

*Lawrence T. Cohen**Peter A. Busby**Graeme M. Clark*

Department of Otolaryngology,
Bionic Ear Institute, University of
Melbourne, East Melbourne, Vic.,
Australia

Cochlear Implant Place Psychophysics

2. Comparison of Forward Masking and Pitch Estimation Data

Key Words

Cochlear implant
Pitch
Forward masking
Stimulation bipolar,
monopolar
Common ground

Abstract

Results for forward masking and numerical estimation of pitch were compared in a group of 6 adult subjects implanted with cochlear prostheses manufactured by Cochlear Limited. Data were collected for bipolar + 1 stimulation in all subjects, and for stimulation in one other mode, either common ground or monopolar, for all subjects but one. The pitch data show various irregularities and in each case can be seen to be broadly consistent with the corresponding forward masking data. It is shown that a 'centre of gravity' of the forward masking distribution varies with masker electrode in a manner that is qualitatively very similar to the variation of pitch estimate. It is suggested that, while pitch estimation results are consistent with those from forward masking, the latter contain more detailed information that may be useful in understanding intersubject variations in speech comprehension.

Introduction

Multiple-channel speech-processing strategies for cochlear implants [1-6] make use of the variation of pitch percept with place of

electrical stimulation within the cochlea [5, 7-13]. Place pitch representation may be studied psychophysically by obtaining subjective pitch estimates and by forward masking measurements, which may be indicative of the distribution of neural excitation. This study considers forward masking and numerical estimation of pitch, and the relationship between the data produced by these techniques. A companion paper [14] considers numerical

Portions of this work were presented at the 125th Conference of the Acoustical Society of America, Ottawa, May 1993, and at the International Cochlear Implant, Speech and Hearing Symposium, Melbourne, 1994.

estimation of pitch in subjects with deeply inserted electrode arrays.

Pitch estimation has been used recently by Busby et al. [7] to assess quantitatively the pitch percepts obtained by cochlear implant patients. Their data for 9 subjects using bipolar stimulation demonstrated that for most subjects there was a fairly regular reduction of pitch with insertion distance of the stimulated electrode. In the companion paper to the present study [14], where the subjects had more deeply inserted electrode arrays, pitch again varied fairly regularly for most subjects. However, we drew attention to a small number of cases where, after decreasing regularly for the more basal electrodes, pitch estimates showed an abrupt decrease, followed by a region of low pitch. We also observed substantial differences between pitch functions for bipolar and monopolar stimulation. When common ground stimulation was used, Busby et al. [7] had observed striking examples of non-monotonic variation of pitch estimate with insertion distance. These examples of anomalous pitch functions and the differences between pitch estimates for different modes of stimulation require further study.

Forward masking [15–17] may give an indication of the distribution of electrically evoked neural excitation in the cochlea. The amount of forward masking of a probe electrode by a masker electrode has been taken as an indicator of the extent to which the neural excitation produced by the masker overlaps the region of neural excitation produced by the probe. Shannon [18] has shown that the adaptation occurring in forward masking of cochlear implant patients is equivalent to that observed in forward masking of normal-hearing subjects. However, as Javel [19] has also demonstrated that little or no adaptation is present for electrical stimulation of primary afferent auditory nerve fibres, it appears that most of the forward masking occurs more cen-

trally than the 8th nerve, both in normal hearing and during electrical stimulation. Therefore, a forward masking pattern may result from both spread of peripheral neural excitation and central interaction between masker and probe. It would be difficult to separate these effects, but in the case of electrical stimulation with presently available prostheses, the peripheral spread would be quite broad and can be expected to be the dominant factor, except perhaps in prelinguistically deafened subjects. As the neural region excited by a stimulus may be reflected also in the pitch percept produced, forward masking and pitch estimation measurements may be related, and should together provide a clearer understanding of the variations that occur with changing place of stimulation.

Five of the subjects in this study had the standard Cochlear Limited implant [20, 21], which allows bipolar or common ground stimulation. One subject had a variant of that device known as the ‘20 + 2’, which also enables monopolar stimulation, using a choice of two remote ground electrodes, ‘ball’ and ‘plate’ [14, 22]. In the present study, we collected a substantial body of forward masking data from implant subjects, using different modes of stimulation. This would provide information on the neural excitation patterns produced by different modes of stimulation. A principal aim was to compare forward masking and pitch estimation data for the same subjects, in order to determine whether there was a relationship between the two. Further, it was thought that forward masking data might help to explain anomalous pitch estimation results.

Table 1. Summary of subject histories and electrode array insertions

Sub- ject	Age years	Age at confirmation of profound-total hearing loss, years	Cause of deafness	Age at implantation years	Estimated array insertion distance mm at el 22	Estimated array insertion angle degrees at el 22
S1	18	16	congenital, progressive	17	23.6	518
S5	68	62	Ménière's disease?	66	22.1	511
S7	66	26	unknown progressive	65	21.2	426
S9	48	41	unknown progressive and acoustic trauma	42	18.5	374
S10	57	35	otosclerosis	51	19.7	356
S11	73	38	otosclerosis	66	13.3	270

Insertion distance was taken from the round window and insertion angle from approximately the basal end of the organ of Corti, both to the most apical electrode band (el 22). S1 and S10 were male, while S5, S7, S9 and S11 were female.

Materials and Methods

Subjects

Six adult subjects from the University of Melbourne Cochlear Implant Clinic, at the Royal Victorian Eye and Ear Hospital, participated in the study. Information about the subjects is summarised in table 1. In each subject, the electrode array was inserted into the scala tympani through a cochleostomy. The subject numbering is consistent with that used in the companion paper [14]. S1, S5 and S7 were common to the two studies. The subjects were implanted with either the standard Cochlear Limited 22-channel device (S1, S7–S11) or the 20 + 2 (S5). S11 was able to participate for only about half the time necessary to collect a full set of data. S9, S10 and S11 were subjects for the pitch study of Busby et al. [7], being their P5, P1 and P2, respectively. Pitch estimates were repeated for S9 and S10 but were taken from the data of Busby et al. for S11.

