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FACTORS PREDICTING POSTOPERATIVE SENTENCE SCORES IN POSTLINGUISTICALLY DEAF ADULT COCHLEAR IMPLANT PATIENTS

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A sample of 64 postlinguistically profoundly to totally deaf adult cochlear implant patients were tested without lipreading by means of the Central Institute for the Deaf (CID) sentence test 3 months postoperatively. Preoperative promontory stimulation results (thresholds, gap detection, and frequency discrimination), age, duration of profound deafness, cause of deafness, lipreading ability, postoperative intracochlear thresholds and dynamic ranges for electrical stimulation, depth of insertion of the electrode array into the scala tympani, and number of electrodes in use were considered as possible factors that might be related to the postoperative sentence scores. A multiple regression analysis with stepwise inclusion of independent variables indicated that good gap detection and frequency discrimination during preoperative promontory testing, larger numbers of electrodes in use, and greater dynamic ranges for intracochlear electrical stimulation were associated with better CID scores. The CID scores tended to decrease with longer periods of profound deafness.

KEY WORDS — cochlear implantation, profound deafness, promontory stimulation, sentence test.

INTRODUCTION

Since 1982, over 120 patients have been implanted in Melbourne with the 22-electrode cochlear implant manufactured by Cochlear Proprietary Limited.[1] The benefit of the implant to these patients has varied over a considerable range, to the extent that over one third of them have been able to use the telephone for simple conversations[2] and a few have received so little benefit that they do not use the device for more than 1 or 2 hours per week. In the selection and preoperative counseling of the patients, it would be very helpful to be able to predict whether the result was likely to be good or poor. This paper considers a number of factors that might be used to make such a prediction, in the light of the Melbourne experience so far.

A number of previous authors have discussed the possibility that electrical stimulation of the promontory might be used as a preoperative measure of nerve survival and/or likely benefit from a cochlear implant.[3-10] Controversy exists as to the prognostic value of promontory stimulation results, as it has been shown that this procedure may not give a good indication of the percentage of surviving dendrites.[3,5] Cases of poor or negative promontory stimulation responses associated with good implant outcome have been reported.[4,6] However, some correlation has been found between preoperative and postoperative data in some patient populations.[7,8,10] In assessing the usefulness of promontory stimulation data it is also relevant to consider the correlation (if any) of preoperative thresholds with postoperative intracochlear thresholds. If these two measures are both related to the size of surviving neural populations, one would expect them to be highly correlated with one another. The present analysis includes intracochlear as well as promontory thresholds.

Previous studies[11-14] have shown correlations of patient age and duration of deafness with postoperative speech results. Other variables included in this analysis were cause of deafness, which is known to affect the survival of ganglion cells in profound deafness,[15] and depth of insertion of the electrode array into the scala tympani, which is known to affect the range of pitch sensations produced.[16] A variable that is similar to the depth of insertion is the number of electrodes in use in the patient's speech processor. This number is particularly important in the coding strategy of the Cochlear prosthesis, because it affects the number of frequency steps that are available to code the spectral peaks. Number of electrodes in use and dynamic range of electrical stimulation have both been found to be related to vowel and consonant recognition in patients using the Cochlear prosthesis.[11,12]

METHODS

From the patients implanted in Melbourne, a sample of 64 postlinguistically deaf adults and teenagers whose native language was English was chosen. Children still developing spoken language, prelinguistically deaf adults and teenagers with poorly developed spoken language, and foreign language speakers were excluded because of the overriding

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factor of language competence that applies to these groups.

Preoperatively, all of these patients underwent transtympanic promontory stimulation. An uninsulated fine-gauge needle was passed through the posterior-inferior quadrant of the tympanic membrane approximately halfway between the umbo and the annulus onto the promontory. In some cases topical anesthesia was used. The electrode was held in place by an aural speculum with a small magnet on its inner wall. The ground electrode was placed on the ipsilateral cheek.

Over the years in which the data were collected, the current waveform used for promontory stimulation was changed from biphasic pulses of short duration to a square wave with a 100% duty cycle. The change was made because it was found that the threshold of pain was lower relative to the threshold for sound sensations with the pulsatile waveform. The first 14 patients were tested with the pulsatile waveform, and the rest were tested with square waves. In order to compensate for the different waveforms, the pulsatile thresholds were converted to equivalent square wave currents with the same charge per phase.

