode configuration, while another could entail the application of -100, -100 and 200 A currents on a similar electrode configuration.

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They defined the stimulation pattern which was required in the Organ of Corti and calculated the stimulation currents on five electrodes necessary to produce the stimulation pattern.

One of the device objectives of the Clarion implant is increasing the transmission speed of auditory information to the nerve fibres (Kessler, 1999). The idea is thus to transmit all temporal and place information that are available to the normal auditory system via electrical stimulation to the nerve fibres in the deaf cochlea in such a way that the auditory centres in the brain cannot distinguish between the normal and electrically transmitted information. Preservation of the temporal structure of the speech signal (and thus the transmission speed of temporal information) could be improved if stimuli can be presented on several electrodes simultaneously. This is because nerve fibres at different locations in the cochlea frequently need to be activated synchronously (or pseudo-synchronously as implemented by the CIS strategy) to render understandable speech. To replicate the natural properties and normal physiological processing of sound, simultaneous analogue stimulation (SAS) on multiple electrodes has recently been reimplemented in the Clarion speech processor (Kessler, 1999). The SAS strategy has its roots in compressed analogue strategies (Kessler, 1999; Loizou, 1999), which implemented simultaneous bipolar analogue stimulation and were used in the Ineraid (Tye-Murray et al., 1992) and UCSF/Storz (Schindler & Kessler, 1989) devices.

Alternative electrode configurations that could improve the transfer of both place and temporal information are investigated in this chapter. The combined FE-nerve fibre model described in Chapter 2 is used to investigate 1) the focussing ability of quadrupolar and tetrapolar electrode configurations and 2) the simultaneous presentation of stimuli on multiple electrodes to provide more degrees of freedom in shaping the excitation profile and to preserve the temporal structure of the auditory signal that is transmitted to the nerve fibres in the cochlea.

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2 EXCITATION PATTERNS OF MULTIPLE ELECTRODE CONFIGURATIONS

2.1 FE Model

The FE model (Chapter 2) was used to investigate four types of electrode configurations that are either not used or are in experimental use in cochlear implants: enhanced tripolar, quadrupolar, tetrapolar and pseudo-continuous electrode configurations. The medial electrode array was used to construct all the multipolar electrode configurations since it has been proved (both experimentally and through models of the implanted cochlea) that perimodiolar arrays render better selectivity than arrays further away from the modiolus (Chapter 3; Shepherd, Hatsushika, & Clark, 1993).

2.1.1 Enhanced tripolar electrode configurations

Table 5.1. Details of enhanced tripolar electrode configurations

Abbreviation	**Stimulation current ratio**	**Electrode geometry**	**Description**
TRI1	1:2:1	point	Three radial pairs spaced NBP
TRI2	1:2:3	point	
TRI3	2:4:3	point	

The enhanced tripolar electrode configuration described here is really a hexapolar mode because it comprises three electrode pairs. However, since the electrode pairs are in a radial configuration, only three degrees of freedom are available to shape neural excitation, similar to a true tripolar mode. Since localised activation can be achieved with radial electrode configurations (Chapter 3), the possibility of using this characteristic simultaneously on three electrode pairs to manipulate the shape of neural activation was investigated. Because each "pole" in the tripole has its own return electrode, the total current injected need not be balanced between the "poles", i.e. currents on the active electrodes (i.e. the electrodes closest to the nerve fibres)

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may be in phase.

2.1.2 Quadrupolar electrode configurations

Table 5.2. Details of quadrupolar electrode configurations

Abbreviation	**Stimulation current ratio**	**Electrode geometry**	**Description**
QUAD1	2:1	banded	Three narrowly (NBP) spaced electrodes
QUAD2	1:-2:1	banded	Three normally (BP) spaced electrodes
QUAD3	1:-2:1	banded	Three widely (BP+1) spaced electrodes
QUAD4	1:-2:1	point	Three closely (NBP) spaced electrodes
QUAD5	1:-2:1	point	Three radial pairs spaced NBP
QUAD6	1:-1:-1:1	banded	Two sets of normally (BP) spaced electrodes separated by a BP+1 electrode separation

A quadrupolar electrode configuration consists of either three electrodes where the centre electrode carries twice the inverted current of the lateral electrodes (i.e. two dipoles with one common pole), or four electrodes forming two separate dipoles. The three-electrode quadrupole will hereafter be called an "overlapping" quadrupolar configuration, whereas a four-electrode quadrupole will be referred to as a "non-overlapping" quadrupole. The effects of the following parameters on the focussing ability of quadrupolar electrode sets were investigated: (1) proximity of the poles (QUAD1, QUAD2 and QUAD3), (2) the use of point electrodes instead of banded

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electrodes (QUAD4 and QUAD5) and (3) separation of the central, combined pole into two poles (QUAD6). QUAD5 is similar to the enhanced tripolar configurations because it comprises three radially oriented electrode pairs.

2.1.3 Tetrapolar electrode configuration

Table 5.3. Details of tetrapolar electrode configurations

[1] The return electrode is a large electrode (comprising five FE model segments from segment 54 to segment 58) toward the apex inside the scala tympani.

[2] The return electrode is located somewhere outside the cochlea.

[3] The return electrode is a common ground type configuration where the part of the electrode that is not used is short-circuited and used as the return electrode.

Abbreviation	Stimulation current ratio	Electrode geometry	Description
TET1	1:1:-4:1:1	banded	Five NBP spaced electrodes
TET2	1:1:-4:1:1	banded	Five BP spaced electrodes
TET3	-4:-3:-1:-3:-4	banded	AR[1], MONO[2], CGND[3]
TET4	-1:-3:-4:-3:-1		

A tetrapolar electrode configuration comprises five electrodes. Focussing and shaping of excitation patterns were individually investigated. Focussing of the excitation pattern was investigated by spreading the stimulation current on the lateral electrodes in an overlapping quadrupolar electrode configuration over two lateral electrodes on each side of the central electrode (TET1) while keeping the current on the central electrode fixed. The surface area of the side poles was thus increased thereby decreasing the current density from these poles. The effect of interelectrode separation was also investigated (TET2).

Shaping of the neural activation pattern was investigated by a simultaneously activated set of five electrodes (TET3 and TET4). Two "inverse" stimulus

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distributions were selected: the first (TET3) had its strongest activating ability (i.e. highest absolute stimulation current) on the two outer electrodes and the weakest activating ability (i.e. lowest absolute stimulation current) on the centre electrode, while the second stimulus distribution (TET4) had its strongest activating ability on the centre electrode and the weakest on the outside electrodes. The objective was thus to obtain -shaped (TET3) and V-shaped (TET4) neural activation patterns. A banded electrode geometry was selected because the Nucleus electrode could potentially be used in this configuration (although the implanted hardware of the Nucleus device does not currently allow stimulation on more than one electrode pair).