Apparatus

The electrode array of the standard Cochlear Limited (Nucleus) implant [20, 21] has 22 conducting platinum electrode bands and 10 stiffening bands. The bands are numbered here in a basal to apical direction, 1–22 for the conducting bands. All bands on the array are placed at intervals of 0.75 mm. In bipolar stimulation (BP + n), current flows between the nominal band

(electrode n, say) and electrode n + m + 1. In common ground (CG) stimulation, current passes between the nominal electrode band (electrode n) and all other conducting bands shorted together. The 20 + 2 [22] differs from the standard electrode array in that the 2 most basal conducting bands are disconnected, and 2 extracochlear electrodes (ball and plate) are provided instead. The provision of these electrodes makes possible monopolar (Mono) stimulation, in which current passes between a nominal intracochlear electrode (electrode n) and an extracochlear electrode. Biphasic current pulses were used for all stimuli, the two phases having equal duration and current.

C-Level and T-Level Current Measurements

We define the C-level as the loudest comfortable stimulus level and the T-level as the softest definitely audible stimulus level. In the measurement of C-level and T-level currents, the pulse rate was 250 pulses/s and the stimulus duration was 600 ms. The pulse duration was 200 μ s/phase for all subjects except S1 (100 μ s/phase) and S5 (50 μ s/phase). Three stimulus modes were used: BP + 1, CG and Mono. C-levels and T-levels were obtained as described in the companion paper [14].

Pitch Estimation

The stimulus parameters of pulse repetition rate, pulse duration and stimulus duration were as de-

scribed above. The current levels were equal to the C-levels measured above and were loudness balanced at a comfortable level. Bipolar stimuli were used for all subjects, CG for all but S1 and S5, and Mono only for S5. The bipolar stimuli were BP + 1 for all except S9 (BP + 2). Pitch was measured using a single-interval numerical estimation procedure, identical to that used and described in the companion paper [14]. The stimuli were presented in randomised blocks containing 5 presentations of each stimulus for all subjects except S5 (4 presentations). Two blocks were presented to each subject. For each subject, a block contained stimuli for the 2 modes to be tested, except for S1 (only BP + 1) and S5 (BP + 1 and 2 monopolar modes).

Forward Masking

The forward masking techniques used were similar to those described by Lim et al. [17]. A masking burst of biphasic current pulses was followed rapidly by a brief probe burst of biphasic pulses. The masker had a pulse rate of 250 pulses/s and a burst duration of 300 ms. The masker pulse duration was 200 μ s/phase for all subjects except S1 and S5 (50 μ s/phase) and S9 (300 μ s/phase). The probe consisted of 6 biphasic pulses at 250 pulses/s and was, therefore, of 20 ms duration. The separation between the last masker pulse and the first probe pulse was 4 ms. Three masker modes were used, BP + 1, CG and Mono, while the probe mode was BP + 1 for all subjects except S9 (BP + 2). Once the unmasked threshold current had been established for a probe, the probe pulse duration was varied to determine the threshold in the presence of a masker.

Masker electrodes were used at various positions, spanning the electrode array. For S1 and S5, 3 masker positions were used, electrode 18 (apical), 12 (middle) and 6 (basal). For S7, S9 and S10, 4 masker positions were used, electrodes 5, 13, 17 and 19, electrodes 3, 9, 13 and 19, and electrodes 5, 11, 15 and 19, respectively. For S11, time allowed the use of only 2 masker positions (electrodes 11 and 15). For S5, the nominal electrodes for the BP + 1 and Mono maskers were the same. However, for S7, S9, S10 and S11, the CG masker electrodes were offset from the BP + 1 masker electrodes by 1 electrode, corresponding to positions midway between the bipolar electrode pairs. The maskers were loudness balanced to each other at a comfortable level. Comfortable level was established for an electrode near the middle of the array, with bipolar stimulation. This was the reference stimulus as the subject used a 'mouse' to adjust the current level of each other masker for equal loudness, in a continually alternating presentation. The subject bal-

anced the loudness 4 times and the mean current level was taken.

The masking for the probe on electrode i , M_i , is defined as the difference in decibels between the masked threshold pulse duration, P_i , and the unmasked threshold pulse duration (for normalised masking, see Appendix 1). The unmasked threshold current of the probe on electrode i , I_i , was first measured, using a fixed pulse duration of 50 μ s/phase. A second threshold measurement was then performed for the probe in the presence of a masker, adjusting the probe pulse duration while the current was held at I_i . A single masking measurement was made for each combination of masker and probe. For a given probe electrode, the unmasked threshold and the masked thresholds for each of the masker modes were measured in the same session.

Pulse duration was used as the variable in the masking measurements because the Cochlear Limited implant allows finer control of loudness by variation of pulse duration than of current. The choice of 50 μ s/phase as the unmasked threshold pulse duration allowed the pulse duration to be increased by up to 18 dB during measurement of the masked threshold, as the maximum available pulse duration was 400 μ s/phase. The unmasked threshold current, I_i , was determined by an adaptive 4-interval forced-choice technique, using a PEST algorithm with a probability of 0.66 and a W (deviation limit of the sequential test) of 1.0 [23]. Each trial consisted of 4 observation intervals of 20 ms separated by 400-ms intervals of silence: one observation interval contained the probe, the others no stimulus; the interval in which the signal was presented was randomised. The masked threshold pulse duration, P_i , was determined similarly. In this case, each trial consisted of 4 observation intervals of 324 ms separated by 400-ms intervals of silence: one observation interval contained the masker and stimulus, the others only the masker. Feedback was given to the subject after each trial, indicating the correct choice. Each adaptive run began with the probe clearly audible. When measuring the unmasked probe threshold, the initial and final step sizes of current were approximately 1.72 and 0.21 dB, corresponding to current level steps of 8 and 1, respectively. For each step of current level, the Cochlear Limited device produces a current increase of approximately 2.5% [4]. When measuring the masked probe threshold, the initial step size of pulse duration was 8 μ s/phase, while the final step size was 1 μ s/phase.

