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Psychophysical assessment of stimulation sites in auditory prosthesis electrode arrays

Bryan E. Pfingst^{a,*}, Rose A. Burkholder-Juhasz^a, Teresa A. Zwolan^{a,b}, and Li Xu^{a,c}

^a Kresge Hearing Research Institute, Department of Otolaryngology, University of Michigan Health System, Ann Arbor, MI 48109-5506, USA

^b Hearing Rehabilitation Center, Department of Otolaryngology, University of Michigan Health System, Ann Arbor, MI 48108, USA

^c School of Hearing, Speech and Language Sciences, Ohio University, Athens, Ohio 45701, USA

Abstract

Auditory prostheses use implanted electrode arrays that permit stimulation at many sites along the tonotopic axis of auditory neurons. Psychophysical studies demonstrate that measures of implant function, such as detection and discrimination thresholds, vary considerably across these sites, that the across-site patterns of these measures differ across subjects, and that the likely mechanisms underlying this variability differ across measures. Psychophysical and speech recognition studies suggest that not all stimulation sites contribute equally to perception with the prosthesis and that some sites might have negative effects on perception. Studies that reduce the number of active stimulation sites indicate that most cochlear implant users can effectively utilize a maximum of only about seven sites in their processors. These findings support a strategy for improving implant performance by selecting only the best stimulation sites for the processor map. Another approach is to revise stimulation parameters for ineffective sites in an effort to improve acuity at those sites. In this paper, we discuss data supporting these approaches and some potential pitfalls.

Keywords

Auditory prosthesis; cochlear implant; psychophysics; detection threshold; electrode discrimination; modulation detection; channel interaction; speech recognition

1. Introduction

Despite improvement in overall performance of patients with cochlear implants over the past several decades, variability across patients in speech recognition, music perception, and psychophysical acuity remains a significant concern. There are many factors that are believed to contribute to variability in perception with cochlear implants. These include conditions in the implanted cochlea such as auditory nerve survival patterns, bone growth, and positioning of electrodes in the scala tympani; deafness-induced plasticity in the central auditory pathways; and cognitive factors.

*Corresponding author. Tel: +1-734-763-2292; fax: +1-734-764-0014. E-mail address: bpfingst@umich.edu (B.E. Pfingst).

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There is ample evidence to suggest that variables at the level of the implanted cochlea contribute appreciably to the observed variation in subject performance. One key set of evidence comes from studies of variation in psychophysical performance along the stimulation sites in a multisite electrode array. This variation can be large, and the patterns of variation differ across subjects. Figures 1 and 2 show examples of variation across stimulation sites in two psychophysical measures. Figure 1 shows examples of across-site variation in psychophysical detection thresholds (T levels) and maximum comfortable loudness levels (C levels). Figure 2 shows examples of across-site variation in modulation detection thresholds (MDTs) which assess the ability of the subject to detect amplitude modulated signals as a function of modulation depth. This and similar measures of temporal acuity have been shown to correlate with speech recognition (Cazals, 1994; Fu, 2002; Colletti and Shannon, 2005). Spatial acuity, which can be assessed in terms of the ability of subjects to discriminate one stimulation site from its neighbors or to pitch-rank sensations for stimulation of various sites along the tonotopic axis, also varies across stimulation sites (Zwolan et al., 1997; Pfingst et al., 1999; Donaldson and Nelson, 2000). The most parsimonious explanation of this site-to-site variation is that conditions near the electrodes affect the psychophysical results. Histological studies have revealed several conditions that could lead to variation in the temporal and spatial patterns of responses in neurons stimulated by each of the implanted electrodes. These conditions include various patterns of nerve loss, and the growth of fibrous tissue and new bone in the implanted cochleae (Hinojosa and Lindsay, 1980; Nadol, 1997; Fayad and Linthicum, 2006; Somdas et al., 2007).

The potential contribution of peripheral variables to patient performance and the potential of using psychophysical measures to assess the contribution of these variables have motivated us to focus our research on the patterns of psychophysical data across stimulation sites in the electrode array. We have also examined the relationships among the across-site patterns of various psychophysical data, and the relationship of these patterns to speech recognition.

In this paper, the term “stimulation site” refers to the location within the scala tympani (or within the auditory nerve or an auditory nucleus) where current is delivered. It is determined by the location and configuration of the electrode or combination of electrodes used to deliver the stimulation from a single channel of the processor. For multielectrode sites, it is determined by the parameters of the currents delivered to each of the component electrodes. Thus, for monopolar (MP) stimulation of a cochlear implant (stimulation between an electrode in the scala tympani and an extracochlear electrode), it is equivalent to the location of the stimulated scala-tympani electrode and can be labeled by the number of that electrode. For bipolar (BP) stimulation of a cochlear implant (stimulation between two electrodes in the scala tympani, typically spaced about 0.75 to 3.0 mm apart), it is determined by the location of the two intrascalar electrodes between which current is passed. For studies reported here, the number of the more basal electrode in a bipolar pair is used to name the stimulation site. With tripolar (TP) or multipolar phased array (PA) stimulation (in which a stimulating electrode in the scala tympani is flanked by two or more return electrodes), the name of the site is based on the number of the middle electrode. Current-steering techniques can be used to direct the stimulation to various locations with respect to the implanted electrodes by adjusting the parameters of the current delivered through each electrode. This can provide a number of stimulation sites that is larger than the number of implanted electrodes. These are sometimes referred to as “virtual sites”.

The focus of this paper will be on psychophysical assessment of cochlear implants, where the majority of the data exist. However, some of the principles discussed here are also applicable to other implants in the auditory nerve and central auditory pathways, and we will discuss these prostheses at the end of the article.