2.1.4 Pseudo-continuous electrode configurations

Table 5.4. Functions implemented over CON1 and CON2 electrode configurations. The shapes of the functions are shown in Figure 5.9.

Function	Expression	Scaled stimulation currents in A applied on the FE model sections indicated below.										
		9	10	11	12	13	14	15	16	17	18	19
CON1	$f_1(x) = \sin(x) + \sin(2x)$	-46	-55	-60	-59	-54	-48	-42	-39	-42	-49	-60
CON2	$f_2(x) = \sin(0.9x) + \sin(2.5x)$	0	-11	-28	-47	-62	-69	-67	-60	-50	-43	-43

The possibility to shape the potential distribution at the nerve fibres in a continuous fashion was investigated by activating a large number of electrodes simultaneously. Two arbitrary stimulus distributions were investigated and their details are given in Table 5.4. The electrode configuration comprises 11 "line" electrodes defined on the perimeter of the electrode carrier on the boundaries of each segment of the FE model. Three types of return electrodes were modelled: AR, MONO and CGND. Details of the return electrodes are given in Table 5.3.

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2.2 Modelling of auditory nerve excitation

Neural excitation patterns were again calculated with the GSEF model by determining the threshold current at which a specific modelled nerve fibre will generate a propagating action potential. However, since stimulation currents were not equal on all electrodes, scaling of potential distributions were performed relative to the maximum current applied on any one of the electrodes. Consequently, only relative thresholds were determined, i.e. spatial tuning curves relative to the minimum threshold current (dB above threshold) were calculated. A relative indication of threshold currents was obtained from AF contours where a higher absolute value of the activating function indicates lower threshold currents.

2.3 Focussing and shaping ability of multi-electrode systems

Because the CFI defined in Chapter 2 is not clearly visible or does not exist in the excitation patterns of most multi-electrode systems, an alternative measure had to be defined to quantify the focussing ability of multi-electrode systems. If multimodal excitation exists for an electrode set, the *unimodal* focussing ability *UF* of an electrode set and associated stimulus pattern is defined as follows: If *W* is the projection of the electrode contacts on the basilar membrane, *P* is spread of excitation of the primary peak in the excitation profile at the current intensity relative to the threshold current (dB above threshold) *L* where the lowest side-lobe in the excitation pattern appears, the focussing ability of the electrode set is defined as

$$UF = \frac{W}{P} \cdot \frac{L}{20} \tag{5.1}$$

for a given stimulus pattern (Figure 5.1). A "perfectly" focussed excitation pattern is defined to have P=W and L = 20 dB. The value of L is limited to 20 dB, i.e. if L is found to be greater than 20 dB, its value would be set equal to 20 dB. This facilitates calculation of *UF* for electrode configurations that do not display side-lobes in the electrical tuning curves, e.g. monopolar electrode configurations. 20 dB was selected because this is approximately the maximum dynamic range for a cochlear implant wearer (Shannon, 1983). A *UF* value equal to 1 describes a perfectly

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focussed electrode according to this definition. In other words, the closer to 1 an electrode set's *UF* value, the better its focussing ability. Typically, electrode sets would exhibit *UF* values far less than 1 because, even though the lowest side-lobes might approach 20 dB above threshold, the spread of excitation at high stimulus intensities is always wider than the projection of the electrode contacts along the length of the basilar membrane if the electrodes are separated from the nerve fibres. Since the equation does not compensate for distance from the electrodes to the target nerve fibres, electrodes that are located further away from the nerve fibres will (correctly) exhibit less focussed excitation because of current spread in the volume conductor. *UF* essentially gives an indication of how the spread of excitation at a specific stimulus intensity compare for different electrode and stimulus configurations. *UF* is defined only over the stimulus intensities below where the first side-lobe in each neural response appears.

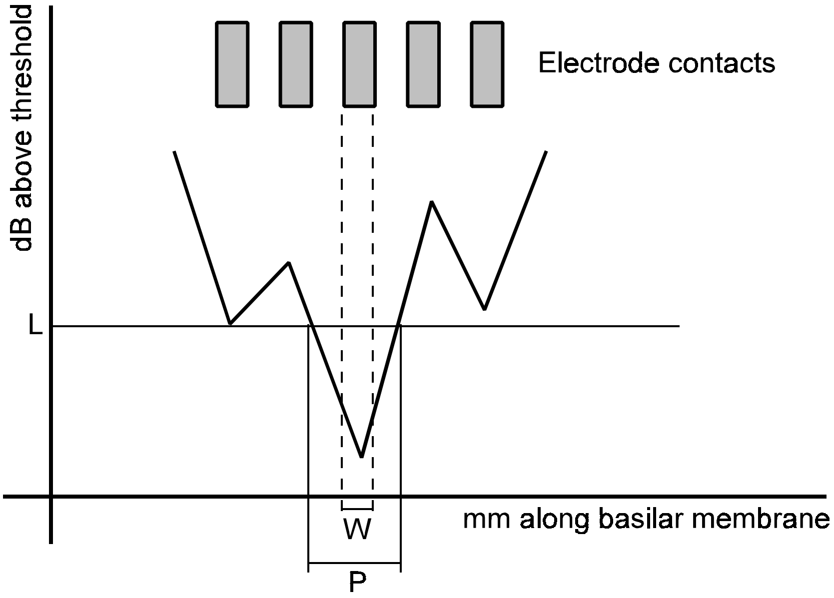

Figure 5.1. Schematic representation of parameters in definition of UF.

Although *UF* cannot be measured in implant wearers, it could potentially be measured in animals. Kral et al. (1998) measured electrically evoked spatial tuning curves in cats for a number of electrode configurations. Spatial tuning curves were measured by recording thresholds of single units in the internal auditory meatus as a result of electrical stimulation.

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To quantify the shaping ability of electrode sets, the correlation coefficient between the stimulus distribution on the electrodes and the electrical tuning curve was calculated and the threshold data were plotted versus stimulation current. This gave an indication of the linearity of the relationship between the stimulus distribution and the neural response profile and of the deviation of this relationship from linearity.