Each patient was implanted with the 22-electrode intracochlear implant developed by the University of Melbourne and Cochlear Proprietary Limited.[1,17] Intracochlear thresholds and maximum comfortable levels were measured by the audiologist, and the wearable speech processor was programmed. For the first 10 weeks after the operation, the patients were counseled in the use of the implant and given practice at various communication tasks. The threshold and comfortable levels were adjusted as the patients became more familiar with the sounds. At the end of the 10 weeks, the patients were evaluated with a number of speech tests, including the Central Institute for the Deaf (CID) Everyday Sentence Test.[18] This test consists of lists of 10 everyday sentences containing 50 key words. The patient's score is the number of key words recognized. The test was presented from a tape recorder, in a free field at a level of 65 to 70 dB sound pressure level by means of the wearable speech processor and the ear-level microphone, and without lipreading. This test was selected for use in this study because the result was available for most patients and, of all the tests, it most closely estimates the benefit of implantation to the patient in real conversational situations.

During the period in which the data were collected, the wearable speech processor was improved. The largest change occurred with the introduction of a two-formant (F0F1F2) speech coding scheme to replace the original single-formant (F0F2) scheme.[11,19,20] To compensate for the effect of this change, the CID sentence scores of the 16 patients who used the F0F2 processor were multiplied by a constant factor (2.15), making the mean score for this group equal to the mean score of the remaining 48 patients who used the F0F1F2 processor. This procedure removes the effect of the processor change from the statistical analyses that follow.

One further adjustment to the data was required before the statistical analysis. It is possible to program the 22-electrode implant in several different electrode configurations, known as common ground, bipolar, bipolar-plus-one, bipolar-plus-two, etc. In the common ground mode, the electrical current flows between a selected electrode and all other electrodes of the array. In the bipolar modes, current flows between two selected electrodes. The selected electrodes are adjacent in the bipolar mode, have one unselected electrode between them in the bipolar-plus-one mode, and so on. Each mode produces a different intracochlear threshold, because the electrical current distribution in the cochlea is different. Forty-two patients used the bipolar-plus-one mode, and the intracochlear thresholds for the other patients were corrected to equivalent bipolar-plus-one values. The corrections were made by adding the average differences between threshold levels for different electrode configurations measured in a separate experiment for three patients (see Appendix).

RESULTS

Table 1 summarizes the distribution of each variable for the group of patients. Not all of the data were available for every patient, especially promontory stimulation thresholds, as these were not always measured at all three pulse rates. No attempt was made to reach a threshold for sound at levels higher than the threshold for pain. Out of the 64 patients, 58 reported hearing a sound for at least one frequency of stimulation. The current level steps used to measure intracochlear thresholds correspond to equal ratio increments of about 2%, with level 200 corresponding to 1.5 mA. The waveform used was a biphasic pulse with duration of 200 μs per phase and various rates between 100 and 200 pulses per second. The threshold values used in the analysis were those programmed into the speech processor at the time the CID sentence test was carried out.

In addition to the variables listed in Table 1, each patient was assigned a "stim-code" that summarized the frequency discrimination and gap detection performance during promontory stimulation. A stim-code of 1 was assigned to 29 patients who showed no evidence of discrimination of the different pulse rates used, and poor gap detection thresholds (greater than 50 milliseconds). Twenty-four patients who showed evidence of frequency discrimination or good gap detection but not both were assigned a stim-code of 2. Eleven patients who showed both

TABLE 1. SUMMARY OF VARIABLE DISTRIBUTIONS FOR PATIENT SAMPLE

Variable	*N*	*Minimum*	*Maximum*	*Mean*	*SD*
Age (y)	64	14	75	50.0	15.8
Duration (y)	64	1	53	14.6	12.5
Hearing (dB HTL)	61	90	125*	115.2	10.5
T-50 (μA)	39	1	128	16.0	20.5
S-50 (μA)	29	1	128	18.3	23.4
T-100 (μA)	56	1	188	21.4	26.7
S-100 (μA)	41	1	188	21.4	29.3
T-200 (μA)	41	1	113	32.4	30.8
S-200 (μA)	25	1	90	23.8	24.6
T-basal (cl)	61	60	230	115.3	29.3
T-middle (cl)	61	57	197	117.4	29.7
T-apical (cl)	59	15	221	109.0	39.0
Range (cl)	59	8	108	42.5	21.0
Electrodes	59	9	21	17.3	3.6
Depth (mm)	64	10	25	20.3	3.4
CID (%)	61	0	100	33.2	28.4
CID-lip (%)	38	4	88	47.4	22.2

