"A Cochlear Nucleus Auditory prosthesis based on microstimulation"

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SUMMARY AND ABSTRACT

The overall objective of this project is to develop an auditory prosthesis that is based on microstimulation within the human ventral cochlear nucleus. A major task in achieving this objective is to specify the configuration of the microelectrode array, including the lengths and spacing of the microelectrodes, as well as the location and angle at which they are to be inserted into the brainstem. The neuronal cytoarchitecture indicates that the electrodes should be inserted into the central area of the nucleus, where the multipolar cells are clustered. Anatomical studies were performed on the cochlear nuclei of persons with normal hearing, and on those from persons with neurofibromatosis 2 (NF2), in whom the auditory nerve had been completely ablated after removal of vestibular schwannomas. The nuclei of the NF2 patients was somewhat atrophied and narrowed, particularly along the lateral-medial direction. A related consideration is that the optimal distributions of electrode lengths is somewhat dependant upon the angle at which the arrays is inserted into the nucleus. With a ventral approach, the greatest problem is the extreme narrowness of the nucleus along the mediolateral dimension. If a penetration is not made along the long dimension of the narrow VCN, the tips of longer electrodes are more likely to fall outside the VCN . With a more lateral approach, the electrodes will cross the tonotopic planes of the VCN at about a 45^{o} angle, similar to what would occur with a ventral approach, but and they must be short enough so as not to completely penetrate the narrowed nucleus.

Psychophysical studies in which various sound processor strategies were simulated in subjects with normal hearing indicated that the penetrating microelectrodes ideally should be designed so as to span the entire tonotopic gradient of the ventral cochlear nucleus, in equal increments. The analysis of normal human brainstems and brainstems following single and bilateral vestibular schwannomas suggest that penetrating electrodes should range in length from 1.0 mm to 3.0 mm in order to span the entire range of acoustic frequencies when the array is inserted along a dorso-ventral direction, and should be slightly shorter in order to span the axis when the array is inserted more laterally. Our present design contains two 3 mm stabilizing pins and 8 active electrodes, staggered in length between 1 and 2 mm. Depending upon the angle of insertion, this array may not span the entire tonotopic axis of the VCN. However, this error will cause a loss of access to the position of the VCN representing high acoustic frequencies. The psychophysical studies indicate that this condition is preferable to loosing access to the lower frequencies, as would occur if the electrodes all were too long.

1.0 ANATOMICAL CONSIDERATIONS IN THE DESIGN OF A MICROELECTRODE ARRAY FOR THE HUMAN VENTRAL COCHLEAR NUCLEUS

1.1 Introduction

The overall objective of this project is to develop an auditory prosthesis that is based on microstimulation within the human ventral cochlear nucleus. A major task in achieving this objective is to specify the configuration of the microelectrode array, including the lengths and spacing of the microelectrodes, as well as the location and angle at which they are to be inserted into the brainstem. A continuing issue has been the "fit" of the array to its target, the human cochlear nuclei. Since the current field generated by a penetrating electrode will be confined to the area immediately vicinity of the electrode tip, the placement of the device will determine the type of information transferred to higher auditory centers. This is an important consideration because prosthetic stimulation is intended to create percepts that facilitate speech perception.

1.2 Definition of the target area

A basic assumption is that the cochlear nuclei are the optimal site at which to deliver the stimulation from a brainstem auditory prosthesis. Figure 1.1 shows a sagittal section through a human cochlear nucleus. Anatomical and functional studies in animals are the basis for disqualifying the dorsal cochlear nucleus (dcn in Figure 1.1) as a target for microstimulation. These studies show that the output from the dorsal cochlear nucleus does not contribute to sound detection (Masterton, Granger and Glendenning, 1994), but rather is involved in determining the location of a sound source (Sutherland, Glendenning and Masterton, 1998) and orientation of the head and body toward the sound source (May, 2000).

The optimal target area is further limited by the fact that the ventral cochlear nucleus (VCN) is not homogeneous in its cytoarchitecture. Rather, it consists of clusters of functionally specialized neurons which differ in their projections to higher auditory centers. One subdivision of the nucleus which is particularly prominent in the human cochlear nuclear complex is the small cell cap (Fig. 1.1, cap). This area has been shown to contain virtually all of the neurons in the ventral nucleus which contain the inhibitory transmitters GABA and glycine (Kohlston et al., 1992; Moore et al., 1996). The axons of these small inhibitory cells form primarily intranuclear projections, and contribute very little to ascending pathways from the VCN. This lack of projection to higher auditory centers should disqualify the cap area from consideration as a target of microstimulation.