3 RESULTS

3.1 Focussing of neural excitation patterns

AF contours of the potential distributions generated with various electrode configurations and stimulus distributions (Figure 5.2) show that (1) trimodal excitation could occur for overlapping quadrupolar electrode configurations, (2) the central region of excitation of overlapping quadrupolar configurations is likely to be excited at lower stimulus intensities than the lateral regions, since the intensity of the activating function is much higher for the central region than for the lateral regions, (3) narrowly spaced quadrupoles will exhibit higher minimum threshold currents than widely spaced quadrupoles because the absolute maximum intensity of the activating function is lower for narrowly spaced quadrupoles (e.g. QUAD1) than for more widely spaced quadrupoles (e.g. QUAD3), (4) increasing the interelectrode separation has a defocussing effect on the central (and lateral) regions of excitation (compare QUAD1 to QUAD3), (5) similar to bipolar and monopolar stimulation (Chapter 3), point electrode geometries are expected to require lower stimulus current intensities to elicit a response than banded electrode geometries (compare QUAD1, QUAD4 and QUAD5), and (6) there should not be much difference in either minimum threshold currents or focussing ability between using point electrodes and radially oriented point electrode pairs to create a quadrupole (compare QUAD4 and QUAD5).

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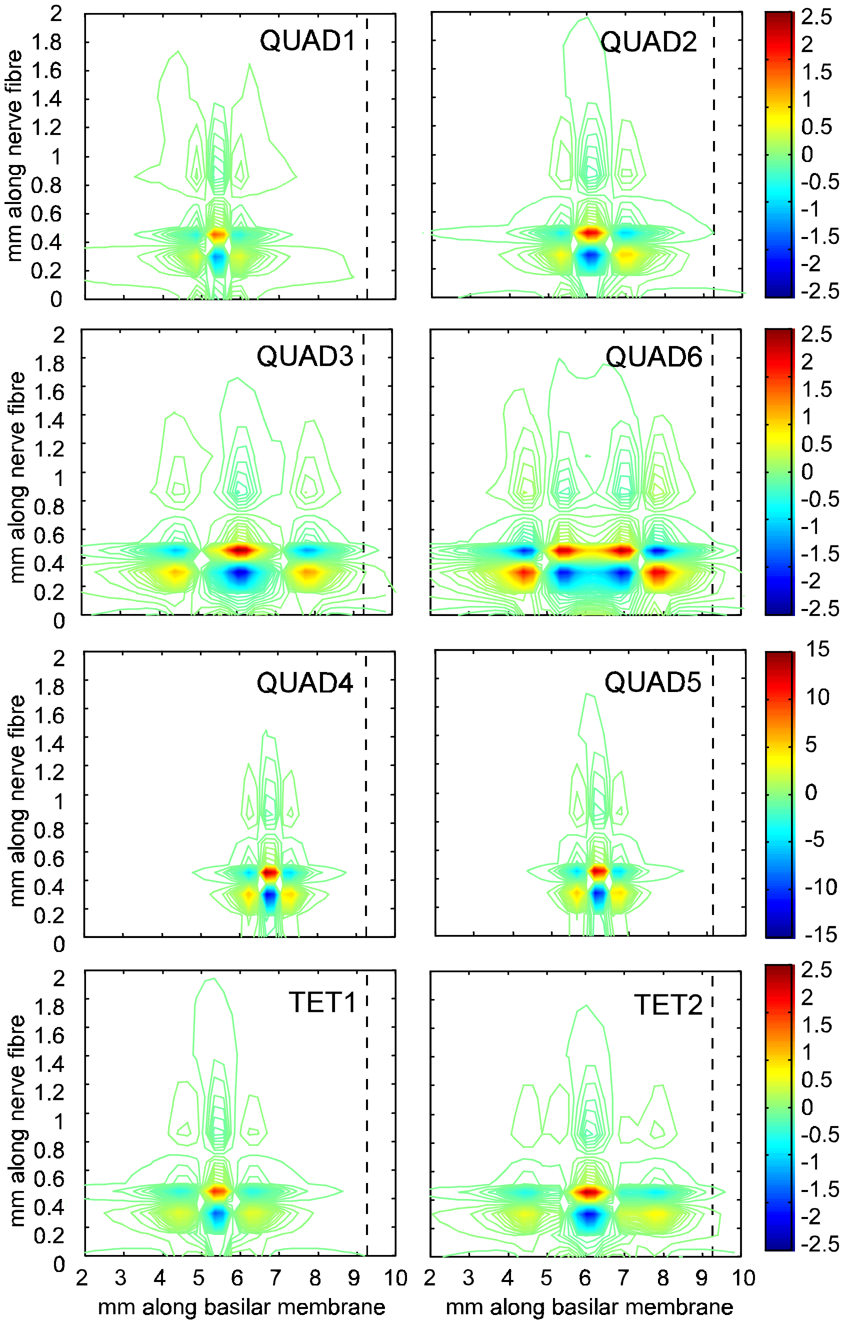

Figure 5.2. AF contour plots showing possible regions and spread of excitation along the basilar membrane as a result of stimulation with different quadrupolar and tetrapolar electrode configurations. The spatial scales of all the graphs are the same and are indicated for the left graphs (ordinate) and for the lower graphs (absisca). The colourbar multiplication factor is 10^4 mV/ms.

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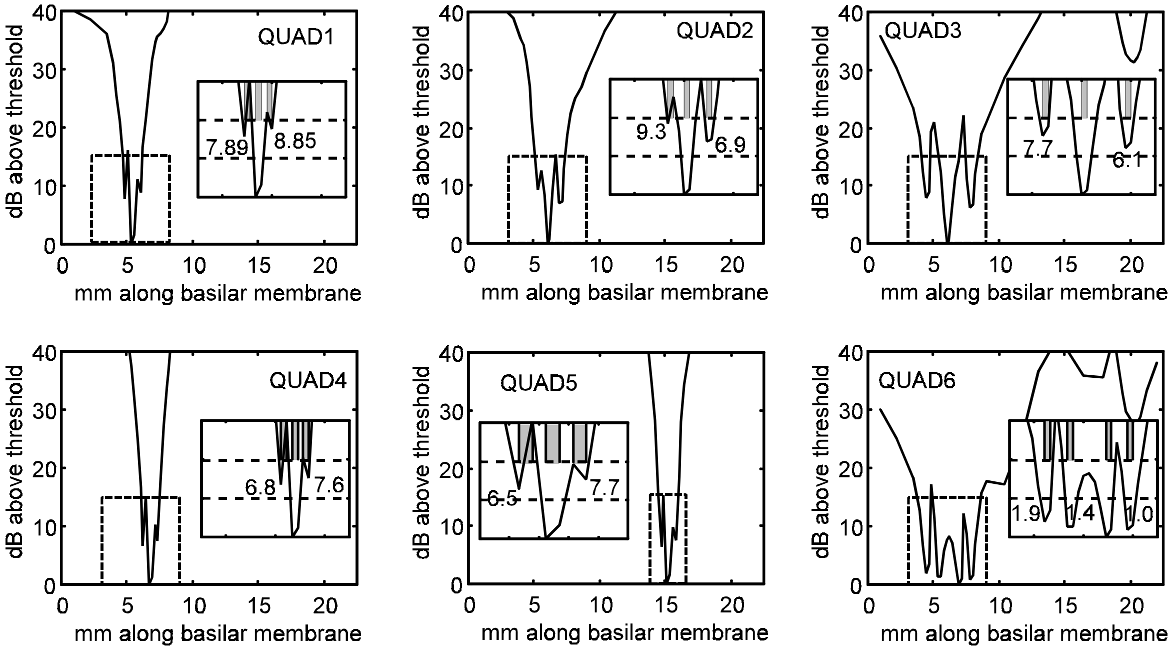