N — number of patients for whom data were available for each variable; age — patient's age at implantation; duration — length of profound deafness prior to implantation; hearing — minimum hearing threshold for acoustic signals in decibels hearing threshold level (dB HTL) for frequencies 0.5, 1, 2, and 4 kHz measured preoperatively in implanted ear; T-50, T-100, T-200 — promontory stimulation thresholds in microamperes (μA) at which any sensation was first detected for square wave currents at 50, 100, and 200 Hz, respectively; S-50, S-100, S-200 — corresponding thresholds for detection of hearing sensation (ie, excluding tactile, pain, throbbing, and other sensations); T-basal, T-middle, T-apical — thresholds measured in current levels for hearing sensations with intracochlear pulsatile stimulation at most basal, middle, and most apical electrodes used by patient; range — number of current level (cl) steps between threshold and maximum comfortable level on middle electrode; electrodes — number of intracochlear electrodes used to code speech; depth — length of electrode array inserted into scala tympani through round window as estimated by surgeon at time of implantation; CID — postoperative open-set CID Sentence Test score for hearing without lipreading; CID-lip — score on different list from CID Sentence Test presented from videotape as lipreading test with no auditory signal.

*Value 125 dB was used for 27 patients who did not respond to sound at limit of audiometer.

TABLE 2. SIGNIFICANT CORRELATIONS BETWEEN PAIRS OF VARIABLES

Variables	*r*	*p*	*N*
T-50 and S-50	.985	.000	29
T-50 and T-100	.924	.000	37
T-50 and S-100	.964	.000	25
T-50 and T-200	.628	.000	32
S-50 and T-100	.951	.000	27
S-50 and S-100	.966	.000	24
S-50 and T-200	.600	.002	23
T-100 and S-100	.998	.000	41
T-100 and T-200	.767	.000	39
T-100 and S-200	.818	.000	23
S-100 and T-200	.805	.000	28
S-100 and S-200	.820	.000	19
T-200 and S-200	.997	.000	25
T-basal and T-middle	.326	.010	61
T-basal and T-apical	.446	.000	59
T-middle and T-apical	.580	.000	59
T-basal and electrodes	−.431	.001	59
T-apical and electrodes	−.339	.010	57
Electrodes and depth	.278	.033	59
Range and electrodes	.273	.037	59
Duration and age	.391	.001	64
Duration and stim-code	−.344	.005	64
Duration and CID	−.421	.001	61
Age and stim-code	−.334	.007	64
Age and CID	−.319	.012	61
Stim-code and CID	.449	.000	61
T-basal and age	.324	.011	61
T-basal and CID	−.272	.039	58
T-middle and duration	.268	.037	61
Electrodes and CID	.429	.001	56
Range and CID	.398	.002	56

r — Pearson correlation coefficient, p — probability of achieving correlation coefficient of magnitude greater than r by chance, N — number of patients for whom values of both variables were available. Other abbreviations as in Table 1.

were assigned a stim-code of 3. It was not always possible to carry out the full promontory stimulation procedure, so some patients with stim-codes of 1 and 2 might have received a higher stim-code if the procedure had been completed. Patients were also classified according to their cause of deafness: 29 unknown, 10 otosclerosis, 7 meningitis, 6 trauma, and 12 other (including radiation damage, antibiotic ototoxicity, syphilis, autoimmune disease, Meniere's disease, Usher's syndrome, and mumps).

Several statistical analyses were carried out on the data. First, a Pearson correlation coefficient was calculated for each pair of variables. Table 2 shows those correlation coefficients that were significantly different from zero with $p < .05$.