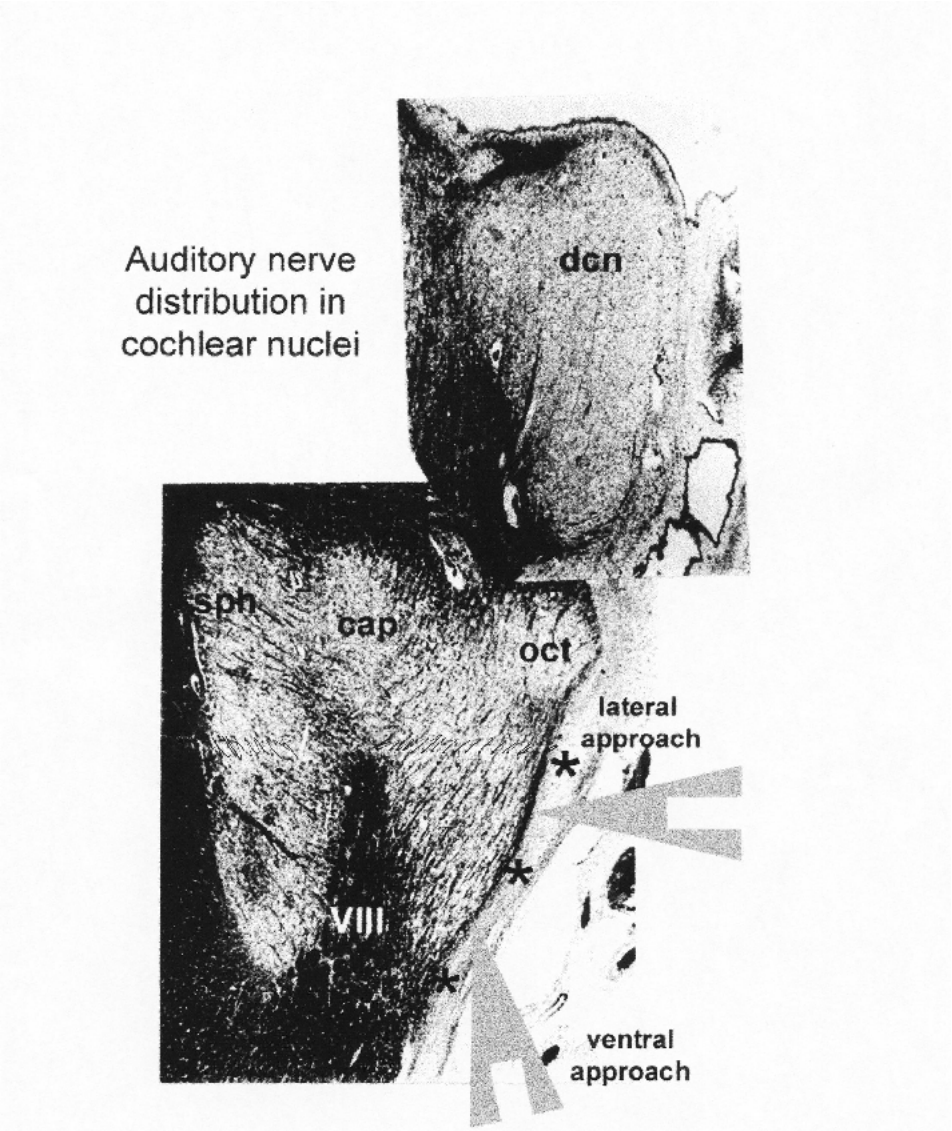
Auditory nerve
distribution in
cochlear nuclei
dcn
sph
cap
oct
lateral
approach
VIII
ventral
approach

Figure 1.1

There are other portions of the VCN which would not be ideal sites for implantation of the array. The rostral tip of the VCN consists mainly of rounded neurons which are homologous to the spherical cells of nonhuman species (Fig. 1.1, sph). This cell population projects only to the medial and lateral nuclei of the superior olivary complex (Warr, 1982; Cant and Cassaday, 1986), where information on interaural differences in stimuli is extracted. The information synthesized by the olivary nuclei is believed to function in spatial localization of stimuli, and thus may not be relevant for monaural speech perception. A second area which would not be a suitable target is the octopus cell region at the caudal end of the VCN (Fig. 1.1, oct). This group of large neurons forms a projection to the periolivary cell groups (Strominger and Strominger, 1971). They respond to cochlear nerve activity only with an "onset" burst, thus seeming to function as an alerting system rather than in the analysis of sounds.

These considerations lead us to believe that the optimal target of the penetrating electrode array is the central region of the VCN, which contains predominantly multipolar cells, a heterogeneous class of neurons which project directly to the inferior colliculus (Adams, 1979; Brunso-Bechtold et al., 1981). Though stimulation sites should be confined to the multipolar cell area of the VCN, another goal is to distribute the sites across the tonotopic planes of the nucleus. Subsequent to tumor removal, the peripheral segments of the cochlear nerve axons will degenerate because they have been severed from their somata in the spiral ganglion. A basic assumption is that the tonotopic organization imposed on cochlear nucleus neurons by the nerve will remain after the axons degenerate. This assumption is supported by the fact that some patients with the surface ABI are capable of a degree of pitch discrimination between individual electrodes. Figure 1.1 illustrates the course of cochlear nerve axons, and thus the orientation of the tonotopic (isofrequency) planes in the VCN. It can be seen that there is an upward angulation of the cochlear nerve axon fascicles as they run from the nerve root toward the caudal and rostral ends of the nucleus. Within the human ventral nucleus, we assume that there is a full representation of high-to-low auditory frequencies across the dorsoventral dimension of the nerve's distribution, with low frequencies represented close to the surface of the brain, and high frequencies represented deeper (more ventromedially), as has been described in many other mammalian species, including the monkey (Moskowitz and Liu, 1972).

1.3 Surgical approach to the target

Because stimulation from microelectrodes is restricted to a small area surrounding the electrode tip, it will be necessary to place the device very precisely in the nucleus. Thus electrode design, including shaft length and the lateral spacing between individual stimulating electrodes, must take into consideration the point of entry and the angle of penetration into the VCN. In the cat and other nonhuman

mammals, the VCN is almost entirely superficial, lying immediately deep to the pial surface of the brainstem and forming a prominent protuberance on its surface. Only the rostral most tip of the nucleus is covered by the cerebellar flocculus. In man, the body of the VCN is covered to a variable degree by the flocculus and by the fibers of the middle cerebellar peduncle (Moore and Osen, 1979a). Because the nucleus is not visible on the brainstem surface, it has been considered necessary to select a surface landmark for inserting the penetrating electrodes, with this point of entry determining the orientation of the array within the VCN.