Figure 5.3. Electrical tuning curves for quadrupolar electrode configurations. An enlargement of the primary region of activation (dashed block) is shown as an inset in each figure. Shaded blocks indicate the location of the stimulating electrode pairs. Numbers next to minima in insets indicate dB above threshold for side lobes.

Non-overlapping quadrupolar stimulation (QUAD6) creates four regions of excitation which are expected to occur at approximately the same stimulus intensity. This observation is based on similar absolute intensities of the activating function across al four regions of excitation. The tetrapolar configurations show similar trends with regard to minimum threshold currents and spread of excitation as a function of electrode separation than the quadrupolar modes. However, there is an even greater difference between the absolute activating function intensities at the central and lateral regions of excitation, suggesting that the lateral excitation will occur at higher stimulus intensities relative to the minimum threshold current than for the QUAD modes.

Electrical tuning curves for the different electrode configurations confirm the qualitative observations based on AF contours. Overlapping quadrupolar stimulation creates trimodal excitation patterns (QUAD1 to QUAD5 in Figure 5.3). Four minima

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are created in the electrical tuning curve when the poles are individually placed (QUAD6 in Figure 5.3). The lateral lobes in the trimodal excitation pattern appear at a few dB above threshold in contrast to the almost equal threshold values of the bimodal peaks created with bipolar electrode configurations and with the non-overlapping quadrupolar configuration. The stimulus intensities where side lobes appear in the electrical tuning curves are given in the insets in Figure 5.3. For the tetrapolar configurations where the lateral poles are spread over two electrodes, the side lobes in the electrical tuning curves are more suppressed (0.9 to 1.65 dB) than for the quadrupolar configurations (Figure 5.4). UF was calculated for all electrode configurations and is shown in Figure 5.5 as a function of electrode configuration in the order of best to worst focussing ability. UF is somewhat less for tetrapolar configurations than for quadrupolar configurations with corresponding interelectrode separation. QUAD1 displays the best focussing ability of all the QUAD modes.

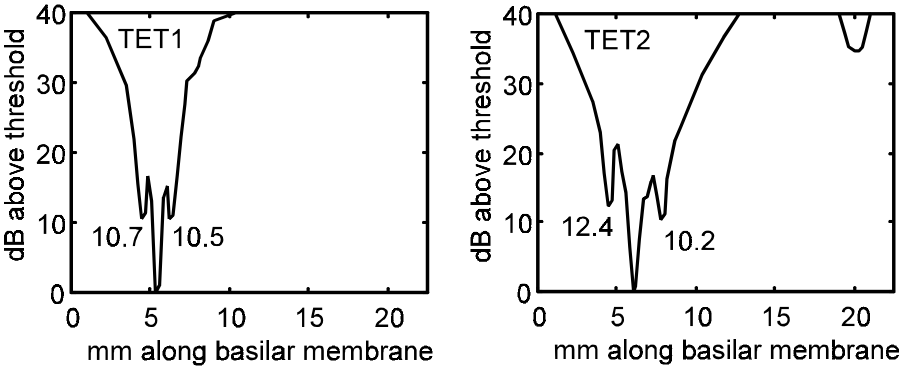

Figure 5.4. Electrical tuning curves for tetrapolar electrode configurations TET1 and TET2. Numbers next to minima indicate dB above threshold for side lobes.

No ectopic excitation of nerve fibres originating from superior cochlear canals is predicted below 40 dB above threshold for narrowly spaced (NBP and BP for quadrupolar and NBP for tetrapolar) electrode configurations. Ectopic stimulation is, however, present for more widely spaced electrode configurations (BP+1 separation for quadrupolar and BP separation for tetrapolar) and also for the non-overlapping quadrupolar configuration (QUAD6).

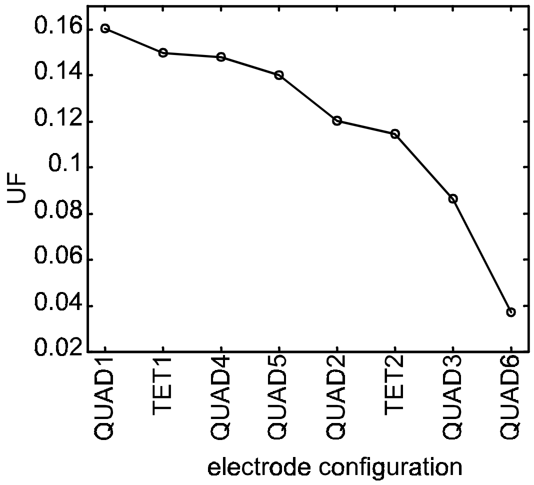

Figure 5.5. UF as a function of electrode configuration.

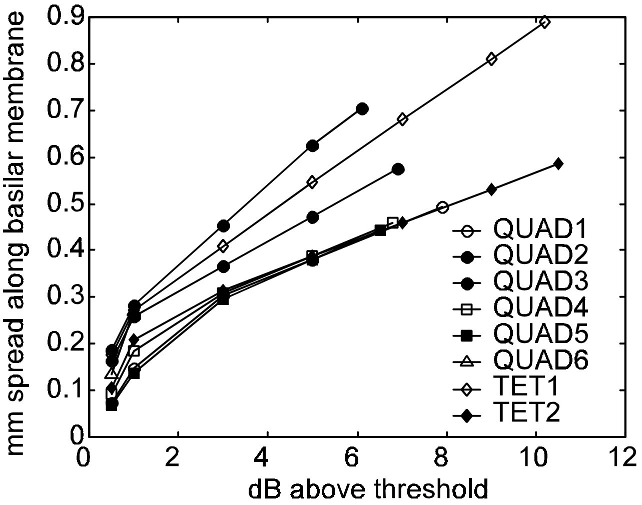

Figure 5.6. Focussing of multipolar electrode configurations. The datum point at the highest stimulus intensity (dB level) of each curve corresponds to the stimulus intensity where the lowest sidelobe in the electrical tuning curve appears.