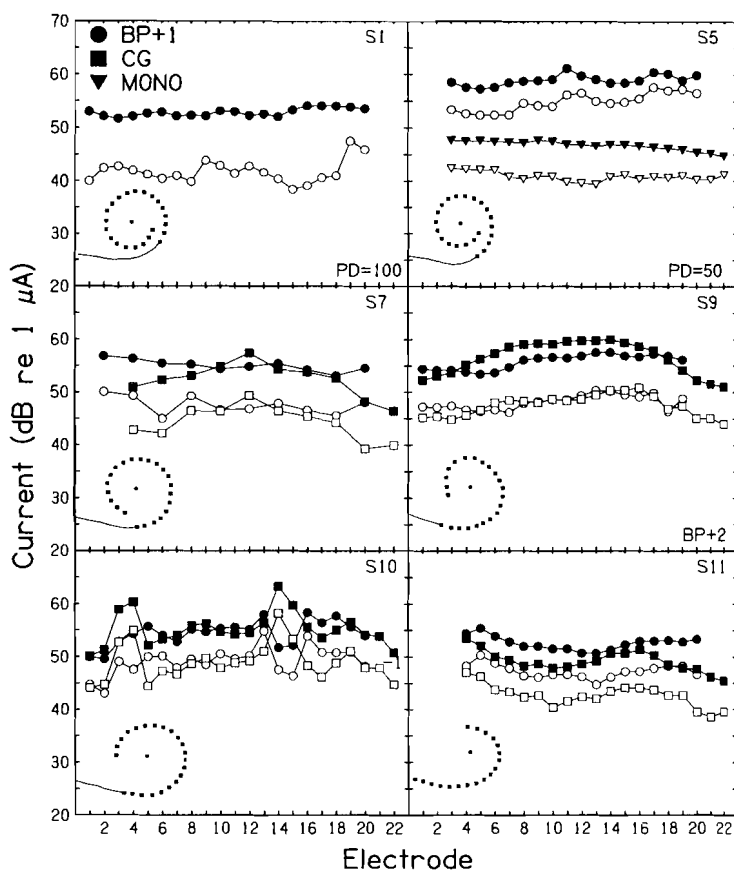


Fig. 1. Current levels required to produce C-levels and T-levels for all patients, in decibels re 1 μA . The filled symbols show the C-levels and the unfilled symbols the T-levels. The circles show levels for BP + 1 stimulation, the squares for CG and the inverted triangles for Mono with the ball electrode (in S5 only). The pulse duration (PD) was 200 μs /phase for all subjects except S1 (100 μs /phase) and S5 (50 μs /phase). The pulse rate was 250 pulses/s and the stimulus duration 600 ms. BP + 2 was used for S9. A small reconstruction of the X-ray of the implanted electrode array is shown for each subject.

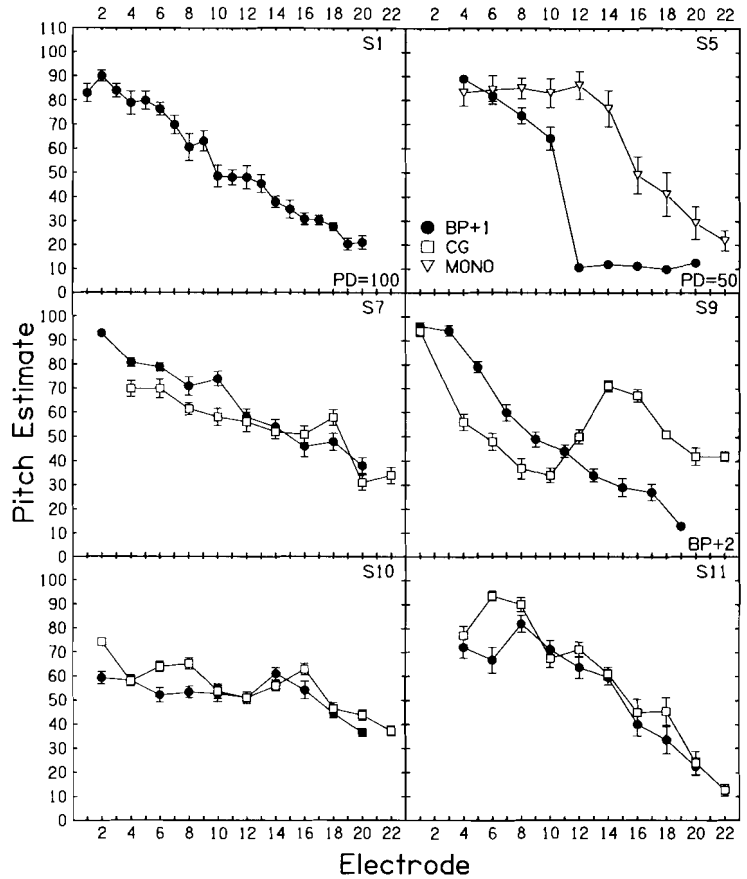
Results

C-Level and T-Level Current Measurements

C-level and T-level currents are shown in figure 1 and, in addition, small reconstructions of the X-rays of the implanted arrays [24]. Only the conducting bands are shown. The subjects are arranged in order of decreasing insertion depth of the most apical band, and the X-rays reveal the wide range of insertion depths. The X-rays also allow the reader to see the spatial relationships between the electrode bands. For Mono stimulation (S5), the levels shown were measured using the ball

ground electrode. The comparable levels using the plate ground electrode were almost identical. Currents were generally lower for CG than for BP + 1 stimuli. In the case of S9, where BP + 2 stimuli were used because the currents required for BP + 1 were unduly high, the bipolar currents were equal to or lower than those for CG in many instances. Currents were considerably lower for Mono than for BP + 1 stimuli, and varied relatively smoothly across the electrode array. In S10, the T-levels and C-levels for CG stimuli were considerably elevated at electrodes 4 and 14. This is thought to have been due to a partial short circuit between electrodes 4 and 14.

Fig. 2. Pitch estimates for all subjects plotted against electrode. The error bars indicate ± 1 standard error of the mean. Pitch estimation is shown by filled circles for BP + 1 stimulation, by open squares for CG and by open inverted triangles for Mono with the ball electrode (in S5 only). The pulse duration (PD) was 200 μ s/phase for all subjects except S1 (100 μ s/phase) and S5 (50 μ s/phase). The pulse rate was 250 pulses/s and the stimulus duration 600 ms. The number of presentations per stimulus was 10 for all subjects except S5, for whom it was 8. BP + 2 was used for S9.



The levels for BP + 1 in the region of electrode 14 were lowered, perhaps because of an increased current spread due to the involvement of electrode 4 when electrode 14 was stimulated. These irregularities in levels were not observed for S10 in the earlier study of Busby et al. [7]. Not all conducting bands for S11 were intracochlear. Therefore the most basal bands were not used and even 1 or 2 that may have been outside the cochleostomy entry point.