Until recently we had assumed that surgeon must inset the array under visual control, and into the free ventroposterior surface of the VCN (The approach indicated as “ventral” in Figure 1.1). As a landmark for this approach, we first considered the stump of the eighth nerve. As reported in 1998, there were problems with this approach, including postsurgical absence of a nerve stump and angulation of the nerve root. We then modeled electrode insertion using the taenia choroidea as a surface landmark. The taenia choroidea is a membrane formed by fusion of the ependymal inner surface of the lateral recess with the outer pial surface of the brainstem. It is visible to the surgeon and is routinely used to locate the foramen of Luschka in order to place the surface ABI in the lateral recess. Our computer reconstructions of the brainstem confirmed that the taenia consistently overlies the posterior VCN, as indicted by the arrows in Fig 1.2.

The possibility of an yet another approach was raised in a recent discussion with neurosurgeon William Hitzelberger. Because a vestibular schwannoma “dissects” the cerebellum off of the brainstem, leaving the CN in a superficial position, an opening the possibility of a more lateral approach into the VCN (“Lateral” in Figure 1.1). Using the “probe” electrode, a disposable device recently approved by the FDA and made available by Cochlear Corporation, the neurosurgeon is able to determine the location of the VCN by recording responses evoked from the brainstem surface. Location of the VCN by direct recordings from the brainstem surface would obviate the need for a visible surface landmark.

1.4 Dimensions of the target area

The complex shape of the nuclei, particularly their flattening in the mediolateral dimension, places significant constraints on the design and placement of an array of penetrating electrodes. The flattened shaped of the human cochlear nuclei over the medial cerebellar peduncle has been advantageous for the use of the surface electrode, since it offers the electrode a greater area of contact. However, a penetrating electrode aimed at the central VCN has a target area with a maximum dimension along any of its axes of only 2-4 mm.

One factor influencing the design of a penetrating electrode is the question of atrophy or distortion of the cochlear nuclei due to loss of the cochlear nerve. Thus it

becomes essential to have an accurate description of the size and shape of the cochlear nuclei in deafened individuals. During contracts I and II, we determined shapes and volumes of the cochlear nuclear complex in seven normal persons and eight profoundly deaf subjects. The population of deaf subjects included one with a unilateral neuroma, but no neurofibromatosis 2 (NF2) subjects. The reconstructions of their cochlear nuclei showed minor variations in the shape of the VCN, but no features were seen that would allow us to distinguish the brains of deaf subjects from those of hearing subjects. Figure 1.2 shows a series of sections in the transverse plane through the rostral-caudal extent of the VCN of a 37 year old person with normal hearing. The sections are spaced 300 μm apart, indicating a total rostrocaudal length of the VCN of about 3 mm. The ventral cochlear nucleus is shown in solid black. The sequence of sections shown diagonally across the figure were cut approximately normal to the long axis of the brainstem, so “rostral” is towards the top of the head, and “caudal” is towards the feet. The nucleus has a generally bulbous shape, particularly in its central region. In the inset at the upper left, a lateral projection of the nucleus onto a sagittal plane shows that it has a height of about 4 mm in its posterior and central segments, decreasing to about 2 mm at the rostral tip. In the inset at the lower right, a projection of the nucleus onto a frontal plane shows that it varies in width from about 1 mm caudally to 2 mm centrally.

During these early studies, we were aware that the profoundly deaf subjects retained a population auditory nerve fibers which, though fewer than the normal 30,000 axons, consisted of several thousand fibers (Moore et al., 1994, 1997). Neurofibromatosis 2 could present a different situation in that after resection of the vestibular schwannoma, there is complete destruction of the auditory nerve and subsequent degeneration of its neuropil within the VCN. During contract III, we obtained the brainstem of an NF2 subject who had undergone bilateral removal of vestibular tumors 10 and 7 years previously and who has been implanted with a surface ABI device at the time of the second tumor surgery. In this subject, unlike the deaf subjects analyzed previously, there was a significant (30-50%) reduction in the volume of the cochlear nuclei. We later received the brainstem of a second NF2 subject with a more aggressive form of the disease but the cochlear nuclei were so degenerated that we could not reliably determine their borders, and thus could not create a reconstruction.

Figures 1.3 and 1.4 illustrate the ventral cochlear nuclei on both sides of the brainstem of the first NF2 subject. The spacing between sections is identical to that of the normal subject (300 μm), and the reduced number of sections indicates that the nucleus had a rostrocaudal extent of only about 2 - 2.5 mm. In the inset in upper part of the figures, the lateral projections show that the nucleus’s dorso-ventral extent is similar to that of the normal subject (approximately 4 mm). In the insets in the lower part of the figures, the projection onto a frontal plane show that the width of the caudal

part of the VCN does not exceed 1 mm, while its rostral part is somewhat broader.