Figure 5.6 shows spread along the basilar membrane as a function of stimulus intensity up to current intensities where side lobes appear in the electrical tuning curves. Results for QUAD6 could not be calculated above 1 dB above threshold because of side-lobes appearing at approximately 1 dB above threshold.

The slope of the lines give an indication of the rate of change in the spread of excitation as a function of stimulus intensity. The shallower the slope of the line, the less the increase in spread of excitation as a result of increasing stimulus intensity. The initial steep slopes of the curves indicate that the spread of excitation increases rapidly at very low relative stimulus intensities. In the model, this slope mostly reflects the difference in excitation threshold current between the two nerve fibres opposite the boundaries of the exciting electrode. Narrower electrode configurations (QUAD1, QUAD4, QUAD5 and TET1) display the shallowest slopes overall, indicating less widening of the region of excitation with increasing stimulus intensity than when wider spaced electrode configurations are used.

The interpretation of UF is clear in Figure 5.6 where curves corresponding to lower values of UF (and therefore exhibiting lower unimodal focussing ability) are located towards wider spread of activation values on the ordinate and vice versa.

3.2 Shaping of neural excitation

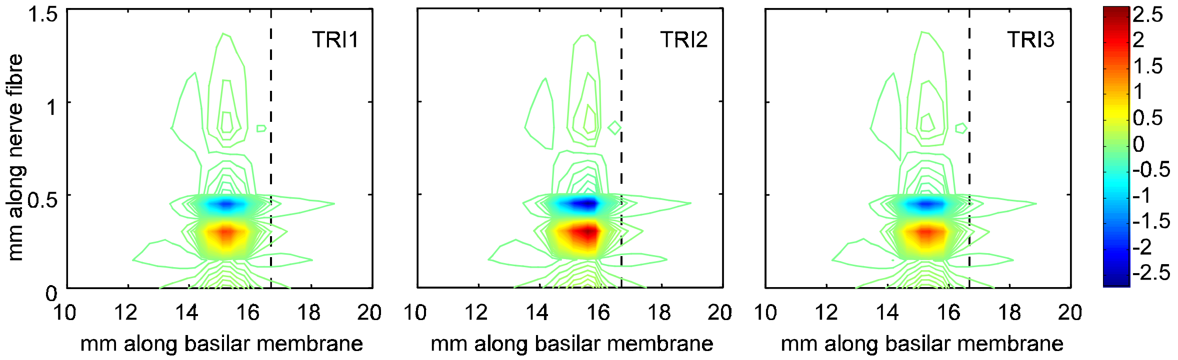

Figure 5.7. AF contours of enhanced tripolar electrode configurations showing the shaping properties of the potential fields. The multiplication factor scale on the colourbar is 10^5 mV/ms.

For tetrapolar and pseudo-continuous electrode configurations (Figure 5.9), AF contours show that different stimulus distributions will activate the nerve fibre population in different ways. Similar to enhanced tripolar configurations, lower threshold currents are predicted for nerve fibres close to electrodes carrying higher stimulus currents relative to their neighbours, i.e. lateral electrodes in TET3 and central electrode in TET4 (Figure 5.9). This is confirmed by AF contours for the same stimulus distributions created with the analytical model (right graphs in Figure 5.9).

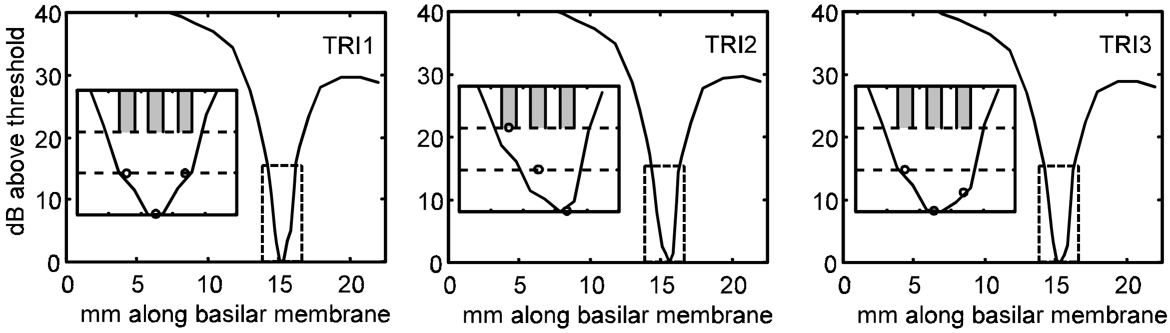

Figure 5.8. Electrical tuning curves for enhanced tripolar electrode configurations. An enlargement of the primary region of activation (dashed block) is shown as an inset in each figure. Shaded blocks indicate the location of the stimulating electrode pairs. An inverted representation (i.e. highest stimulus intensity is located at 0 dB and lower stimulus intensities are placed towards higher thresholds) of the stimulus distribution on the electrodes is shown with open circles in each inset.

The effect of the 3-D structure of the cochlea on excitation patterns is clearly visible in Figure 5.9 where the AF contours obtained with the FE model show a possible region of excitation in the third half-turn of the cochlea model for the TET configurations.

The open circles in Figure 5.10 give an indication of the shape of the stimulus distribution and of the location of the electrodes along the length of the basilar membrane for multipolar shaping electrode configurations. When an AR return electrode is used, manipulation of the excitation profile is relatively well achieved in the vicinity of the electrode set. However, the accumulated current at the return electrode causes excitation of nerve fibres at lower stimulus currents than those required for excitation at the active electrodes (solid lines in graphs of TET configurations in Figure 5.10) (not shown for the pseudo-continuous electrode sets).