Pitch Estimation

Pitch estimates for all subjects are plotted against electrode number in figure 2. The data

for S1 and S5 are identical to those given in Cohen et al. [14]. Although pitch data were given for S7 in that study, the data here are for a pulse duration of 200 μ s/phase, rather than 100 μ s/phase. For all stimulus modes in all subjects, except CG in S9, there was a general reduction of pitch estimate with electrode number. For bipolar stimulation, the reduction was fairly regular for S1, S7 and S9. The nature of the pitch functions for S5, and in particular the irregularity of the function for BP + 1 stimulation, has been discussed at length in Cohen et al. [14]. For S10, the pitch function for BP + 1 stimulation was quite flat compared to those for other subjects, with a

maximum at electrode 14. The pitch data for S11 were taken from Busby et al. [7], where pitch estimates for both BP + 1 and CG appear twice in different contexts. The data for each stimulation mode were combined in figure 2, and the resulting pitch functions were fairly regular apart from electrodes 4 and 6. Electrode 4, and possibly electrode 6, was extracochlear.

For S7 the pitch function for CG stimulation had a lesser slope than that for BP + 1, and there was an increase at electrode 18, followed by an abrupt decrease at electrode 20. For S9, Busby et al. [7] have already reported a non-monotonic pitch function for CG stimulation, and our data are in agreement. The overall slope was less than for BP + 2, and there was a broad minimum at electrode 9, followed by a broad maximum at electrode 15. The pitch estimate was higher for BP + 2 than for CG for electrode numbers less than 11, but lower for electrode numbers greater than 11. For S10, the pitch function for CG stimulation was quite flat, as for BP + 1. As stated above, the pitch function for CG stimulation of S11 was fairly regular and not very different from that for BP + 1, aside from the basal electrodes 4 and 6.

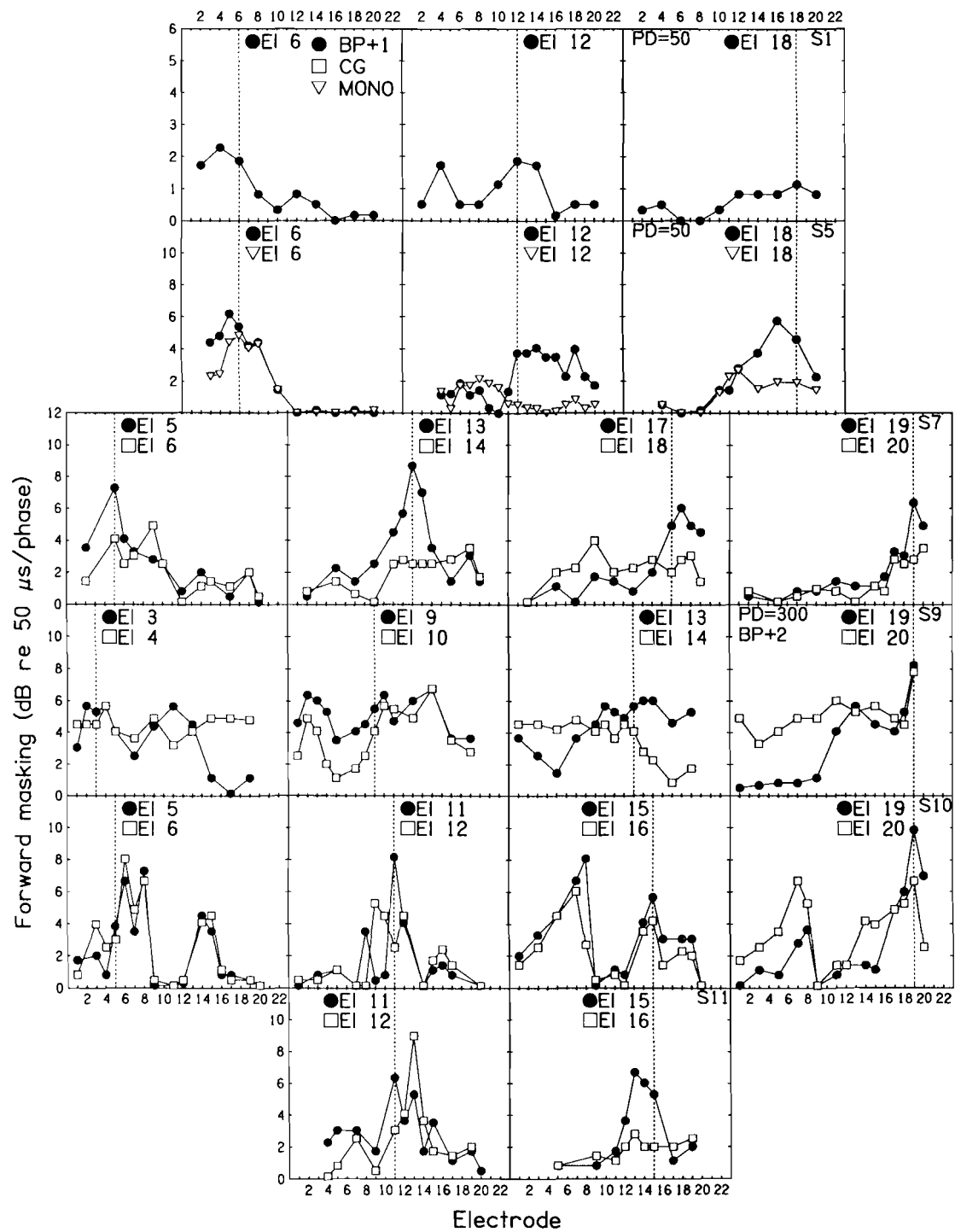
Forward Masking

Forward masking results for all subjects are shown in figure 3. Each row represents a subject and each frame within a row represents a different masker electrode position, moving from basal in the left frame to apical on the right. Ideally, if current spread is very localised, we would expect to observe a masking pattern where masking is strongest at the masker electrode position and falls away rapidly on either side of it. The raw forward masking patterns are quite complex. In the Discussion we will reduce them to a more manageable quantity, a 'centre of gravity' of the masking distribution.

BP Maskers. For BP + 1 stimuli, the most clearly localised masking patterns were seen for S7 and S11. For S1, the masking was mainly around the position of the masker. Note, however, the masking peaks at electrode 4 when the masker was at electrode 12 or even at electrode 18. (Note also that the masking scale for S1 is half those for the other subjects.) For S5, the masking patterns were around the masker position for maskers at electrodes 6 and 18. However, for the masker at electrode 12, masking was strong over the apical half of the array. For S9, although the masking patterns were broad, they were increasingly apical in distribution as more apical maskers were employed. For S10, the masking patterns had two peaks, except for the masker at electrode 11. A possible explanation is that current tended to flow through the presumed partial short circuit between electrode bands 4 and 14, causing neural excitation in both regions. A complicating factor is that all probe stimuli involving electrode bands 4 or 14 would also be affected (i.e. 2, 4, 12 and 14).