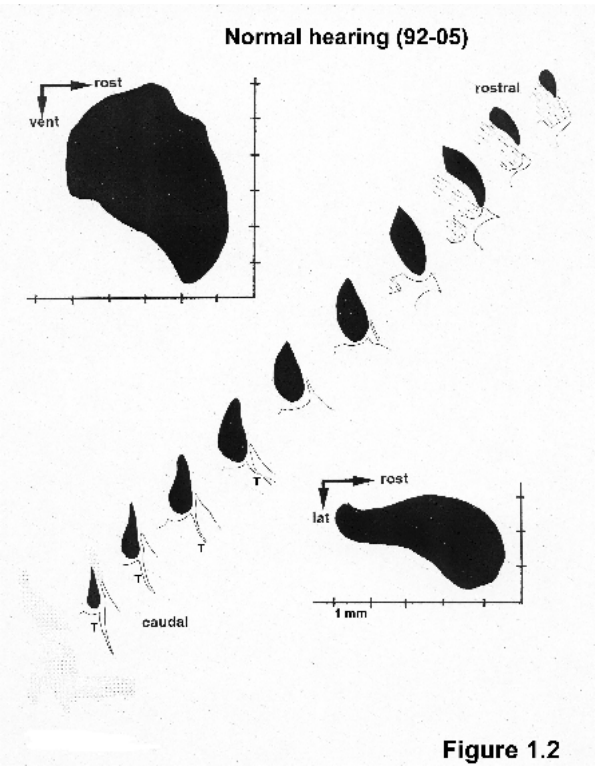

Figure 1.2

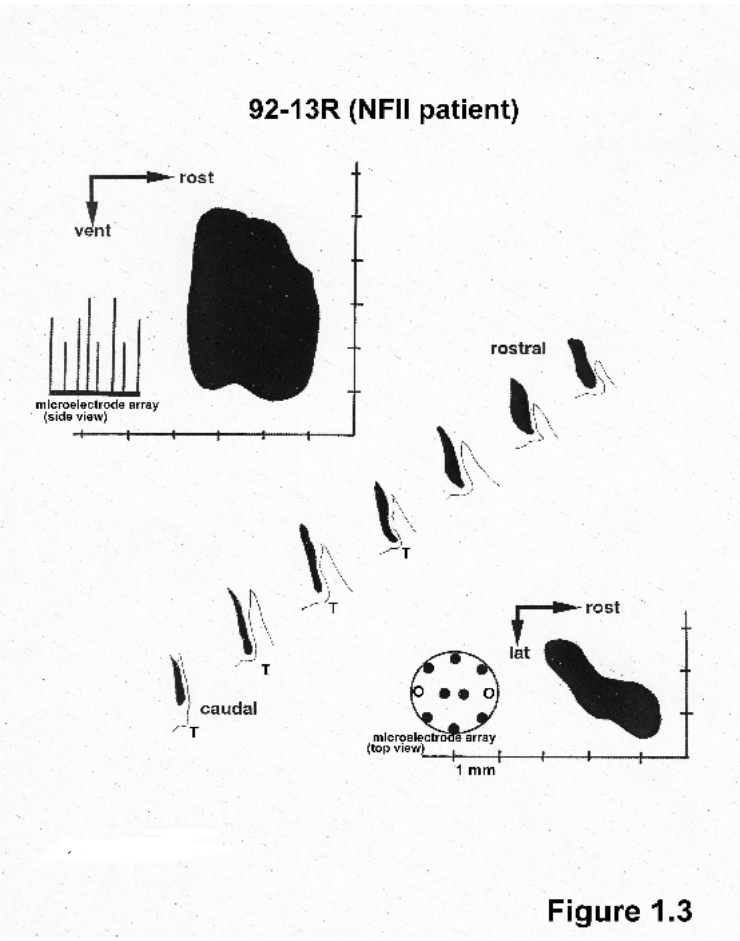
92-13R (NFII patient)
rost
vent
microelectrode array
(side view)
rostral
T
T
T
caudal
T
rost
lat
microelectrode array
(top view)
1 mm

Figure 1.3

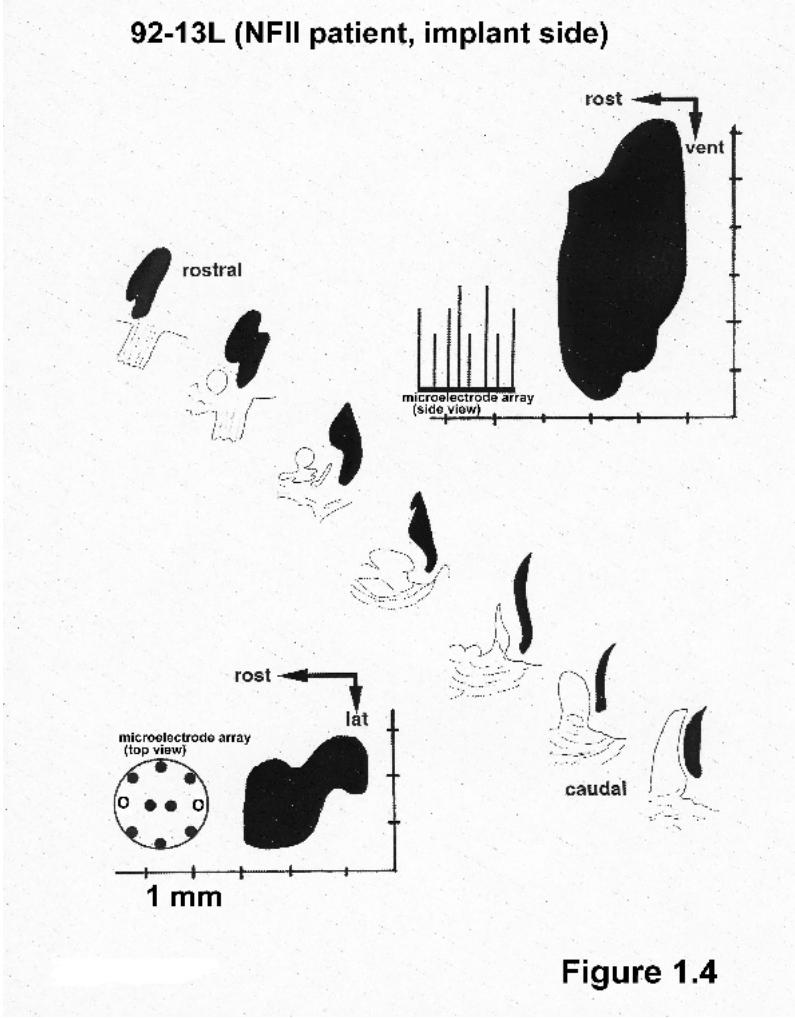
92-13L (NFII patient, implant side)
rost
vent
rostral
microelectrode array
(side view)
caudal
rost
lat
microelectrode array
(top view)
1 mm