2. Mechanisms Underlying Across-Site Patterns

The functional variation across stimulation sites includes thresholds for stimulus detection, loudness, and spatial and temporal acuity. In this paper we will discuss the idea that selecting individual sites based on psychophysical performance and/or optimizing stimulation parameters at ineffective sites might benefit the overall performance of the cochlear implant user. To fully utilize the data on across-site patterns of psychophysical measures, it will be helpful to understand the mechanisms underlying these patterns. This knowledge will guide strategies for optimizing auditory prosthesis performance.

Mechanisms underlying across-site patterns of implant function are not well understood but current data suggest some possible mechanisms and some directions for future research. First, there can be large differences in psychophysical responses for sites that are closely spaced. Additionally, the across-site patterns of these measures vary considerably from subject to subject (Figures 1 and 2). These results are consistent with the idea that across-site threshold patterns are due to localized conditions in the cochlea as described in the Introduction above. Second, the across-site patterns of some psychophysical skills seem to be related to one another (i.e., correlated across stimulation sites), while others are not. For example, in preliminary studies we found that MDTs were significantly correlated across stimulation sites with gap-detection thresholds but poorly correlated with T levels (Burkholder-Juhász and Pfingst, 2008). This suggests that the underlying mechanisms controlling the across-site patterns are not always the same. Third, there is an inverse relationship between the magnitude of variation in T levels and speech recognition (Pfingst et al., 2004; Bierer, 2007). That is, subjects with the largest variation in T levels across sites had the poorest speech recognition. This suggests that the mechanisms that create the local variation are detrimental to the perception of complex signals such as speech with the cochlear prosthesis.

It is useful to consider probable causes of the across-site variation in psychophysical detection thresholds and other psychophysical measures. One variable might be the distances from the electrodes to the sites of action-potential initiation. These distances depend on a number of conditions that occur in the deafened, implanted cochlea including the position of the electrodes within the scala tympani with respect to the modiolar wall (Saunders et al., 2002); the presence of fibrous tissue and new bone within the scala tympani that obstructs the current path between the electrodes and the neurons (Somdas et al., 2007); and neural pathology that varies along the length of the cochlea, influencing the position of the remaining excitable neurons with respect to each stimulation site (Hinojosa and Lindsay, 1980; Nadol, 1997; Fayad and Linthicum, 2006). Current levels decrease as a function of the distance between the electrodes and the sites of action-potential initiation. Therefore, other things being equal, greater distances will result in higher thresholds, and large site-to-site variation in these distances will result in large site-to-site variation in detection thresholds. However, in reality the picture is more complicated. For example, the effects of distance depend on the characteristics of the tissue lying between the electrodes and the neurons. In addition, the effectiveness of the currents reaching the neurons depends on the locations of action potential initiation on the neurons and the orientations of the neurons with respect to the current paths (Rattay et al., 2001 a & b; Whiten and Eddington, 2007).

A second variable potentially affecting psychophysical responses and across-site variation in those responses is the spatial extent and pattern of neurons activated by each stimulation site. By spatial extent, we mean the extent of activated neurons along the tonotopic axis of the cochlea. Spatial extent is typically assessed by spatial tuning curves or psychophysical tuning curves based on threshold measurements. Electrical stimulation of sites in the fluid-filled scala tympani typically generates relatively large current fields, resulting in excitation of a large spatial extent of neurons at levels slightly above the neural threshold (Hartman et al., 1987;

Snyder et al., 1990; Bierer and Middlebrooks, 2002). Thus, there is probably significant overlap in the neural populations activated when adjacent sites in the implant are stimulated. If one assumes that detecting electrical stimuli requires integration of activity across all activated neurons (an unproven assumption), then in theory, greater overlap and greater diversity in the activated neural populations decreases the likelihood that detection thresholds for the two sites will be different. However, in considering the spatial extent of excitation, it is important to take the spatial pattern of excitation into account. The electrical fields generated by stimulation sites are not uniform across the spatial extent of excitation, so we would not expect the pattern of excitation to be uniform. For example, we would expect higher discharge rates near the stimulation site than at locations lateral to the stimulation site, provided the neurons have not reached rate saturation, or the peak rate in the case of nonmonotonic rate-level functions. The temporal response patterns of neurons are also likely to vary across the spatial extent of excitation. Thus, while the spatial extent of neurons excited in any manner by the electrical stimulus might be very similar for two stimulation sites, the patterns of activity within the areas of excitation might be very different for the two sites. This may explain why the psychophysical responses at adjacent sites can be quite different despite considerable overlap in the borders of the activated neural population. Unfortunately, the spatial pattern of excitation is potentially very complex and thus much more difficult to characterize than the spatial extent of activity.

A third potential cause of across-site variation in psychophysical performance is the condition of the activated neurons. Factors such as myelination of auditory nerve fibers and the condition of the auditory nerve peripheral process have known effects on the excitability and temporal properties of auditory nerve fibers (van den Honert and Stypulkowski, 1984; Colombo and Parkins, 1987). There is also evidence that several features of the compound action potential of the auditory nerve are altered when hair cells are present and functioning (Hu et al., 2003). If functioning hair cells are present near the implanted electrodes, they might produce spontaneous activity in the auditory nerve fibers and create a more normal condition of the neurons, which could possibly improve perceptual acuity, particularly for temporal features of electrical stimulation.

Finally, we must consider that the presence of hair cells in the implanted cochlea can allow electrophonic hearing (Stevens, 1937; Le Prell et al., 2006) by activation of the basilar membrane. One likely mechanism for this activation is stimulation of outer hair cells causing them to contract and set up a traveling wave. It is likely that the presence of these cells would not be uniform across the hearing-impaired, implanted cochlea (Gstoettner et al., 2004) so the threshold for eliciting these sensations, or the ability to elicit them at all, would probably vary considerably from one stimulation site to another.