CG Maskers. For S7, masking was smaller in amplitude with CG than with BP + 1 maskers. The patterns for the CG masker at elec-

Fig. 3. Forward masking measurements for all subjects, one subject per row. Forward masking is shown in decibels re a probe pulse duration of 50 μ s/phase and is plotted against probe electrode. Note that the masking scale for S1 is half of that for the remaining subjects. Within a subject, different frames show the masking from masker stimuli at different electrode positions, varying from basal maskers on the left to apical maskers on the right. BP + 1 maskers were used with all subjects except S9 (BP + 2). CG maskers were used with S7, S9, S10 and S11, while Mono maskers were used with S5 (using the ball ground electrode). The pulse duration (PD) of the maskers was 200 μ s/phase for S7, S10 and S11, 50 μ s/phase for S1 and S5 and 300 μ s/phase for S9. The probe electrodes were BP + 1 for all subjects except S9 (BP + 2).



trode 18 was clearly more basally distributed than that for the BP + 1 masker at electrode 17, while those for CG maskers at electrodes 6 and 14 were slightly more apically distributed than those for their BP + 1 counterparts, electrodes 5 and 13, respectively. For S9, the masking patterns were broad. For CG, however, it was clear that the centre of gravity of the masking distribution did not shift monotonically with the change of the masker position. In particular, note that the CG masker at electrode 14 produced a considerably more basal distribution than did the CG masker at electrode 10. Not also that, while the pattern for electrode 10 (CG) was more apical than that for electrode 9 (BP + 2), the pattern for electrode 14 (CG) was more *basal* than that for electrode 13 (BP + 2). For S10, the patterns for CG maskers were generally not very different from those for BP + 1. However, the pattern for electrode 20 (CG) was clearly more basally distributed than that for electrode 19 (BP + 1). For S11, the masking pattern for the CG masker at electrode 12 was similar to that for the BP + 1 masker at electrode 11, although its peak was a little more apical. The masking for the CG masker at electrode 16 was smaller in amplitude than that for the BP + 1 masker at electrode 15.

Monopolar Maskers. Monopolar maskers were used with only 1 subject (S5), but both her pitch estimation and her forward masking data were of interest. Her pitch data are discussed at length in Cohen et al. [14]. Her masking patterns for Mono maskers at electrodes 6 and 18 had similar distributions to those for BP + 1 maskers. However, the pattern for a Mono masker at electrode 12 was basally distributed, while that for a BP + 1 masker was apically distributed.

Discussion

The forward masking patterns showed large variations among subjects and, in some of them, considerable differences between modes. Two of the subjects (S5 and S9) had been chosen because of known anomalies in their pitch estimation functions [7, 14]. The pitch estimation data (fig. 2) and the forward masking data (fig. 3) for these subjects appeared to be consistent in the sense that a high-pitched stimulus produced a basal masking distribution, while a low-pitched stimulus produced an apical masking distribution. For example, for BP + 1 stimulation in S5, while a fairly high pitch estimate was obtained for electrode 6, low and approximately equal pitch estimates were obtained for electrodes 12 and 18. Consistently, while the forward masking distribution for electrode 6 was basal, those for electrodes 12 and 18 were fairly broadly spread over the apical half of the array. Similarly, where the pitch estimates for BP + 1 and Mono stimulation of electrode 12 were low and high, respectively, the forward masking distributions were apical and basal. In S9, the pitch estimation functions for BP + 2 and CG stimulation cross at electrode 11: BP + 2 produced the higher pitch sensations for lower-numbered electrodes, while CG produced the higher pitch sensations for higher-numbered electrodes. While the forward masking distribution for electrode 9 (BP + 2) was more basal than that for electrode 10 (CG) the distribution for electrode 13 (BP + 2) was more apical than that for electrode 14 (CG). This relationship between pitch estimate and predominant region of forward masking, namely that the lower the pitch estimate the more apical is the forward masking distribution, seems quite reasonable. However, there are several tacit assumptions, including the following: the more apical the neurons excited by electrical stimulation, the low-

er the pitch sensation; the probe electrodes excite progressively more apical neurons (discussed further below); the forward masking distribution gives an approximation to the neural excitation pattern produced by a stimulus.

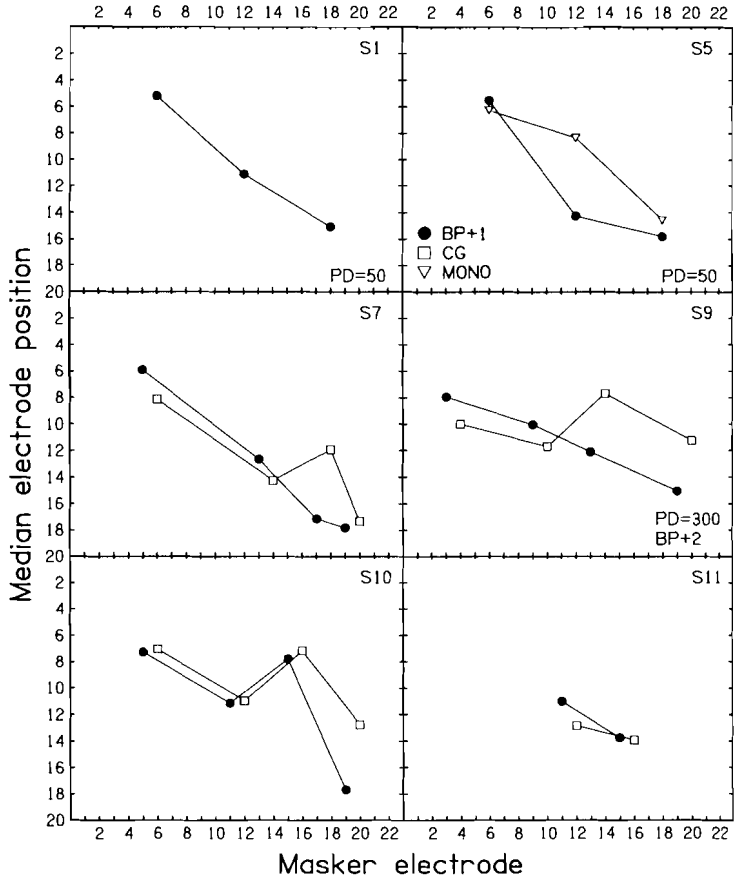
Simplification of Forward Masking Data

We sought to quantify the effective place on the array of a forward masking distribution, by calculating a centre of gravity. Reducing each forward masking distribution to a single number would facilitate a visual comparison of the pitch and forward masking data. A median electrode position was found such that equal areas under the masking curve were present on either side. At the ends of the array, the masking function was arbitrarily rounded off, being assumed to reduce linearly to zero masking at points 2 electrodes beyond the most extreme electrodes measured at either end. It was hypothesised that the median electrode position might be related to the subjective pitch of the masking stimulus. The data from figure 3 were processed in this way, yielding figure 4, in which the median electrode position is plotted against the electrode number of the masker. A small number for the median electrode position indicates predominantly basal masking.