Figure 1.4

1.5 Dimensions of the electrode array

The insets in Figures 1.3 and 1.4 show top and side views of the proposed electrode array. The top views of the array (adjacent to the ventral projections at the bottoms of the figures) show the distribution of eight stimulating electrodes (solid circles) and two stabilizer pins (open circles). This is the array's "footprint" when it is inserted by the ventral approach. Six of the working electrodes are distributed in a ring that is 2 mm in diameter, with a spacing of 0.5 mm between each stimulating site. Two others are positioned near the center of the ring. With a ventral approach, the most serious problem is the extreme narrowness of the nucleus along the mediolateral dimension. If a penetration is not made along the long dimension of the narrow VCN, the tips of stimulating electrodes will not lie within the nucleus. Because the tips of longer electrodes are more likely to fall outside the VCN if the insertion is not precisely along the long axis of the nucleus, we have specified rather short electrodes, and the chance of their tips coming to lie outside of the nucleus is reduced if the angle of insertion is not optimal. With a lateral approach, the electrodes cross the tonotopic planes of the VCN at about a 45^{o} angle (Figure 1.1) similar to what would occur with a ventral approach. However with this approach, the electrodes must be short enough so as not to penetrate completely through the nucleus. With either approach, it is difficult to predict precisely how the electrodes will be related to the isofrequency planes, but this scattered pattern of stimulation sites should result in activating different tonotopic regions of the VCN.

Whatever the array's angle of entry, the cochlear nuclei are never directly in contact with the brain surface. A layer of overlying tissue approximately half a millimeter thick, and probably glial in nature, lies between the cochlear nuclei and the ependymal or pial surface. This peripheral rim of tissue is featureless in both cell and myelin stains, suggesting that it consists of astrocytic processes. If this tissue rim is, in fact, a hypertrophied glial limitans, penetrating cochlear electrodes will have to be sturdy enough to pierce this tough layer. Also, the thickness of this layer must be included in the calculations of shaft lengths.

To accommodate either a ventral or a lateral approach (or something in between), we are proposing an array with electrode lengths of 1 mm (3 electrodes) , 1.5mm (3 electrodes) and 2 mm (2 electrodes) and a spacing of 0.5 mm between the individual electrodes (solid circles). Two electrically inactive shafts with lengths of 3 mm have been added to the design for stability after insertion into the tissue (open circles). While the geometry of the nucleus, the changes occurring after tumor resection, and uncertainly regarding the precise angle of insertion has pushed us towards this "conservative" design with mostly short electrodes, another factor is introduced by the results of psychophysical studies that are discussed in the next section.

2.0 PITCH DISTRIBUTION OF ELECTRODES IN AN AUDITORY PROSTHESIS: IMPLICATIONS FOR THE DESIGN OF THE MICROELECTRODE ARRAY

2.1 Introduction

Electrical stimulation of the human cochlear nucleus for prosthetic benefit has been under development for more than 20 years. The first human was implanted with the Auditory Brainstem Implant (ABI) in 1979 at the House Ear Institute (HEI) in Los Angeles. From 1979 to 1992 only a few patients were implanted with the ABI and speech processors were limited to single-channel models. In 1992 HEI, Huntington Medical Research Laboratories (HMRI), and Cochlear Corp collaborated on the design and development of a multi-channel ABI with an 8-electrode surface array, which was implanted in the first human patient in 1993 under an IDE from the FDA (G930077/S26). Since that time 75 multichannel ABIs have been implanted at HEI and more than 50 additional patients at other co-investigator sites. In July 2000 the FDA panel reviewed the results from the multichannel ABI clinical trials and gave unanimous approval for a PMA. Formal FDA approval was received on October 20, 2000.

Although the multichannel ABI has been determined to be a clinically safe and effective device for restoring hearing sensations to patients with no remaining auditory nerve, ABI patients cannot recognize speech as well as cochlear implant patients with the same device. Without lip-reading, the average sentence recognition score is about 90% correct for cochlear implant listeners, but less than 10% correct for ABI listeners. Only a few ABI listeners can recognize 50% of the words in sentences with the stimulation from the ABI alone. The reasons for this large difference in performance between CI and ABI are not clear, but there are two prevailing hypotheses: poor tonotopic selectivity and bypassing intrinsic processing. The “poor tonotopic selectivity” hypothesis suggests that ABI performance is poorer than CI performance because the surface electrodes of the present ABI device do not provide good selectivity in stimulating the tonotopic axis of the cochlear nucleus. The CI generally produces excellent electrode specific pitch sensation because the electrodes are spaced along the normal tonotopic axis of the scala tympani. In contrast, the ABI surface electrode is not well aligned with the tonotopic axis of the human cochlear nucleus. The “bypassing intrinsic processing” hypothesis supposes that the ABI electrode stimulates several different types of neurons in the cochlear nucleus in a non-selective manner. The normal differences in processing of those cells are therefore lost and higher auditory centers that depend on that specific processing at the level of the CN do not receive the correct information. When the auditory nerve is stimulated in a cochlear implant these processing mechanisms intrinsic to the CN may still be able to provide higher auditory centers with the necessary neural pattern information, but electrical stimulation in the CN by means of an array of microelectrode may not allow these intrinsic processing mechanisms to function properly.

Penetrating microelectrodes for stimulation of the human cochlear nucleus have been under development for more than 12 years under this NIH contract. Penetrating microelectrodes can stimulate highly selective areas of the human cochlear nucleus and such stimulation produces tonotopically restricted activation in higher auditory centers, such as the inferior colliculus (McCreery et al., 1998). Excellent tonotopic selectivity should be achievable with penetrating electrodes, potentially overcoming a major shortcoming of the surface ABI electrodes. It is not clear if penetrating microelectrodes will allow improved intrinsic processing, compared to surface electrodes. If the penetrating electrodes stimulate a localized area of neurons that are relatively peripheral in the processing sequence, then additional intrinsic processing may be able to occur as in cochlear implants. However, if the stimulated region is later in the processing sequence, even spatially selective microstimulation may not be able to improve ABI performance.