The four variables discussed above (distance from the electrodes to the sites of action-potential initiation, spatial extent and pattern of neurons activated, condition of the activated neurons, and electrophonic hearing) are not mutually exclusive. In some cases, they are affected by common underlying variables. For example, if higher currents must be delivered to achieve stimulus detection because the electrodes are distant from the neurons, these higher currents are also likely to result in a greater spatial extent of neural activation. Nevertheless, it is useful to consider which of these variables might be most important for a given psychophysical measure.

Electrode configuration has large effects on across-site variation of some psychophysical functions, particularly detection thresholds. This fact may be helpful in identifying the potential mechanisms underlying across-site variation in psychophysical measures. Monopolar (MP) stimulation typically produces a broad current field, which activates a large number of neurons, even at levels near the threshold of the most sensitive neurons (Hartmann et al., 1990; Bierer and Middlebrooks, 2002). Bipolar stimulation using electrodes in close proximity (e.g. BP+0

with an interelectrode distance of about 0.75 mm), produces narrower patterns of excitation under some conditions, although the effects are not consistent (Bierer and Middlebrooks, 2002; Kwan and van den Honert, 2006). Tripolar (TP) or quadrupolar stimulation produces a more restricted current field and a smaller spatial extent of excitation (Spelman et al., 1995; Bierer and Middlebrooks, 2002). Phased-array (PA) stimulation (which uses a similar principle to tripolar stimulation but with a larger array of electrodes) also produces restricted current fields and spatially-restricted excitation patterns (van Compernelle, 1985; Rodenhiser and Spelman, 1995; van den Honert and Kelsall, 2007).

Across-site variation of T levels and C levels is much smaller for MP stimulation than for more focused stimulation modes such as BP+0, TP and PA (Pfingst and Xu, 2004; Bierer et al., 2007; van den Honert et al., 2007). This could be due to greater spatial extent of the populations being activated by MP stimulation. A greater spatial extent of neurons activated by neighboring stimulation sites might result in greater overlap, and thus similarity, in the neural populations responding to stimulation of those sites and thus less across-site variation in the psychophysical data.

There is evidence, however, that the spatial extent of activated neurons does not significantly affect across-site variations in loudness. This evidence comes from comparing across-site variation for T levels with that for C levels. We know that increases in stimulation level result in large increases in the spatial extent of the activated neural population (Snyder et al., 1990; Bierer and Middlebrooks, 2002). Therefore, if across-site variation decreases as a function of the spatial extent of the activated neural populations, across-site variation for C levels should be much smaller than that for T levels. In fact, however, the across-site variation of C levels is not significantly different from that of T levels (Pfingst and Xu, 2004). On the other hand, the reason that electrode configuration and stimulation level affect across-site variation differently might be because these two variables cause different spatial patterns of neural activation. Further research is needed to determine the details of these activation patterns before we can adequately address this question.

A feasible explanation of the effects of electrode configuration on T levels and C levels is that the effect of distance from the electrodes to the sites of neural activation is less for MP stimulation than for more focused modes of stimulation. This is because the rate at which current levels decrease as a function of distance from the electrodes is smaller for MP stimulation than for more focused stimulation (Spelman et al., 1995). Thus, if this distance varies from one stimulation site to another, the effect on the level of current at the neurons will be less for MP stimulation than for more focused stimulation; i.e. there will be less across-site variation in these current levels for MP stimulation than for focused stimulation modes. However, as noted above, the current-level-versus-distance model is complicated by several factors including the impedance of the tissues between the electrodes and the neurons and the direction of the current paths with respect to the neurons. The excited neural populations activated by the various electrode configurations are probably not identical and current paths from the electrodes to the neurons are probably not identical either. These other variables will most likely play a significant role in determining the effects of electrode configuration on detection thresholds.

In pilot studies, we have found that across-site patterns of MDTs are not similar to those for T levels or C levels. This suggests that different mechanisms underlie the across-site variation in these two measures. The mechanisms underlying across-site variation of MDTs are not known. A feasible mechanism would be variation in the temporal properties of the neurons, which is likely to be altered by pathology following deafness. Loss of myelin or changes in the site of action-potential initiation from peripheral to central processes of the auditory nerve, for example, would alter the response timing of neurons activated by electrical pulses.

3. Identifying effective and ineffective stimulation sites

We consider two approaches for using psychophysical measures to evaluate the various stimulation sites in a patient's auditory prosthesis. One approach is to use psychophysical detection thresholds (T levels) or loudness measures (e.g., maximum comfortable loudness levels - C Levels). This approach is based on the assumption that these T and C levels reflect underlying conditions that affect performance in more complex listening situations and thus can be used to locate the effective and the ineffective or even harmful areas in the implant. This approach has the advantage that T levels and C levels are commonly measured clinically and can be obtained easily and rapidly in a clinical setting. The other approach is to use the results of spatial and/or temporal acuity measures performed at each stimulation site to more directly identify sites where perception is good and those where it is poor. Although this approach is more direct, it is also more time consuming.

3.1 Detection thresholds and other loudness levels

If variation in the distances from the electrodes to the sites of action-potential initiation account for across-site variation in detection thresholds, then T levels might be a useful tool for identifying the effective and ineffective stimulation sites in an implanted prosthesis. This is because most of the variables that would increase the distance from the electrodes to the neurons would be considered detrimental to cochlear implant performance. These variables include loss of functional neurons near the stimulating electrodes, positioning of electrodes along the lateral wall of the scala tympani, and obstructions that lengthen the path of current between the electrodes and the neurons.

Two recent studies have indicated that stimulation sites with high thresholds are associated with poorer spatial tuning (Faulkner et al., 2007; van den Honert et al., 2007). These studies used electrode configurations that have been shown to produce restricted current fields in the vicinity of the electrode array (partial tripolar stimulation and phased array stimulation). These configurations are assumed to be more sensitive to nerve survival patterns than configurations such as MP which typically produce broader excitation patterns. Thus they might be more effective in identifying locations where pathology affects stimulus detection and spatial tuning. Stimulation sites that had the highest thresholds for these configurations tended to have broad spatial tuning compared to those with the lowest thresholds.