Comparison of figures 4 and 2 confirmed that as the masking became more apical, the pitch decreased. The correspondence was generally good, especially in terms of the relationships between different stimulation modes in individual subjects. For S1, a regular increase in masker median electrode position corresponded to a regular decrease in pitch estimate. For S5 the relationships between masker median electrode positions, for either stimulation mode and between the two modes, were qualitatively similar to the corresponding relationships between pitch estimates. In the case of S7, both the forward masking and the pitch data showed a peak at electrode 18

for CG stimulation but not for BP + 1. For S9, the relationships between masker median electrode positions were again reflected qualitatively in those between pitch estimates. In each figure, while the function for BP + 2 stimulation varied regularly, that for CG showed a marked non-monotonicity so that the functions for the 2 modes crossed at about electrode 11. It is of interest that, for BP + 2 stimulation, S9 perceived a clearly regular decrease in pitch with electrode number, in spite of her very broad masking distributions (fig. 3). For S10, the centre of gravity relationships calculated from the forward masking data were qualitatively similar to the relationships seen in the pitch estimation data. While small peaks were present in the pitch data for both modes at around electrode 15, quite large peaks were seen in the masking data. The forward masking data for S10 (fig. 3) appear to be consistent with an electrical connection between electrode bands 4 and 14. The maskers used did not directly involve these bands, except inasmuch as CG uses all bands but the nominal band connected together as a return. Even so, it appears that when the masker produced excitation in the vicinity of electrode 4, excitation also occurred in the vicinity of electrode 14, and conversely. Thus, abnormal masking patterns occurred even for electrodes that did not involve the suspect bands. This is feasible as the short circuit would tend to make the potential in the vicinity of one shorted band equal to that in the vicinity of the other. If the effects seen were due, in fact, to partial short circuits between electrode bands, the data therefore suggest that such short circuits may result in degradation of performance for numerous electrodes, not only those directly involving the shorted bands. For S11, the centre of gravity estimates from the limited masking data were not inconsistent with the pitch estimation

Fig. 4. The median masking electrode position is plotted against electrode. Each forward masking curve of figure 3 was processed to obtain an electrode position such that equal areas of masking occurred on either side. In this way, each raw forward masking curve yielded an estimate of pitch, expressed as an effective position on the array. These plots of median electrode position are to be compared with the pitch estimation data of figure 2. PD = Pulse duration.



data. It is noteworthy that, even for broad and multi-peaked masking distributions like those of S9 and S10, the correspondence between the pitch estimate and median electrode position was fairly good.

In establishing a correspondence between forward masking and pitch estimation data and, in particular, in endeavouring to 'explain' pitch data by analysing forward masking distributions, it should be said that there is a degree of circularity in the underlying argument. It is assumed that the probe stimuli used in producing a masking distribution excite populations of neurons that vary regularly and monotonically with the electrode number

of the probe. In order to be able to interpret the neural excitation pattern due to a masker electrode in terms of the behaviour of probe electrodes, it is necessary that we have some knowledge of the excitation patterns of the probes. As an example of the possible interpretive difficulties, consider the case of S5, where the forward masking distribution (fig. 3) corresponding to a BP + 1 masker at electrode 12 extended fairly uniformly over the apical half of the array. This uniformity might have occurred because all the apical probe stimuli (BP + 1) excited the same set of neurons. This suspicion is strengthened by the fact that the forward masking distributions

for *all* maskers were fairly uniform in the apical half of the array.

One way to minimise the likelihood of such errors would be to obtain pitch estimates for the probe electrodes, initially at a comfortable level. If these estimates decreased regularly and substantially with depth of the probe electrode, one might be reasonably confident of the distinctness, and regularity of variation, of the sets of neurons being stimulated. If the estimates at the comfortable level did not vary appropriately, pitch estimation could be repeated at a lower level, more representative of probe levels during the masking process. Another possibility would be to maintain the probes at a fixed level a little above threshold so that the distinctness of excited neural populations could reasonably be assumed and to vary the level of the masker.

Another uncertainty concerning forward masking is whether the ‘spread’ takes place peripherally or centrally. Arguably, the results might be similar, as far as the effect on the ability to distinguish different stimuli is concerned. For that reason it may be hard to answer the question psychophysically. A comparison of forward masking distributions with electrically evoked compound action potential distributions [25–27] could help to determine whether the spread occurs peripherally. It would be useful, also, to use computer models of current spread and neural excitation, comparing the predictions with forward masking distributions and attempting to explain the causes of the psychophysical anomalies observed.

The data tend to confirm the existence of a simple relationship between pitch percept and forward masking distribution and therefore probably neural excitation distribution. Further research is required to confirm that relationship, to quantify it and to determine its limits of applicability. Further research might then address the question of how pitch varies

with systematic changes in forward masking distribution. The changes in masking distribution could be achieved by varying the stimulation mode, for example by varying the band separation in bipolar stimulation. Alternatively excitation patterns could be obtained by stimulating groups of several electrodes in rapid succession. For example, regions of uniform masking might be obtained so that the apical or the basal end point was fixed, while the extent of the distribution was varied. It would be of interest to determine whether, in the case of electrical stimulation, the pitch was associated more with the centre of the masking distribution or with the apical end.

While this study indicates that variation of pitch estimate with electrode can be estimated from forward masking data, the converse is clearly not true. More detailed information is contained in forward masking data than in pitch estimation data. We have shown (S5 in Cohen et al. [14]) that extreme anomalies in pitch estimation functions may be associated with degradation in speech perception. However, to date it has not been demonstrated that a clear correlation exists between pitch estimation functions and speech perception. This question should certainly be studied further, but with the very detailed information that forward masking can provide, it may well be a more powerful tool for the study of intersubject differences in speech perception. However, measurement of forward masking is also very time-consuming, prohibitively so in a clinical context. The development of a faster forward masking technique would enable it to be used more widely.