The second analysis consisted of a number of *t* tests comparing the groups of patients with a particular cause of deafness (otosclerosis, meningitis, and trauma) with the rest of the patients as a group. The independent variables included all those listed in Table 1 together with the stim-code. No significant differences were found for the trauma cases. T-50, S-50, T-100, and S-100 (defined in Table 1) were significantly higher for the meningitic patients than for the others; however, this was because one patient had promontory stimulation thresholds that were three to four times higher than those of any other patient tested. This difference may have been due to poor electrode placement, because the intracochlear thresholds for this patient were not particularly high compared to the rest of the sample. As shown in Table 3, the otosclerotic patients were 15 years older on average. There were marginally significant differences in the "electrodes," CID-lip, and CID variables as well. No other variables showed significant differences between the otosclerosis group and the rest of the patients.

The third analysis was an analysis of variance with stim-code as the independent variable and CID sentence score as the dependent variable. The analysis showed a highly significant effect ($F = 7.347$, $df = 2, 58$, $p < .002$). Post hoc analysis using the least significant difference test indicated that the average CID scores for all three levels of stim-code were significantly different. The average scores were 20.7%, 36.3%, and 55.6% for stim-code values 1, 2, and 3, respectively. This result is consistent with the signif-

TABLE 3. DIFFERENCES BETWEEN PATIENTS HAVING OTOSCLEROSIS AND REST OF PATIENTS

Variable	Otosclerotic Patients Average	N	Other Patients Average	N	t	p
Age (y)	62.5	10	47.7	54	−2.873	.006
Electrodes	15.6	10	17.7	49	1.706	.093
CID-lip (%)	35.5	8	50.6	30	1.755	.088
CID (%)	19.7	10	35.8	51	1.661	.102

N — number of patients in each group for whom data were available, *t* — Student's *t* statistic used to test whether group means were significantly different, p — probability that value of *t* greater than that shown would be achieved by chance. Other abbreviations as in Table 1.

TABLE 4. COEFFICIENTS FROM MULTIPLE REGRESSION OF CID SENTENCE SCORES

Variable	Coefficient	Standard Error	t	p
Stim-code	10.55	4.36	2.42	.019
Electrodes	2.05	0.89	2.30	.026
Range	0.33	0.15	2.22	.031
Duration	−0.53	0.26	2.04	.046

t — Student's *t* value used to test whether regression coefficient is significantly different from zero, p — probability that *t* value of magnitude greater than that shown would occur by chance. Other abbreviations as in Table 1.

icant correlation shown in Table 2.

The final analysis was a stepwise linear regression with CID score as the dependent variable and age, duration, hearing, T-apical, T-middle, T-basal, range, electrodes, depth, stim-code, CID-lip, and otosclerosis as the independent variables (defined in Table 1). Otosclerosis was included as a two-valued variable that was 1 for patients whose cause of deafness was otosclerosis and zero for all other patients. The promontory stimulation thresholds and the etiology groupings other than otosclerosis were not included because the earlier analyses indicated no significant effect of these variables on CID sentence scores. A stepwise linear regression was carried out to determine which independent variables produced a significant increase in the variance accounted for by the regression function. Four of the variables produced regression coefficients that were significantly different from zero with $p < .05$. These coefficients are summarized in Table 4. The regression produced a highly significant result ($F = 9.69$, $df = 4, 51$, $p < .0001$) and accounted for 43.2% of the variance in the data.

DISCUSSION

Promontory Stimulation Thresholds. The thresholds for electrical stimulation of the promontory were consistent across frequency. The means and ranges of threshold values in Table 1 were similar for the different pulse rates, and the high correlations in Table 2 indicate that patients with low thresholds at one frequency also had low thresholds at other frequencies. The range of threshold currents was similar to that observed in the study of Rothera et al.[9] Despite the consistent nature of these measures, no correlation was found with postoperative intracochlear thresholds or CID sentence scores. It is thus unlikely that promontory stimulation thresholds could be used as a predictor of cochlear implant outcome. Possible explanations of the low correlation of promontory and intracochlear thresholds include the variable placement of the promontory electrode, and the broad spread of electrical current that would be influenced by anatomic differences and the electrical properties of surrounding structures. Hochmair-Desoyer and Klasek[10] have reported some correlation between thresholds for promontory stimulation and intracochlear stimulation with a different intracochlear electrode array. Their threshold measures were not correlated with the degree of success of implantation as indicated by speech recognition measures, in accord with the present study.