Further research is needed to determine the implications of high thresholds and broad spatial tuning for perception of complex stimuli with multichannel auditory prostheses. In theory, broad spatial tuning will result in greater overlap of neural populations from sites stimulated by individual channels of the prosthesis and might result in distortion of the information delivered to individual stimulation sites. On the other hand, two other variables that are known to increase the spatial spread of excitation, (i.e., monopolar electrode configurations and high stimulation levels within the dynamic range), both typically result in speech recognition that is equal to or better than that produced by conditions that produce narrower stimulation patterns, i.e., bipolar stimulation and low stimulation levels (Lehnhardt et al., 1992; Zwolan et al., 1996; Pfingst et al., 1997; Skinner et al., 1997, 1999; Franck et al., 2002). Furthermore, studies have found poor correlations between speech recognition and mean BP or MP detection threshold levels across the electrode array (Pfingst et al., 2004; Bierer, 2007). These findings suggest that even if high thresholds are an indication of broad tuning, they might not be a problem for speech recognition. However, in considering the effects of broad spatial tuning, the type of stimulus must be taken into account. For example, in normal-hearing individuals, acoustic simulations of auditory filters that are up to six times broader than normal have minimal effects on speech recognition in quiet but large effects on speech recognition in noise (Baer and Moore, 1993). Furthermore, one must consider that threshold spatial tuning functions do not give the whole picture with regard to the longitudinal pattern of excitation. As noted

above, the magnitude and synchrony of the discharge patterns can differ considerably from region to region within the area of excitation.

3.2 Measures of spatial and temporal acuity

In selecting spatial and temporal measures of acuity, it will be helpful to know how these measures relate to speech recognition. The literature on the relationship between various psychophysical measures and speech recognition contains mixed results with high correlations being found in some studies and no significant correlations being found in others (e.g. see review by Fu, 2002). Probable reasons for these differences include variation across studies in the speech processors, the experience of the subjects, and the nature of the speech tests. Relevance of these variables can be seen in two experiments reported by Donaldson and Nelson (2000) on the correlation between spatial resolution and speech recognition.

The method of determining the spatial resolution of specific sites or regions of the cochlear implant used by Donaldson and Nelson (2000) was to measure subjects' ability to pitch-rank perceptions for stimulation of individual sites along the electrode array. In an initial experiment, Donaldson and Nelson found no significant correlation between place-pitch sensitivity and speech recognition. However, a second experiment did reveal significant correlations. The authors attribute the difference between the earlier and later experiments to two variables: the type of speech processing strategy used and the amount of experience the subjects had with the speech processing strategy. Specifically, they reasoned that the speech processor used in the earlier experiment did not deliver as much spectral information as that used in the later experiment and that spatial acuity made a difference only when finer spectral resolution was available in the signals delivered by the processing strategy. Using similar logic, they argued that good spatial acuity made a difference only for subjects who had sufficient experience with the more advanced speech processing strategy to utilize the available spatial resolution. Other variables must also be considered. As noted above, some speech signals, such as speech in noise, require better spectral resolution (and presumably better spatial resolution in implanted subjects) than speech signals in quiet (Baer and Moore, 1993).

A variety of measures can be considered for assessing temporal acuity. Modulation detection thresholds (MDTs) hold promise as a tool for determining optimal sites in the electrode array since previous studies have indicated that MDTs on single stimulation sites are correlated with speech recognition (Cazals, 1994; Fu, 2002; Colletti and Shannon, 2005). Two factors must be considered if MDTs are to be used to identify effective and poor sites in the electrode array. First, we must consider the modulation detection acuity for single sites. As noted above (Figure 2), MDTs measured using stimulation of one site at a time are highly variable across sites, particularly at lower levels in the dynamic range. Second, we must consider how the MDTs are affected by competing stimulation at nearby sites. Stimulation sites that show good MDTs when stimulated in isolation might show poor modulation detection in the presence of signals on nearby stimulation sites (Richardson et al., 1998). In an auditory prosthesis speech processor, the individual channels carry envelope information that is determined by the information coming from the bandpass filters. Thus, the envelope of the electrical signal on each channel is different. However, if there is sufficient overlap in the neural populations stimulated by two stimulation sites, the temporal patterns of activity evoked in many of the neurons from those two populations will be determined by the envelope information delivered to both sites. Thus, the temporal envelope of the neural response pattern elicited at each site will be distorted relative to the electrical signal at the processor output, and the neural response patterns related to adjacent sites might be too similar to make individual contributions to speech perception. These considerations suggest that the assessment of psychophysical acuity should take into account not only the acuity of individual sites stimulated in isolation but also the acuity of those sites in the presence of stimulation (potential maskers) on other sites. Further

research is needed to evaluate the clinical utility of MDTs obtained on individual sites with and without competing stimulation at nearby sites.

An important consideration in choosing a psychophysical measure for evaluation of stimulation sites in an auditory prosthesis is the similarity between the stimulation parameters used for the psychophysical measure and the stimulation parameters used in the subject's processor. The assumption underlying the evaluation of across-site patterns in auditory prostheses is that the neurons stimulated by a given site during the assessment measure (i.e., the psychophysical test) will be the same neurons stimulated by that site when the subject is using their processor for speech recognition and other complex hearing tasks. The neurons excited by a given stimulation site probably differ as a function of the stimulation parameters. One obvious example is electrode configuration, which can have marked effects on the pattern of neural excitation. This idea is supported by the fact that the across-site patterns of psychophysical measures can be quite different for two different electrode configurations in the same subject. This can be seen, for example, by comparing the across-site patterns of T levels for MP and BP stimulation in Figure 1. Level of stimulation can also affect across-site patterns. For example, compare the across-site patterns for C levels and T levels in Figure 1. These patterns are similar in some subjects but differ dramatically in others. A potential advantage of measures of spectral and temporal acuity over T levels for assessment of good and poor stimulation sites is that these measures can be obtained at stimulation levels similar to those used on a daily basis in the subject's processor.