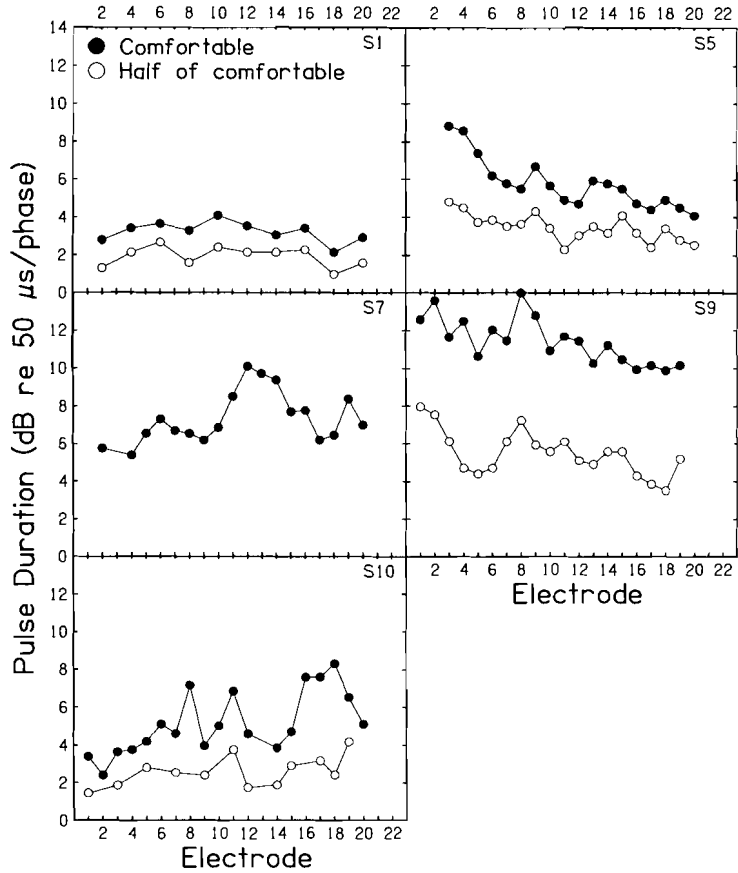


Fig. 5. Probe pulse duration at comfortable loudness (filled circles) and at half comfortable loudness (open circles), in decibels re a probe threshold pulse duration of 50 μs/phase, plotted against electrode for all subjects except S11.

Acknowledgments

This work was supported, in part, by National Institutes of Health Grant DC01282-09. We also wish to acknowledge support provided by the Australian Research Council's Special Research Centre, the 'Human Communication Research Centre' and the National Health and Medical Research Council. Thanks are due to Peter Blamey, Rob Shepherd, Mark White and John Huigen for many useful comments, and to the staff and patients of the Cochlear Implant Clinic at the Royal Victorian Eye and Ear Hospital, Melbourne, for their good-natured assistance. We wish to thank the two anonymous reviewers for their detailed and constructive comments, and one of them for the idea of using probes of fixed level near threshold and varying the level of the masker.

Appendix 1: Normalisation of Forward Masking Data for Differences in Dynamic Range

The unnormalised masking for a probe on the *i*th electrode, as given above, does not allow for differences of dynamic range between electrodes or between subjects. Tong and Clark [16] and Lim et al. [17] employed an expression for the masking that took account of differences in dynamic range across electrodes within a subject but not between subjects. We suggest a modified expression that also takes account approximately of differences in dynamic range between subjects. The normalised masking for a probe on the *i*th electrode, M'_i , is given by the unnormalised masking, M_i , expressed as a percentage of the dynamic range of pulse duration for the *i*th electrode:

$$M'_i = 100 \log_{10}(P_i/50) / \log_{10}(P_i/50). \quad (1)$$

where P_i is the masked threshold pulse duration and $P_{i,c}$ is the pulse duration at comfortable loudness for the i th electrode. In the measurement of both P_i and $P_{i,c}$, the current was fixed at its unmasked threshold value of I_i , which had been obtained using a pulse duration of 50 μ s/phase. The subject adjusted the pulse duration for comfortable loudness at electrode 12. This measurement was performed twice to obtain a mean value. The subject then adjusted the pulse duration of each of the other probe electrodes, at its unmasked threshold current, so that its loudness was equal to that of electrode 12. The mean of two measurements gave $P_{i,c}$.

Thus, if the masked threshold pulse duration of the probe corresponded to its unmasked threshold, the normalised masking would be 0%, while if it corresponded to its unmasked comfortable level, the normalised masking would be 100%. A plot of the normalised masking values, M'_i , for all the probe electrode pairs gives a psychophysical masking curve that takes account approximately of the slopes of the loudness growth functions for the probe electrodes. The expression for the normalised masking assumes that loudness is proportional to the logarithm of the pulse duration.

In order to check the linearity of the relationship between loudness and the logarithm of pulse duration, the pulse duration at half comfortable loudness was also measured for the probe electrodes.

The pulse duration at comfortable loudness is plotted for 5 subjects in figure 5, in decibels relative to 50 μ s/phase [i.e. $20 \log_{10}(P_{i,c}/50)$]. For 3 of the 5, the pulse duration at half of comfortable loudness is also plotted. Here, the subjects adjusted the pulse duration so that the loudness was half of that for the comfortable stimulus. They used a mouse to adjust the pulse duration, as the 2 stimuli alternated. The mean ratio of logarithm of pulse duration at comfortable loudness to that at half of comfortable loudness was 1.92 (SD = 0.41) over all points and the 3 subjects. This finding lends some weight to the assumption in equation 1 that loudness is proportional to the logarithm of the pulse duration. The curves given in figure 5 allow the normalisation of the masking data presented in this study. Normalising the masking data does not substantially affect the pattern of the results. However, while the unnormalised masking amplitudes for S1 are considerably smaller than those for the other subjects, that difference is reduced by normalising the data.