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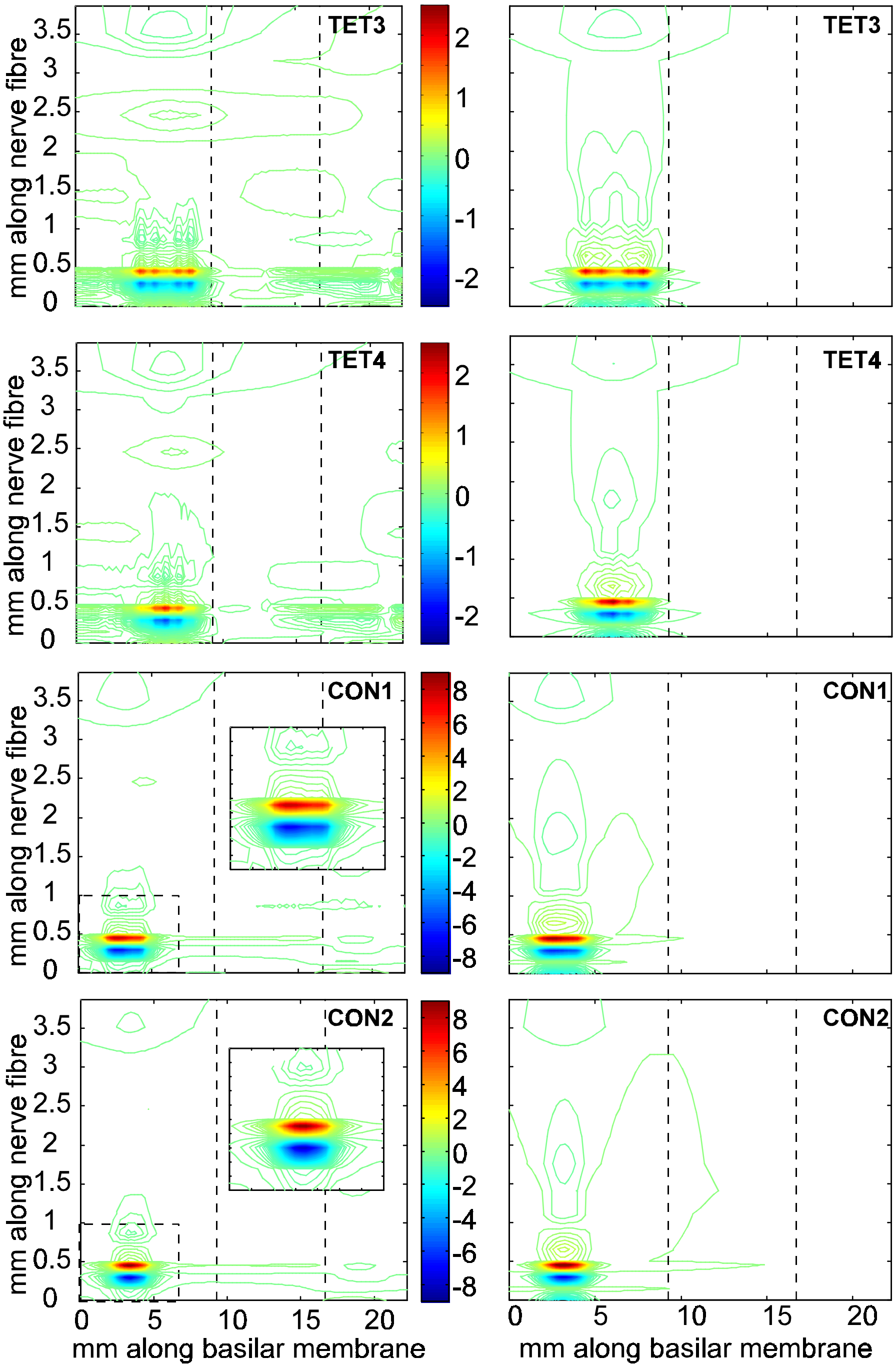

Figure 5.9. AF contours with a distant return electrode (MONO) generated with the FE model (left graphs) and the analytical model (right graphs). The multiplication factor of the scale on the colourbar is 10^4 mV/ms.

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To suppress the excitation of nerve fibres around the return electrode, MONO and CGND return electrodes were used. When a remote (MONO) return electrode is used, the shaping ability of the electrode set is less pronounced but still visible. This is evident from Figure 5.10 where the region of activation is broader and exhibits less localised variations when a remote (MONO) return electrode is used than when an AR or a CGND return electrode is used. A CGND return electrode maintains the shaping profile at the active electrodes in a more localized manner than a MONO return electrode, but creates widespread excitation through all cochlear canals at stimulus intensities below 15 dB above threshold. The dynamic range over which a CGND return electrode will allow selective activation of nerve fibres is thus limited relative to that of a MONO return electrode.

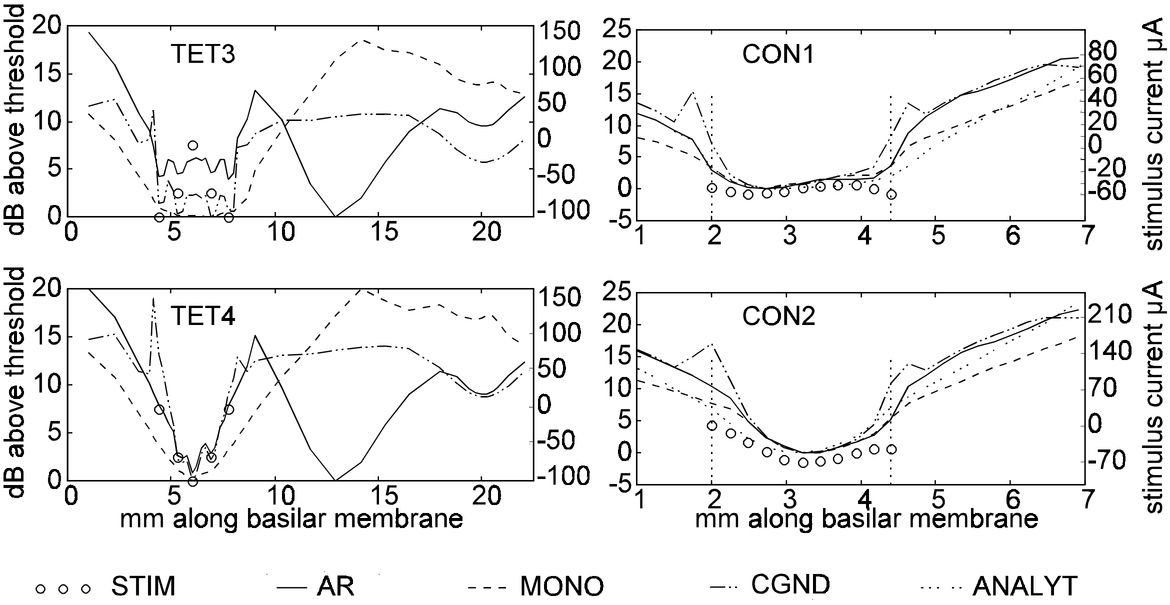

Figure 5.10. Electrical tuning curves for tetrapolar electrode configurations are shown in the left graphs while the same are shown for pseudo-continuous electrode configurations in the right graphs. Open circles indicate the stimulus intensity in A at the location of the active electrodes (scale on the right ordinate).