Note that the across-site variation in MDTs shown in Figure 2 is for MP stimulation. Although MP stimulation often produced broad excitation patterns, differences in MDTs measured at neighboring stimulation sites were sometimes quite large. This suggests that the neural populations activated by nearby MP sites differ in ways that are functionally important.

4. Site-removal strategies

Although most stimulation sites in most subjects' cochlear implants are discriminable from their neighbors (Zwolan et al., 1997; Pfingst et al., 1999; Donaldson and Nelson, 2000), they are apparently not sufficiently discriminable to support the use of a large number of channels in a speech processor. The evidence for this comes from experiments examining the effects of number of channels on speech recognition. Normal-hearing subjects listening to vocoder-like simulations of cochlear prostheses benefit from increases in channel count, up to at least 20 channels (Friesen et al., 2001; Xu and Zheng, 2007). However, many cochlear implant users show little or no increases in speech recognition when the channel count is increased above 4 to 7 channels (Fishman, 1997; Friesen et al., 2001). One factor that may contribute to this loss of channel capacity is channel interaction, which undoubtedly occurs when nearby channels are stimulated in an interleaved fashion.

Since research has indicated that cochlear implant users do not benefit from a large number of stimulation sites, it is worthwhile to consider a strategy that only stimulates those sites that contribute the most to perception. The psychophysical measures discussed above may hold promise as a means for determining which sites to include in the speech processor map. In addition to improving mean spatial and temporal acuity, removal of some stimulation sites could also reduce channel interactions, due to the increased spacing that would be created between some sites.

An alternative strategy for reducing channel interaction would be to use an electrode configuration that produces a narrower field of excitation, such as BP+0 or TP stimulation. However with these configurations are not always practical because they sometimes require currents that exceed the compliance of the implanted stimulators. In addition, we must consider that narrow configurations might result in poorer temporal performance. Recent studies have

shown that modulation detection thresholds and the representation of modulation in auditory cortex are often worse for BP+0 stimulation than for MP stimulation (Burkholder-Juhasz et al., 2007; Pfingst et al., 2007a).

Removal of some of the available sites in a patient's processor map is common in audiological practice. Mostly, site-removal is based on patient reports of unpleasant sensations or evidence of electrical problems such as electrodes with high impedances or shorts. Site-removal based on psychophysical acuity was first studied by Zwolan et al. (1997). In that study, an electrode-discrimination procedure was used to estimate how well stimulation sites conveyed distinct spectral information. Sites that were found to be indiscriminable from neighboring sites were removed from the processor map. After removing selected sites, a new frequency-allocation table was applied. The revised frequency allocation preserved the assignment of the full frequency range by allocating wider ranges of frequencies to the remaining sites. This strategy was partially successful in improving speech recognition. Seven of the nine subjects tested showed improvements on at least one of four speech-recognition tests when switched to the reduced-site maps. Several recent studies have also shown that removing some sites from the processor map can result in improved speech recognition, although the effects depend on the subjects and on what other conditions are changed (Arnoldner et al., 2007; Finley et al., 2007; Gani et al., 2007). In the remainder of this section, we will discuss additional data and considerations relevant to a more general development of the site-selection strategy.

A key issue in designing a site-selection strategy is deciding which psychophysical measures to use as a basis for site selection. We consider two general approaches. One approach is to remove sites that cause large across-site variation. This approach is based on the finding that high across-site variation in T levels and C levels is associated with poor speech recognition (Pfingst et al., 2004; Pfingst and Xu, 2005; Bierer, 2007). Thus, for example, it might be beneficial to deactivate stimulation sites with the highest T levels and those with the lowest T levels, in order to provide more uniform conditions across the array of stimulation sites. Further research is needed to determine if across-site variance of other measures is also correlated with speech recognition.

A second, more direct, approach is to remove sites that show poor psychophysical performance, such as high thresholds or poor acuity. The two approaches overlap somewhat in that removing sites with poor performance for a particular measure will reduce the across-site variation in that measure. Alternatively there might be an advantage to removing sites with the best performance as well as those with the worst in order to achieve greater consistency of information across channels.

Several factors must be taken into account when selecting stimulation sites to be removed from the processor map. First, careful consideration must be given to the psychophysical data on which the site selection strategy is based. In our pilot studies, we have found that the across-site patterns of various types of psychophysical measures are seldom identical. A site where performance is relatively effective for one measure might show relatively poor performance for another measure. This finding raises two potential problems. First, there may be too few sites that are effective in all measures. Conversely, removing sites that are poor in any of the measures could result in a processor map with too few sites. Second, removing a site that is ineffective in one function but effective in another may weaken overall performance for the function for which the site is most effective. Further research is needed to find measures that give the strongest correlations with speech recognition and that yield the best results when used as criteria in the site-selection strategy. We hypothesize that measures that assess both channel interaction and temporal envelope perception, such as MDTs in a multichannel stimulation context, will be the most highly correlated with speech recognition and hold promise as tools for determining optimal stimulation sites.

When removing sites from a processor map, it is important to not deviate too much from the normal tonotopic map, particularly if the subject has experience using the device with a particular frequency-band allocation. Several investigators have studied the effects of perceptual shifts created by assigning outputs of band-pass filtered signals to points in the cochlea that are higher or lower in best frequency than the center frequencies of the filters (e.g., Fu and Shannon, 1999). Shifts of about 4 mm or more cause serious reductions in speech recognition (Fu et al., 2002). The amount of shift that can be tolerated depends on a number of other variables including the width and center frequencies of the bandpass filters (Baskent and Shannon, 2004). Furthermore, with training, some subjects can at least partly adapt to the shifts. However, complete adaptation to large shifts has not been reported (Fu et al., 2002). Large gaps in the frequency spectrum (holes in hearing) should also be avoided, although small gaps can be tolerated fairly well (Shannon et al., 2002).