References

- 1 Cohen LT, Clark GM, Whitford I A: Forward masking patterns and pitch estimation for bipolar and remote ground stimulation in a subject implanted with a Cochlear Pty. Limited '20 + 2' cochlear implant. *J Acoust Soc Am* 1993;93:2333.
- 2 Cohen LT, Busby PA, Clark GM: Variations of place pitch: Studies employing pitch estimation and forward masking with 20 + 2 and standard Nucleus implants. *International Cochlear Implant, Speech and Hearing Symp*, Melbourne, 1994.
- 3 McDermott HJ, McKay CM, Vandalı AE: A new portable sound processor for the University of Melbourne/Nucleus limited multielectrode cochlear implant. *J Acoust Soc Am* 1992;91:3367-3371.
- 4 Skinner MW, Holden LK, Holden TA, Dowell RC, Seligman PM, Brimacombe JA, Beiter AL: Performance of postlinguistically deaf adults with the wearable speech processor (WSP III) and mini speech processor (MSP) of the Nucleus multi-electrode cochlear implant. *Ear Hear* 1991;12:3-22.
- 5 Tong YC, Clark GM: Absolute identification of electric pulse rates and electrode positions by cochlear implant patients. *J Acoust Soc Am* 1985;77:1881-1888.
- 6 Wilson BS, Finley CC, Lawson DT, Wolford RD, Eddington DK, Rabinowitz WM: New levels of speech recognition with cochlear implants. *Nature* 1991;352:236-238.
- 7 Busby PA, Whitford LA, Blamey PJ, Richardson LM, Clark GM: Pitch perception for different modes of stimulation using the Cochlear multiple-electrode prosthesis. *J Acoust Soc Am* 1994;95:2658-2669.
- 8 Dorman MF, Smith L, McCandless G, Dunnivant G, Parkin J, Dankowski K: Pitch scaling and speech understanding by patients who use the Ineraid cochlear implant. *Ear Hear* 1990;11:310-315.
- 9 Eddington DK: Speech discrimination in deaf subjects with cochlear implants. *J Acoust Soc Am* 1980;68:885-891.
- 10 Shannon RV: Multichannel electrical stimulation of the auditory nerve in man. I. Basic psychophysics. *Hear Res* 1983;11:157-189.
- 11 Tong YC, Black RC, Clark GM, Forster IC, Millar JB, O'Loughlin BJ, Patrick JF: A preliminary report on a multiple-channel cochlear implant operation. *J Laryngol Otol* 1979;93:679-695.
- 12 Tong YC, Clark GM, Blamey PJ, Busby PA, Dowell RC: Psychophysical studies for two multiple-channel cochlear implant patients. *J Acoust Soc Am* 1982;71:153-160.

- 13 Townshend B, Cotter N, Van Comperolle D, White RL: Pitch perception by cochlear implant subjects. *J Acoust Soc Am* 1987;82:106-115.
- 14 Cohen LT, Busby PA, Whitford LA, Clark GM: Cochlear implant place psychophysics. I. Pitch estimation with deeply inserted electrodes. *Audiol Neurootol* 1996;1:265-277.
- 15 Shannon RV: Multichannel electrical stimulation of the auditory nerve in man. II. Channel interaction. *Hear Res* 1983;12:1-6.
- 16 Tong YC, Clark GM: Loudness summation, masking and temporal interaction for sensations produced by electric stimulation of two sites in the human cochlea. *J Acoust Soc Am* 1986;79:1958-1966.
- 17 Lim HH, Tong YC, Clark GM: Forward masking patterns produced by intracochlear electrical stimulation of one and two electrode pairs in the human cochlea. *J Acoust Soc Am* 1989;86:971-980.
- 18 Shannon RV: Forward masking in patients with cochlear implants. *J Acoust Soc Am* 1990;88:741-744.
- 19 Javel E: Acoustic and electrical encoding of temporal information; in Miller JM, Spelman FA (eds): *Cochlear Implants: Models of the Electrically Stimulated Ear*. New York, Springer, 1990, pp 247-295.
- 20 Clark GM, Pyman BC, Webb RL, Bailey QE, Shepherd RK: Surgery for an improved multiple-channel cochlear implant. *Ann Otol Rhinol Laryngol* 1984;93:204-207.
- 21 Clark GM, Blamey PJ, Busby PA, Dowell RC, Franz BK, Musgrave GN, Nienhuys TG, Pyman BC, Roberts SA, Tong YC, Webb RL, Kuzma JA, Money DK, Patrick JF, Seligman PM: A multiple-electrode intracochlear implant for children. *Arch Otolaryngol* 1987;113:825-828.
- 22 Von Wallenberg EL, Laszig R, Gnadeberg D, Battmer RD, Desloovere C, Lehnhardt E, von Ilberg C: Initial findings with a modified Nucleus implant comprised of 20 active intracochlear and 2 extracochlear reference electrodes. *Proc 3rd Int Cochlear Implant Conf, Innsbruck, 1993*.
- 23 Taylor MM, Creelman CD: PEST: Efficient estimates on probability functions. *J Acoust Soc Am* 1967;41:782-787.
- 24 Cohen LT, Xu J, Xu SA, Clark GM: Improved and simplified methods for specifying positions of the electrode bands of a cochlear implant array. *Am J Otol*, in press.
- 25 Brown CJ, Abbas PJ: Electrically evoked whole-nerve action potentials: Data from human cochlear implant users. *J Acoust Soc Am* 1990;88:1385-1391.
- 26 Stypulkowski PH, van den Honert C: Physiological properties of the electrically stimulated auditory nerve. I. Compound action potential recordings. *Hear Res* 1984;14:205-223.
- 27 Carter PM, Fisher AR, Nygard TM, Swanson BA, Shepherd RK, Tykocinski M, Brown M: Monitoring the electrically evoked compound action potential by means of a new telemetry system; in Clark GM, Cowan RSC (eds): *International Cochlear Implant, Speech and Hearing Symposium - Melbourne, 1994*. *Ann Otol Rhinol Laryngol* 1995;104(suppl 166):48-51.



Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Cohen, Lawrence T.; Busby, Peter A.; Clark, Graeme M.

Title:

Cochlear implant place psychophysics: 2. Comparison of forward masking and pitch estimation data

Date:

1996

Citation:

Cohen, L. T., Busby, P. A., & Clark, G. M. (1996). Cochlear implant place psychophysics: 2. Comparison of forward masking and pitch estimation data. *Audiology Neuro Otology*, 1, 278-292.

Persistent Link:

<http://hdl.handle.net/11343/27475>

File Description:

Cochlear implant place psychophysics: 2. Comparison of forward masking and pitch estimation data