The primary motivation for using penetrating microelectrodes in an ABI (PABI) is to attain better access to the tonotopic lamina in the cochlear nucleus. Different electrode locations should produce strong differences in pitch percepts. The absolute pitch of the electrodes is also a key factor in designing a speech processor, because preliminary experiments have shown the importance of matching the frequency content of speech to the tonotopic location of the electrode (Fu and Shannon, 1999). A mismatch of only 3-4 mm along the cochlea, which is less than one octave according to the Greenwood map (1990) , can produce a dramatic reduction in speech recognition in cochlear implant listeners and in normal hearing listeners in which this condition is simulated. In a cochlear implant the electrodes are arranged longitudinally in the scala tympani along the tonotopic gradient, so that the electrodes are relatively simply ordered by pitch. However, in the ABI (and particularly in the PABI) the pitch ordering of the electrodes is not simple. Some patients with the surface ABI report pitch as increasing from medial to lateral electrodes and other patients have the reverse ordering. Many ABI patients experience strong pitch changes in the rostro-caudal dimension of the electrode array. With penetrating electrodes, the pitch ordering might be even more disorganized, because the electrodes might stimulate various tonotopic lamina depending on the length of the electrodes and the thickness of the pial layer covering the cochlear nucleus. Thus, an important aspect of designing an ABI with penetrating electrodes is to ensure that the electrodes cover a wide pitch range in the nucleus and that the speech processor is matched to the pitch of the electrodes. We conducted the following experiment in normal-hearing listeners to assess the importance of the distribution of pitch across electrodes.

Effect of overall frequency range

An important consideration in setting up the parameters of a speech processor for the PABI is the assignment of frequencies to electrodes (Shannon et al., 1998). If

the array of electrodes does not produce percepts of pitch that cover the entire frequency range, some accommodation must be made in the frequency assignments. For example, consider the possibility that four of the penetrating electrodes produce auditory sensations, but that all four electrodes produce similar low pitches. Will the best speech recognition performance be achieved when the entire frequency range is partitioned into four frequency bands and each band is assigned to an electrode (broadband), or when a more limited overall frequency range is used, with a total pitch range limited to the range covered by the electrodes (matching condition)?

To better understand the potential importance of these issues we measured vowel and consonant recognition in normal-hearing listeners in conditions designed to simulate possible PABI outcomes. We simulated four different distributions of pitch across penetrating electrodes. For each electrode pitch distribution, we measured speech recognition as a function of the frequency-electrode mapping.

2.2 Methods

2.2.1 Acoustic Simulations of Implant Speech Processors

Acoustic simulations were constructed using noise-band speech processors as described by Shannon et al. (1995). The speech signals were digitized at a 22 kHz sample rate and passed through a pre-emphasis filter to whiten the spectrum (6dB/octave decrease below 1200 Hz). The signal was then split into frequency bands (6th order Butterworth filters). The envelope was extracted by half-wave rectification and low-pass filtering (-18 dB/octave filters with a cut-off frequency of 220 Hz). The envelope from each band was then used to modulate wide-band white noise. The modulated noise was frequency-limited by filtering. In some conditions the filters were the same filters used in the analysis bands ("matched" conditions), while in other conditions the band-pass filters were different in center frequency and bandwidth from the analysis filters (Figure 2.1). The band-pass filtering reduces the modulation depth to some degree because it removes the modulation side bands. The resulting modulated noise from each band were combined,