Another consideration in designing a clinically useful site-selection strategy is time. The amount of time required to collect the psychophysical data might be long, reducing the clinical usefulness of the procedure. Further research is needed to determine which measures are most effective and efficient so that time-consuming multiple measures can be avoided.

Finally, we must consider that subjects might need time to learn to utilize the new processor maps. The amount of experience needed to utilize improvements in processing parameters seems to vary widely across experiments. Some reports suggest that subjects need a long period of practice in order to utilize improvements in their processors (e.g., Donaldson and Nelson, 2000) while other studies have found significant improvements immediately after revising the processor maps (e.g., Arnoldner et al., 2007; Finley et al., 2007). The need for practice and/or training with experimental processor maps may depend on each subject's unique ability to adapt to new auditory stimulation. In addition, the type and the extent of the modification made to a processor map may influence the amount of training required. Finally, some methods of training may be more effective than others, and the appropriateness of a training method may also depend on how changes are implemented in a processing strategy. These factors should be taken into consideration when evaluating the efficacy of experimental processor maps.

5. Parameter-adjustment strategies

An alternative, or supplemental, approach to the site-removal strategy is to adjust stimulation parameters on a site-by-site basis in an attempt to improve the psychophysical acuity of ineffective sites in the electrode array. One of the most promising and easily controlled variables for this approach is stimulation level. Adjusting the stimulation level of individual sites should be an effective method for improving cochlear implant users' psychophysical skills because psychophysical performance on a wide variety of auditory tasks increases with increases in stimulation level. In a normal ear, psychophysical performance for acoustic stimulation typically improves rapidly as a function of level above the detection threshold and reaches asymptote within the first third of the dynamic range. However, for cochlear-implant stimulation, psychophysical and speech recognition performance often shows improvement through a large portion of the dynamic range, so even small changes in level can have significant effects. Thus, increasing electrical stimulation on some stimulation sites may result in improvements in psychophysical perception.

Audiologists typically make adjustments in the level of electrical stimulation in several ways. During the initial activation, T-level and C-level values are entered in the processor map for each stimulation site. These values can be made on the basis of actual psychophysical T-level and C-level measurements or they can be estimated based on electrophysiological measurements (Franck and Norton, 2001). Sweeps of the entire electrode array are then typically made at a given percentage of the dynamic range in order to determine if any of the

sites are abnormally loud or soft and adjustments are made accordingly. When multiple sites are activated, the overall loudness is likely to be greater than when sites are activated individually. To correct for this, the audiologist presents live-voice stimuli through the speech processor and makes global adjustments in C levels until the listener reports that the speech is comfortably loud. These methods assure that stimuli delivered by the processor will be audible and will not be uncomfortably loud. Such mapping techniques appear to be sufficient for the majority of patients who demonstrate excellent speech-recognition skills in quiet when using hearing alone. Some recipients, however, demonstrate poor speech-recognition skills, despite repeated assessments of their T and C levels. These individuals might benefit from stimulation-level increases designed to optimize the acuity at ineffective stimulation sites. Selective stimulation-level increases could also help a much larger group of patients who have difficulty with speech recognition in noisy environments.

Increasing stimulation level at selected sites should lead to improvements in a wide range of psychophysical skills because almost all psychophysical measures examined in cochlear implant users improve as a function of stimulation level. Intensity discrimination (level difference limens in dB of current) improves as a function of stimulation level (Pfingst et al., 1983; Shannon, 1983; Nelson et al., 1996). All temporal processing skills that have been tested also benefit. These include pulse rate discrimination (Pfingst et al., 1994), frequency discrimination (Pfingst and Rai, 1990), modulation frequency discrimination (Morris and Pfingst, 2000), modulation detection (Shannon 1992, 1993; Galvin and Fu, 2005; Pfingst et al., 2007b), gap detection (Shannon, 1989; Chatterjee et al., 1998; Hanekom and Shannon, 1998), and sensitivity to binaural timing (van Hoesel, 2007). Examples of MDT versus level functions are shown in Figure 3.

Increases in stimulation level benefit spatial acuity in some cases, but not in others (McKay et al., 1999; Pfingst et al., 1999). Under many circumstances, electrode-place discrimination improves as a function of level. However, the pattern of improvement varies across stimulation sites. Examples are shown in the middle panel in Figure 4. Furthermore, in some cases, increases in stimulation level result in decreases in electrode-place discrimination (see the top panel in Figure 4). Nonmonotonic effects of level on electrode-place discrimination have also been found (see the lower panel in Figure 4). These data suggest that stimulation-level increases should be considered on a site-by-site basis and guided by psychophysical data.

One way to increase stimulation levels in commercially available speech processors is to raise the value of the T levels in the subjects' processor maps. This procedure reduces the range of current delivered to the stimulation site by truncating the lower end of the dynamic range, causing stimuli to be presented in the remaining higher portion of the range. It would not be appropriate to raise the C level in the processor, because this would allow stimulation at uncomfortably high levels. In fact, it might be appropriate to lower the C levels entered into the processor map for some sites, particularly if these sites demonstrate degradation in electrode discrimination and channel separation when stimulation occurs at the upper levels in the dynamic range.

Several studies have found that speech-recognition scores of cochlear implant users increase as a function of stimulation level (Franck et al., 2002; Skinner et al., 1997; Skinner et al., 1999). These studies utilized several different methods to increase stimulation levels in the speech processor maps. Skinner and colleagues (1999) compressed the speech signal and increased stimulation level by artificially raising the specification of T levels in the speech processor map using two methods. The difference among the methods was the minimum stimulation level used. The acceptable minimum stimulation levels for each subject were determined using ascending loudness judgments at each site. Each subject identified one stimulation level as soft and another stimulation level as medium-soft. These two values were

then used as the new T levels in the processor map. Subjects used the experimental programs in a variety of quiet and noisy listening environments for a two-week period and then selected which program they preferred. Speech recognition scores obtained with the preferred, raised-level program were compared to scores obtained when subjects used their normal processor. The results indicated that open-set word-recognition scores in quiet and sentence-recognition scores in noise were better with the raised-level programs. At the conclusion of the study, all subjects preferred to use the raised-level program.