Figure 5.11 (threshold versus stimulus current) shows that there is a definite, almost linear relationship between the stimulus distribution on an electrode set and the excitation profile of the nerve fibres. The correlation coefficient is mostly greater than

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0.9 and approaches 1 in many cases. The greatest deviations are seen when the stimulus distribution is increasing in magnitude at the boundaries of an electrode set relative to the neighbouring electrodes in the set, e.g. TET3 and CON1.

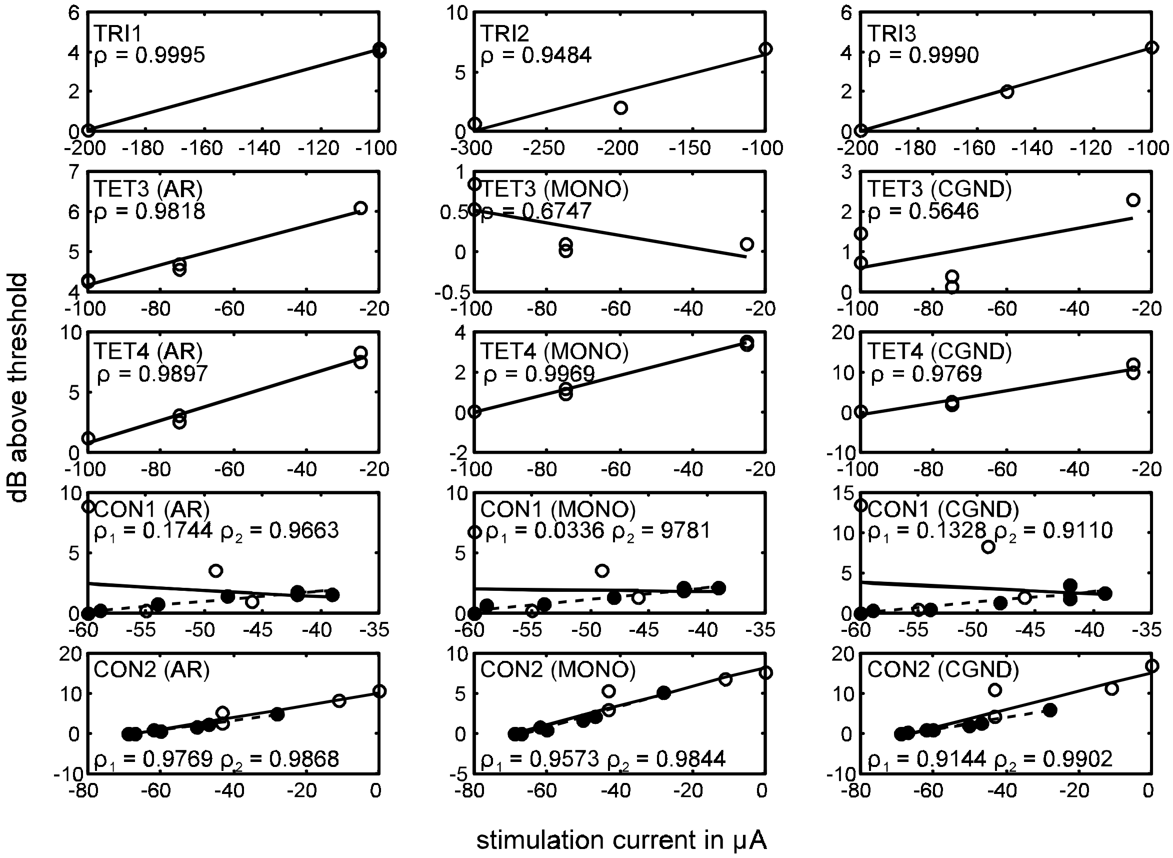

Figure 5.11. Shaping properties of electrode sets characterized by correlation coefficient and distribution of data points relative to linear fit through data points. Two correlation coefficients are given for the pseudo-continuous electrode configurations: $_1$ is for the complete data set while $_2$ is for the data set excluding data for the first and last two electrodes of the set. Solid lines show a linear least squares fit through the data while dotted lines show the same for the limited data set for the pseudo-continuous electrode configurations.

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The linear relationship between stimulus distribution and excitation profile also breaks down at the boundaries of the pseudo-continuous electrode sets. If, however, the excitation profile on nerve fibres next to the lateral two electrodes on each side of the electrode set is disregarded, the linear relationship between stimulus distribution and excitation profile becomes very strong (correlation coefficient greater than 0.9) for all types of return electrodes used.

4 DISCUSSION

4.1 Focussing of neural excitation patterns

Model results confirm the focussing ability of overlapping quadrupolar electrode configurations as reported by other researchers (Jolly, Spelman, & Clopton, 1996; Kral et al., 1998). It was also shown that spreading the current of the lateral poles in the quadrupole over two electrodes on both sides of the central pole could suppress side-lobes in the excitation profile. This approach is similar to the approach of Kral et al. (1998) who used an additional remote electrode to return some of the current injected from the central electrode that would otherwise be returned by the lateral electrodes. QUAD5, which is configured from an enhanced tripolar electrode set, is also similar to the electrode configuration used by Kral et al.

The resolution of the data that Kral et al. (1998) measured in cats is not sufficient to calculate *UF*. Also, the measured electrical tuning curves do not show definite lateral minima as displayed by results from the model. All the same, *UF* was estimated as 0.043 for an electrical tuning curve measured *in vivo* for a tripolar configuration where the current intensity on the lateral electrodes was suppressed by 10 dB from that injected by the central electrode. This low value of UF compared to the values calculated for the modelled electrode configurations could be because uncurved banded electrode arrays (similar to the arrays used in the Nucleus implant) were used for the measurements. This type of array is frequently located distal from the nerve fibres (Roland et al., 2000). Spread of excitation is larger for arrays located further

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from the nerve fibres (Chapter 3), which could cause less pronounced trimodal excitation patterns. However, both the modelled and the measured electrical tuning curves show suppression of the side-lobes in the excitation profile because the lateral poles do not carry the full complement of the current injected by the central pole. Also, measured data (Kral et al., 1998) confirm the findings that (1) spread of excitation is less for the focussing electrode configurations than for monopolar electrode configurations and (2) unimodal focussing can be achieved through excitation with multiple electrode configurations.