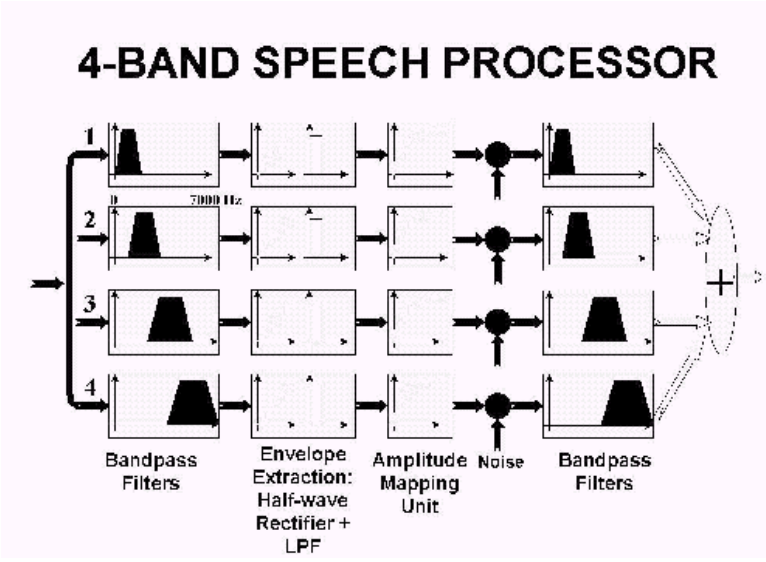

Figure 2.1

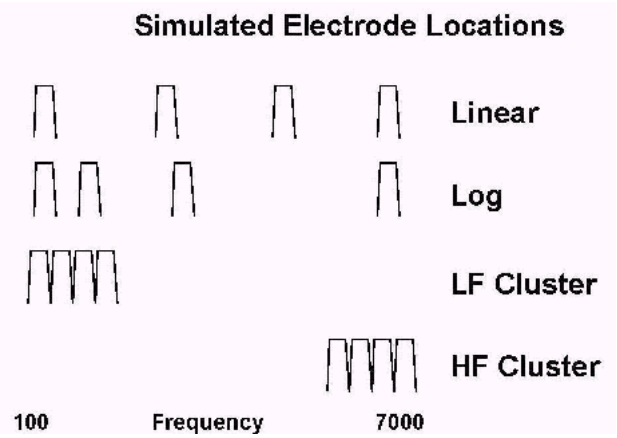

Figure 2.2

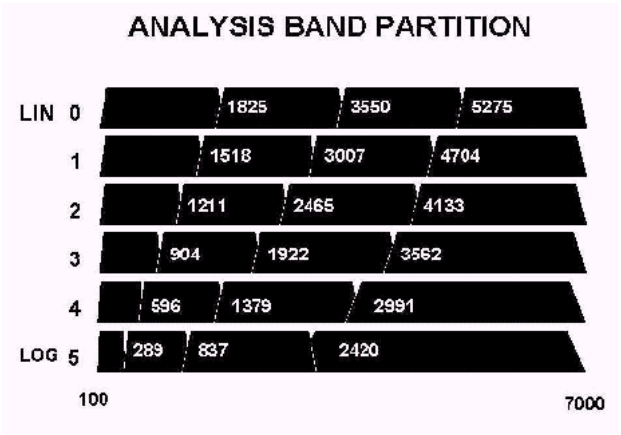

Figure 2.3

low-pass filtered at 8 kHz, amplified (Crown D75) and presented to the listener through headphones (TDH-49).

Noise carrier bands were designed to simulate the stimulation that might be achieved by penetrating electrodes. Conditions were designed to represent a wide range of possible outcomes with a PABI. The high spatial localization of stimulation with a penetrating electrode was simulated by a 100-Hz wide carrier band of noise, filtered with 6th order bandpass filters (Butterworth, 36 dB/oct slopes). Four "electrode" outcomes were simulated by four narrow band noise carriers: four electrodes (1) spaced linearly in frequency, (2) spaced logarithmically in frequency, (3) all four clustered at a low frequency, and (4) all four clustered at a high frequency (Figure 2.2). Center frequencies of the four bands were 500, 700, 900 and 1100 Hz for the low-frequency cluster, 3000, 4000, 5000, and 6000 Hz for the high-frequency cluster, 500, 2500, 4500, and 6500 Hz for the linear spacing, and 500, 1180, 2760, 6500 Hz for the logarithmic spacing. These four conditions constitute two cases of desirable tonotopic spacing (covering the entire auditory pitch range) and two cases of sub optimal tonotopic spacing (all four electrodes close together in pitch). For each of these electrode spacing conditions we measured consonant and vowel recognition for 6 different partitions of the frequency range from 100-7000 Hz, ranging from linear frequency spacing of the four bands to logarithmic spacing (Figure 2.3). An additional condition measured speech recognition for the high- and low-frequency clusters when the analysis filters were matched to the carrier bands.

2.2.2 Speech Materials and Methods

Phoneme recognition performance was assessed using two sets of speech materials: medial vowels and medial consonants. Vowel recognition was measured in a 12-alternative identification paradigm, including 10 monophthongs and 2 diphthongs,

presented in a /h/-vowel-/d/ context, e.g., "heed", "hid", "hayed", "head", "had", "hod", "hawed", "hoed", "hood", "who'd", "hud", "heard". The tokens for these closed-set tests were digitized natural productions from 5 men, 5 women, 3 boys, and 2 girls, drawn from the material collected by Hillenbrand et al. (1994). Consonant recognition was measured in a 16-alternative identification paradigm, for the consonants /b d g p t k l m n f s ∫ v z j θ/, presented in a /a/-consonant-/a/ context. Five male and five female talkers each produced each of 16 consonants, resulting in 160 tokens (Shannon et al., 1999). A stimulus token was randomly chosen from all 180 tokens in vowel recognition (or from 160 tokens in consonant recognition) and presented in random order. Following the presentation of each token, the subject responded by pressing one of 12 buttons in the vowel test (or one of 16 buttons in the consonant test), each marked with one of the possible responses. No feedback was provided, and subjects were instructed to guess if they were not sure, although they were

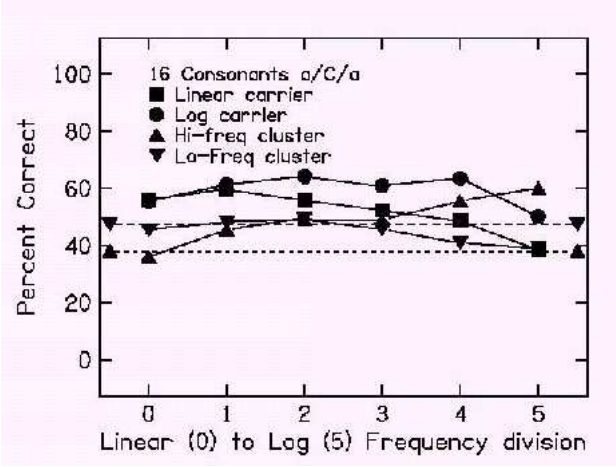

Figure 2.4

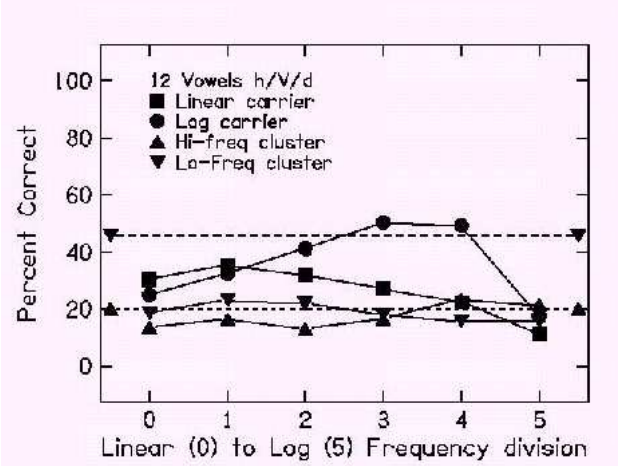

Figure 2.5

cautioned not to provide the same response for each guess. The subjects started the formal test without training and with no appreciable period of adjustment to the new processor simulation. Each run consisted of 15 presentations of each vowel or 10 presentations of each consonant. Each data point represents the average of one run from three listeners.