Franck and colleagues (2002) generated experimental processor maps that compressed the speech signal into various percentages of the dynamic range. Speech recognition was then evaluated at each compressed level. For the majority of listeners, syllable recognition scores increased as a function of stimulation level throughout most or all of the dynamic range. However, for some listeners, speech recognition performance plateaued in middle or upper regions of the dynamic range and then declined as stimulation level was increased further. These results suggest that some cochlear implant recipients have an optimal level of stimulation below the upper limit of the dynamic range and that exceeding this level may negatively affect speech recognition.

The negative effects of increased stimulation observed in some cochlear implant users may be due to rate saturation and/or increased channel interactions. In order to reduce or prevent such negative effects, one should determine which sites suffer from interactions at increased stimulation levels. Psychophysical measures such as forward masking, electrode discrimination, and modulation-detection interference are potential tools for identifying such sites.

In the studies described above, some subjects demonstrated improved speech recognition when stimulation levels were increased at all sites. However, the relationship between stimulation level and psychophysical acuity is variable from one site to another within a subject's auditory prosthesis. The examples of variability in MDT versus level functions and electrode discrimination versus level functions such as those shown in Figures 3 and 4 lead us to believe that adjustment of stimulation levels on a site-by-site basis would have some advantages over global adjustment of stimulation levels. However, the efficacy of adjusting stimulation levels based on site-by-site measures of spatial and temporal acuity still needs to be tested.

A number of other stimulus parameters are known to affect psychophysical acuity. For example, modulation detection is generally better for low pulse rate carriers than for very high pulse rate carriers (Galvin and Fu, 2005; Pfingst et al., 2007b). Effects of carrier rate are somewhat variable across subjects and across stimulation sites, but further research is needed to determine if there are optimal rates for individual stimulation sites. If optimal rates differ across sites, it might be possible to improve overall performance by setting an optimal rate on each site. This would be difficult in an interleaved stimulation strategy but might work well with strategies that use simultaneous stimulation or combined interleaved and simultaneous stimulation.

6. Auditory nerve, brainstem and midbrain implants

The focus of this paper has been on psychophysical assessment in cochlear implants. In theory, the principles discussed here are applicable to other implants in the auditory pathways, including auditory nerve (Middlebrooks and Snyder, 2007 and article in this issue), brainstem (McCreery, this issue) and midbrain implants (Lim et al., this issue). However, the analysis reviewed here is directed at cases in which there is variation in the conditions of the neurons and the implanted tissue along the electrode array. One source of variation described for cochlear implants, the distance between the electrodes and the sites of action potential initiation, is likely to be greatly reduced in auditory nerve and CNS implants, particularly in

cases where the electrode array penetrates the nerve or nucleus. However, the condition of the neurons is likely to vary across stimulation sites in some locations. In the auditory nerve, this variation is expected due to partial degeneration of the nerve following deafness. Implants in the cochlear nucleus are usually placed following removal of an eighth-nerve tumor. Recent evidence suggests that damage done by the tumor or by the surgery to remove the tumor impairs speech recognition relative to that in patients who received cochlear nucleus implants for reasons other than the presence of an eighth nerve tumor (Colletti and Shannon, 2005; McCreery, this issue). If this suggestion is correct, it might be that there are areas of the cochlear nucleus that have been spared this damage and can be accessed by penetrating stimulation probes. Data on penetrating implants to date are insufficient to address this possibility. For electrode arrays on the surface of the cochlear nucleus, place pitch measures have identified differences across subjects that are related to speech-recognition performance (Otto, 2002). This analysis could also be used for site selection.

The central nucleus of the inferior colliculus is remote from the sources of peripheral damage to the auditory nerve and cochlear nucleus, so penetrating electrodes in this region are likely to be near more uniformly healthy neural tissue. However, there is evidence that there are anatomical differences along the rostral-caudal axis of frequency lamina in the inferior colliculus central nucleus that could contribute to differences in performance (Lim and Anderson, 2007). Psychophysical assessment can potentially make a significant contribution to identifying the best stimulation sites in a multiprobe implant at this location.

7. Summary and conclusions

Psychophysical measures of the functional response to stimulation at each individual stimulation site in a subject's cochlear implant reveal large across-site variation in detection thresholds, loudness percepts, and spatial and temporal acuity. The across-site patterns of these data are highly variable across subjects. These observations suggest that the mechanisms underlying this variation are peripheral in origin, possibly including nerve survival patterns, tissue growth in the implanted cochlea, functional states of the surviving neurons, and/or presence or absence of hair cells. These variables can affect the distance between the electrodes and the sites of action potential initiation, the longitudinal extent and pattern of neural activation along the tonotopic axis of the auditory nerve, the response characteristics of the stimulated neurons, and the feasibility of producing electrophonic hearing. The across-site patterns are not the same for all psychophysical measures suggesting that the underlying mechanisms differ across measures. Further research is needed to determine the patterns of these across-site differences in the context of multichannel stimulation, where channel interaction could play a significant role, and to determine the relationship of these measures to speech recognition with auditory prostheses.

Measures of detection thresholds or loudness, as well as direct measures of spatial and temporal acuity across stimulation sites, may help pinpoint problems that lead to suboptimal performance of individuals' auditory prostheses. In designing psychophysical measures for assessment of individual stimulation sites it is desirable to match the stimulation parameters as closely as possible to the parameters used in the processor that the subject uses on a daily basis. Multichannel stimulation should be used in the psychophysical tests in order to assess the effects of channel interaction on performance of the individual sites.