Frequency Discrimination and Gap Detection During Promontory Stimulation. In contrast to the thresholds, the stim-code measure of discrimination of temporal characteristics of waveforms above threshold levels during promontory stimulation did show a consistent relationship with CID scores. It is not known whether the stim-code would be consistent with similar measures using intracochlear stimulation, but it seems likely that this would be the case. At least one previous study[21] has found a similar relationship between speech scores and gap detection thresholds for cochlear implant patients. Given these results, there does seem to be some justification for using electrical stimulation of the promontory as a prognostic procedure before cochlear implantation. It has also been reported anecdotally that patients find it useful to experience the sounds produced by electrical stimulation in forming a realistic expectation of the outcome. In this regard, it has been found very helpful to set up a single-electrode speech processor during promontory stimulation to give the patient a preliminary experience of listening to coded speech.

Postoperative Intracochlear Thresholds. The significant correlations between T-basal, T-middle, and T-apical indicate that there was a tendency for intracochlear thresholds to be similar along the length of the electrode array, ie, a patient with a low threshold in the basal region was also likely to have low thresholds in the middle and apical regions of the array. There were some correlations with other variables in Table 2, such as duration, age, and CID sentence scores. One possible explanation of these trends may be that there is an underlying degeneration of the auditory neurons during deafness that affects both the intracochlear thresholds and the CID sentence scores. The signs of the correlation coefficients indicate that thresholds increase with longer duration of deafness, and CID scores decrease with increasing thresholds. These effects are consistent with the suggested explanation. This link between thresholds and CID scores is a relatively weak one compared to the effects that were

found in the regression analysis that is discussed below.

Dynamic Range of Intracochlear Stimulation. It is somewhat surprising that there was no negative correlation between intracochlear thresholds and range, since the range is equal to the difference between the maximum comfortable level and the threshold. (Correlation coefficients for range and T-basal, T-middle, and T-apical were −.026, −.193, and −.183, with p values of .848, .143, and .173, respectively.) This lack of significant correlation suggests that the absolute thresholds are determined mainly by geometric and electrical properties of the cochlea and electrode array, while dynamic ranges may be affected by independent parameters such as neural survival. The dynamic range affects the loudness variations between electrically coded speech sounds. Such loudness variations are important in recognizing many suprasegmental and segmental features of speech. A larger dynamic range may allow a better representation of loudness and thus a better speech recognition score. The Viennese study[10] found a similar correlation between speech recognition results and dynamic range, and no significant correlation between thresholds and dynamic range.

Number of Electrodes in Use. The speech coding scheme used by the F0F1F2 speech processor uses the full extent of the electrode array to encode the first and second formant frequencies. These frequencies are well known to provide information useful in the recognition of vowels and consonants. The amount of frequency information present in the electrical stimulus is increased if a larger number of electrodes is used. The positive correlation between CID scores and number of electrodes indicates that the patients with more electrodes in use can take advantage of this extra information. The minimum number of electrodes in use was 9 and the maximum was 21. The regression analysis indicates that this difference of 12 electrodes may account for a 24% difference in CID score — a difference that would be of marked benefit to the patient.

The significant negative correlations between intracochlear thresholds and number of electrodes may be due to the effect that the geometric and electrical properties of the cochlea have on these variables. One of the most common reasons for a decrease in the number of electrodes is bone growth in the cochlea restricting the insertion of electrodes. A second reason is that uncomfortable sensations are often associated with high thresholds on basal electrodes. In this case, the electrodes producing the uncomfortable sensations would not be used in speech coding.

Depth of Insertion. Depth was correlated with CID at a marginal significance level ($r = .225$, $p = .081$, $N = 61$). This variable may be important in several different ways. First, the overall sharpness or place pitch sensation produced by an electrode depends on its position in the cochlea. Greater depths of insertion lead to lower place pitch sensations and more natural speech sounds produced by the implant.[16] Second, there is some evidence that nerve survival tends to be greater in apical regions of the cochlea than in basal regions, so deeper insertion of the electrode array may improve the perception of speech. Finally, shorter depths of insertion may be related to the shape of the spiral or bony growth within the cochlea, which might affect electrical current distributions during stimulation. These different current distributions may affect the neural excitation patterns produced during speech coding. It is not possible to tell from the present study which of these effects is most important.