2.3 Results

The results for consonant (Figure 2.4) and vowel recognition (Figure 2.5) show the importance of matching the analysis frequency partition to the tonotopic location of the electrodes. In each figure, the lower dashed line shows the recognition score with

a cluster of high-pitch electrodes when the frequency regions are perfectly matched to the electrode pitch locations. The upper dashed line shows the result from the matched, low-pitch cluster. Both consonant and vowel recognition were poor for the high-pitch cluster. Consonant recognition was poor, but vowel recognition was reasonable for the low-pitch cluster when the analysis bands were matched to the carrier bands, i.e. the simulated condition in which the analysis bands are matched to the electrode pitch.

The four curves in each figure show results from the four simulated electrode locations as a function of the frequency division. Note that the high-frequency and low-frequency clusters produce poor performance for all frequency divisions. This result has important implications for the design of penetrating electrode system, i.e., it is important to achieve a wide range of pitch across the penetrating electrodes.

Consonant recognition was not strongly affected by the different frequency division. This confirms an earlier result (Shannon et al., 1998) and is likely due to the fact that consonant recognition is more heavily dependent on temporal cues and less dependent on spectral cues. Linear carrier bands showed a small advantage when the analysis bands were divided almost linearly (analysis division condition 1). This condition was probably superior to true linear division because it had a frequency division between the lower two bands at about 1500 Hz, an important frequency for dividing speech spectral information. The low-frequency cluster of carrier bands produced uniformly poor consonant recognition regardless of the frequency division of analysis bands. The high-frequency cluster of carrier bands produced best consonant recognition when the analysis bands were divided logarithmically (condition 5).

Vowel recognition was more strongly affected by the analysis and carrier bands than consonant recognition. Both the low-frequency cluster and high-frequency cluster of carrier bands produced very poor vowel recognition for all analysis band divisions. Linearly spaced carrier bands produced relatively poor vowel recognition, which was only mildly affected by the distribution of analysis filter bands. For linear carriers, the best performance was seen with analysis frequency division 1, a similar pattern as was observed for consonants. However, there was a strong effect of analysis frequency division on performance with logarithmically spaced carrier bands. In this case vowel recognition was 30% better with analysis divisions 3 and 4 than with divisions 0 or 5. Overall, there was a strong effect of both analysis and carrier band spacing for vowel and consonant recognition. Best performance was obtained when the carrier bands (simulated electrodes) spanned the entire frequency range logarithmically and when the analysis bands were also divided approximately logarithmically (NOTE: Vowel recognition performance was low for analysis frequency division 5 because that set did not contain a band division near 1500 Hz. From previous work we know that at least one band division near 1500 Hz is critical for good vowel recognition. Analysis frequency divisions 3 and 4 represent compromise conditions where the analysis bands

are nearly matched in spacing to the carrier bands and which contain a band division near 1500 Hz.)

These results imply that penetrating electrode systems should be designed so that the electrodes have the best chance of spanning the entire frequency range and are equally spaced in logarithmic frequency. The normal auditory tonotopic map in the cochlea is organized approximately according to log frequency (Greenwood, 1990) and the "Greenwood mapping" is propagated through all auditory brainstem nuclei. While we cannot know the exact tonotopic map of the human cochlear nucleus, we assume that the "Greenwood tonotopic map" is preserved, but scaled to the size of the nucleus. The primary tonotopic axis of the human posterior-ventral cochlear nucleus (PVCN) is orthogonal to the surface of the brainstem and is approximately 2-3 mm in extent (see Section 1 of this QPR). Ideally, penetrating microelectrodes should be designed so as to span the entire tonotopic range, in equal increments. As noted in Section 1.1, determining the optimal distributions of electrode lengths is not a simple matter, because the depth of a given iso-frequency lamina in the cochlear nucleus below the brainstem surface is dependent on many variables, including the angle of electrode insertion, the thickness of the pial layer covering the nucleus, the distortion of the brainstem surface by the tumor and its removal, and long-term changes in the size and shape of the cochlear nucleus due to the tumor. Our analysis of normal human brainstems and brainstems following single and bilateral vestibular schwannomas suggest that penetrating electrodes should range in length from 1.0 mm to 3.0 mm in order to span the entire range of acoustic frequencies when the electrodes is inserted along a dorso-ventral direction. They should be slightly shorter in order to span the axis if the array is inserted more laterally. Our present design (Figure 2.6) contains two 3 mm stabilizing pins and 8 active electrodes, staggered in length between 1 and 2 mm. Depending upon the angle of insertion, this array may not span the entire tonotopic axis of the VCN. However, this error will cause a loss of access to the portions of the VCN representing high acoustic frequencies; a condition that is preferable to losing access to the lower frequencies, as would occur if the electrodes were too long.

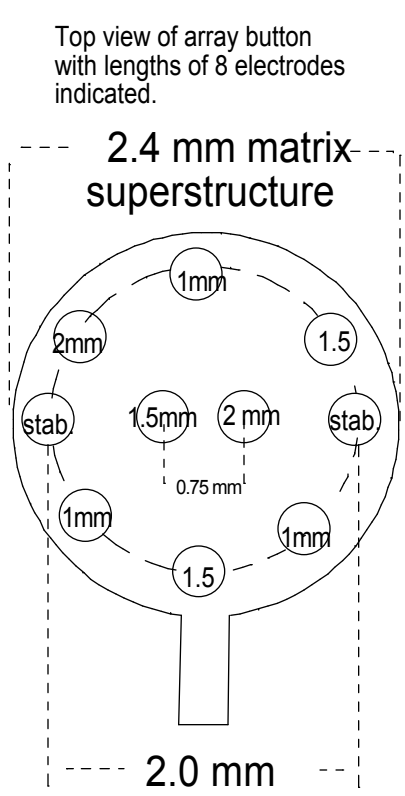

Figure 2-6

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