The psychophysical-assessment data should be useful in designing rehabilitation strategies that treat stimulation sites on an individual basis. We consider two such strategies: a site-selection strategy and a parameter-adjustment strategy as applied to cochlear implants. Similar strategies might also be applicable to auditory nerve and CNS auditory prostheses.

The rationale for the site-selection strategy is that subjects are often only able to benefit from a small percentage of the available stimulation sites in their implant, so there is a potential advantage to selecting only the best sites for the processor map. Site selection could improve mean across-site performance and/or reduce across-site variation. Both have the potential for improving speech recognition. Further research is needed to determine the most effective psychophysical criteria for selection of the sites. We hypothesize that measures that assess both temporal acuity and channel independence will show the highest correlations with speech recognition and be the most efficient for identifying optimal stimulation sites. In employing site-selection strategies, care must be taken to avoid large distortions in the place-pitch map. If psychophysical tests reveal a large number of ineffective sites located in close proximity, then an alternate strategy of adjusting the stimulation parameters of those sites or a combination of site-removal and parameter-adjustment strategies might be more effective.

The objective of the parameter-adjustment strategy is to improve performance at ineffective or potentially harmful sites and thus improve overall mean performance and/or reduce across-site variation. Increases in stimulus level within the dynamic range have been shown to result in improvement of performance on many psychophysical tasks, but increases in level sometimes result in degraded channel independence. We hypothesize that if increases in stimulation level on sites with poor temporal acuity result in improvements in that measure in the context of multichannel stimulation, then level increases at those sites will result in improvements in speech recognition.

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Abbreviations

BP	bipolar
BP+0	bipolar with no intervening electrodes
C level	maximum comfortable loudness level
MDT	modulation detection threshold
MP	monopolar
T level	psychophysical detection threshold level
PA	phased array
P(C)_{max}	percent correct corrected for response bias
pps	pulses per second

TP

tripolar

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Figure 1.

Examples of across-site variation in psychophysical detection thresholds (T levels) and maximum comfortable loudness levels (C levels) from Pfingst and Xu, (2004). Data for 8 subjects are shown. Subject numbers are shown in the lower left corner on each panel (see Pfingst and Xu, 2004 for details). Stimulation sites are given on the abscissa with 1 being at the basal end and 22 at the apical end of the implant. The top row of panels shows data for four subjects with Nucleus CI24M (straight array) implants and the bottom row shows data for four subjects with Nucleus CI24R(CS) (contour) implants. Black symbols and lines are used for BP stimulation and gray symbols and lines are used for MP stimulation. T levels are represented by triangles. T levels were obtained using two methods: a method of adjustment like that used clinically (filled triangles) and a two-alternative forced choice method (open triangles). C levels are represented by filled circles. Triangles pointing toward the left ordinate indicate means of levels across the whole array.

Figure 2.

Across-site variation in modulation detection thresholds (MDTs). Each panel represents a different subject. Data from two experiments are shown. Results of the first experiment are shown by filled triangles. This experiment used a 40 Hz modulation frequency at all available stimulation sites in the subjects' electrode arrays at 30% of the dynamic range (with dynamic range in dB). The second experiment was conducted between one and six months later to check on reliability and to determine effects of modulation frequency. For this experiment data were collected for three sites (4, 11, and 18 except as noted for one subject) at 20, 40 and 80 Hz modulation frequency. These data are shown with open symbols as detailed in the legend (lower right). Data points for sites with multiple measures of MDTs are staggered so the error bars do not overlap. Error bars indicate the minimum and maximum values obtained when measuring MDTs and the symbols indicate the means of these measurements. Some of these data were presented at the Fourth Joint Meeting of the Acoustical Society of America and the Acoustical Society of Japan (Pfingst et al., 2006). Procedures were similar to those for a previously published experiment (Pfingst et al., 2007b).

Figure 3.

Effects of stimulation level on modulation detection thresholds (MDTs) (from Pfingst et al., 2007b). Each panel shows MDT-versus-level functions for a single subject for three stimulation sites (basal, middle and apical) at two carrier rates (250 pps and 4000 pps). The figure legend is shown in the lower right panel. Subject numbers are indicated in the lower left corner of each panel (see Pfingst et al., 2007b for subject details). For each subject, the mean effect of carrier rate, calculated as the mean difference in MDTs (MDT at 4000 pps minus MDT at 250 pps) for all 15 conditions (3 sites $\times$ 5 levels), is shown in the lower right corner of the panel. The panels are arranged in order from highest mean difference value (upper left panel) to the lowest mean difference value (lower right panel). The abscissa gives the stimulation level in percent of dynamic range where dynamic range is in dB of current.

Figure 4.

Effects of stimulation level on electrode-place discrimination (from Pfingst et al., 1999). $P(C)_{\max}$ (proportion of correct responses, corrected for response bias) is plotted as a function of stimulation level in percent of dynamic range (where dynamic range is in dB of current). The $P(C)_{\max}$ scores are for discrimination of a reference electrode pair from its nearest neighbor in the apical direction. A BP+1 electrode configuration (electrode separation of 1.5 mm) was used. To avoid ceiling and floor effects, the 9 examples shown in this figure were selected from a group of 15 cases with moderate electrode discrimination scores at this separation between electrode pairs. Examples of three types of functions are shown: The top panel shows examples from sites for which discrimination was best at low stimulation levels. This type of function was found in 5 of the 15 cases. The middle panel shows examples from sites for which discrimination was best at high stimulation levels. This type of function was found in 7 of the 15 cases. The bottom panel shows functions for the remaining three cases. Reference electrode pairs are identified by subject number (e.g. S2) and stimulation site (e.g. E10) as detailed in Pfingst et al., (1999). Note that functions for 3 sites are shown for subject S8 (Sites 6, 12 and 16). Functions for these three sites are all different from each other.