It has been shown that narrowly spaced electrode sets possess better focussing ability than more widely spaced electrode sets. The implication for the design of intracochlear electrodes is that focussing of excitation patterns could be improved by a combination of increasing the lateral electrode density, i.e. include more electrode contacts per unit length, and using quadrupolar or tetrapolar electrode configurations. Although the side-lobes generated with quadrupolar and tetrapolar electrode configurations could be suppressed even further by using a common ground electrode configuration as return instead of one or two lateral electrodes, the advantage of quadrupolar or tetrapolar configurations is that several regions of focussed excitation can be created simultaneously in SAS (Kessler, 1999) or simultaneous pulsatile (Kessler, 1999) type strategies.

Slightly lower values of UF for the overlapping quadrupolar electrode configurations compared to the tetrapolar configurations suggest that there could be a tradeoff between suppression of side lobes and focussing ability of an electrode set. The ultimate example would be excitation profiles created with monopolar stimulation versus those created with overlapping quadrupolar stimulation. With monopolar stimulation no side-lobes exist in the excitation profile, but the focussing ability of the configuration is low. On the other hand, the focussing ability of overlapping quadrupolar configurations is high but side-lobes exist in the excitation profile within the dynamic range of many cochlear implant users.

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A high lateral electrode density could allow patient-specific electrode configurations with high focussing ability. At locations in the cochlea where low threshold currents are sufficient to excite nerve fibres, narrowly spaced electrode configurations could be used to create electrode sets. An increased number of discrete regions of excitation (relative to the number of regions of excitation created with electrode arrays having a low lateral electrode density) could thus be created in such areas of the cochlea. On the other hand, at locations in the cochlea where surviving nerve fibres are sparse or higher stimulation currents are required to elicit a response, electrode sets could be configured in a BP+x (where x is the number of electrodes separating active electrodes) configuration to lower threshold currents (Figure 5.2). Moreover, electrode sets can be configured to use more than one neighbouring electrode contact to form an "electrode". This could be advantageous when larger stimulation currents are required since an increased electrode surface area will lower the current density on the electrode surface and thus protect the electrode metal from corrosion (Brummer & Turner, 1977).

Curves showing spread of excitation along the basilar membrane as a function of stimulus intensity (in dB) above threshold (Figure 5.5) are equivalent to input-output functions. Recruitment properties of nerve fibres with different diameters are not reflected in the model, i.e. in the current model a homogeneous nerve fibre population is assumed. The approximately linear relationship between relative stimulus intensity and spread of excitation for the focussing electrode configurations show that, up to where side-lobes appear in the excitation profile, the size of the excited nerve population is proportional to the stimulus intensity.

4.2 Shaping of neural excitation patterns

Miyoshi et al. (1999) experimented with shaping of the excitation profile using a tripolar electrode configuration (similar to the overlapping quadrupolar configurations described in this chapter). Monophasic current stimuli were used with the central electrode serving as the cathode and the lateral electrodes as the anodes. It was found that it might be possible to limit the region of excitation and to vary the spatial

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location of the stimulation site by controlling the current on the lateral electrodes. Although the results of Miyoshi et al. do not include the effect of biphasic stimuli (Chapter 3), their results are similar to results obtained with the enhanced tripolar electrode configuration in this chapter. The use of enhanced tripolar configurations rather than normal tripolar or quadrupolar configurations to shape neural excitation profiles is advantageous since no phase reversals that cause irregularities in the excitation profile occur. This is useful when a continuous excitation profile is desired. With the enhanced tripolar electrode configuration side-lobes were thus eliminated by the use of three radially oriented electrode pairs versus the use of monophasic stimuli by Miyoshi et al. to produced the same effect. Results presented in this chapter, based on excitation profiles calculated with biphasic stimuli, support the findings of Miyoshi et al. Firstly, the region of excitation can be limited if a tripole is used in an overlapping quadrupolar configuration (QUAD5). Secondly, the location of the region of excitation can be manipulated (possibly in a continuous fashion as claimed by Miyoshi et al.) by controlling the currents injected from the lateral electrodes relative to that injected by the central electrode.

Model results suggest that the excitation profile could be shaped continuously on nerve fibres covering a larger region of the cochlea through multipolar banded electrode configurations (TET3 and TET4) and pseudo-continuous electrode configurations. Monopolar and common ground return electrodes are more suitable to create continuous excitation profiles than an AR return electrode, but cannot provide the same degree of selectivity and focussing offered by radially oriented electrode pairs. It could thus be advantageous if an electrode array with a large number of radially oriented electrode pairs could be used to create continuous excitation patterns. Such an electrode could provide localised excitation around each electrode pair which could also limit ectopic excitation of nerve fibres originating from other cochlear regions.

The pseudo-continuous electrode configuration of the Clarion implant that exists when the SAS strategy is used, is similar to a low electrode density implementation

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of the shaping electrode configurations discussed in this chapter. Therefore, model results suggest that the Clarion implant could effectively deliver auditory information simultaneously to different nerve fibre populations in the cochlea by using the SAS strategy.

The best electrode configuration for a specific person would once again be determined by the nerve survival pattern in the deaf cochlea as well as the location of the array relative to the surviving nerve fibres. Unfortunately, these parameters cannot be measured or calculated preoperatively. A perimodiolar electrode design could limit variations in array location between cochlear implant users, but nerve survival cannot be controlled. Similar to focussing electrode configurations, an electrode array with a high lateral electrode density could facilitate customization of an electrode array for individual persons by activation of a custom selection of electrodes depending on nerve survival patterns.

5 CONCLUSION

Model results confirm that focussing of excitation around intracochlear electrodes could be improved by using overlapping quadrupolar electrode configurations. These electrode and stimulus configurations create trimodal excitation pattens. The suppression of the side-lobes in trimodal excitation patterns depends largely on the electrode separation and the stimulus distribution. If the stimuli on the lateral electrodes are spread over two neighbouring electrodes, side-lobes in the excitation profile could be suppressed even further. A trade-off could, however, exist between focussing ability of electrode configurations and suppression of side-lobes in the excitation profile.

Results also suggest that the excitation profile could be shaped continuously with enhanced tripolar electrode configurations, multipolar banded electrode configurations and pseudo-continuous electrode configurations. Based on model

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results obtained with shaping electrode configurations, it is concluded 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.

An improved electrode array that facilitates focussing and continuous shaping of neural excitation profiles could be constructed by including a large number of electrode contacts. Banded electrode geometries could provide focussing and shaping of the excitation profile. However, the use of a remote return electrode (which is required if irregularities in the excitation profile are unwanted) could potentially degrade the shaping ability of electrode sets because of current spread. Radially oriented electrode pairs address the return electrode problem by providing a local current return path that limits spread of excitation and facilitates in-phase stimulation on the active electrodes. An array with high lateral electrode density could furthermore facilitate customization of the array for individual implant users by selecting subsets of electrodes based on surviving nerve fibre patterns.