Depth was significantly correlated with number of electrodes, so the significance of number of electrodes in the regression analysis may include a contribution due to depth of insertion.

Lipreading Ability. The variable CID-lip was not significantly correlated with any other variable and did not have a significant effect on the regression analysis.

Age and Duration of Deafness. As discussed above, it is possible that an underlying degenerative process accounts for the negative correlations of age and duration with CID sentence scores and intracochlear thresholds. A strong negative correlation between duration of deafness and spiral ganglion cell count has also been found by Nadol et al.[15]

Cause of Deafness. Although the cause of deafness has been found to affect the number and distribution of surviving auditory neurons,[15,22] the only group that was different from the rest of the patients was the otosclerosis group. In the study of Nadol et al,[15] otosclerosis as opposed to other causes was found to have a relatively small effect on spiral ganglion cell survival. It may be that the importance of otosclerosis is related to the electrical properties of the bone in the region of the cochlea, affecting the current distributions produced by the electrodes, rather than a direct effect on the neural responses. Another possibility is that the marginally lower CID scores arose from the higher average age of the otosclerotic patients.

Preoperative Hearing Thresholds. All of the patients were very deaf, so the variations in residual hearing among the group were not great. Only one patient had a three-frequency (at 0.5, 1, and 2 kHz) average threshold less than 110 dB hearing threshold level, and 27 patients had no measurable hearing at any frequency. The preoperative residual hearing level in the implanted ear was not correlated significantly with any other variable and did not contribute significantly to the regression analysis.

Regression Analysis. The regression analysis indicates that there are some factors that can be used to indicate likely postoperative performance of postlinguistically deaf implant candidates on CID sentences. The regression equation is

$$\text{CID} = 10.55(\text{stim-code}) + 2.05(\text{electrodes}) + 0.33(\text{range}) - 0.53(\text{duration}) - 26.92$$

This equation predicts a CID sentence score of 62% for "ideal" candidates who demonstrated good frequency discrimination and gap detection performance during promontory stimulation, used the full set of 20 bipolar-plus-one electrode pairs, had a good dynamic range of 50 current levels, and were deafened very recently. In contrast, the equation predicts a score of −7% (ie, close to zero) for "poor" candidates who could not discriminate frequencies or detect short gaps during promontory stimulation, used only 10 electrodes, had a dynamic range of 15 current levels, and were deafened 20 years before implantation. The regression analysis predicts average scores rather than a score for an individual, and it must be remembered that considerable variability was not accounted for by the regression. These predictions should therefore be treated cautiously and not be used as a guarantee of success for the patient. In particular they should not be applied to prelinguistically deafened candidates or to young children, who were excluded from the sample in this study.

The data are also dependent on the speech processor and implant system used and are not easily generalized to other cochlear implant systems, although similar trends might be expected. Improvements in speech processing strategies in the near future[23] are likely to improve average CID sentence scores to levels above those predicted by the regression equation. It should also be remembered that the CID sentence data were collected approximately 3 months after the operation, and patient performance continues to improve for several years postoperatively.[24]

Two of the variables in the regression (electrodes and range) are not available preoperatively, although it may be possible to estimate the number of electrodes that can be inserted into the scala tympani from good-quality radiography.

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APPENDIX

APPROXIMATE ADJUSTMENT OF INTRACOCHLEAR THRESHOLD VALUES FOR DIFFERENT ELECTRODE CONFIGURATIONS

At the reviewers' request, the data used for this adjustment are included here. The different electrode configurations or modes of stimulation with the 22-electrode Cochlear prosthesis produce different electrical current distributions in the cochlea. Thus, the threshold current levels will be different for different modes. If it is assumed that threshold corresponds to stimulation of a small number of auditory nerve fibers close to the maximum of the current distribution, the ratios of the threshold currents for different modes will depend on geometric factors only and will be approximately the same for different patients. In considering the common ground mode of stimulation, the geometric factors are different for different active electrodes, depending on their distances from the ends of the array. Thus, different current ratios will apply to the basal, middle, and apical electrodes.

Estimates of the adjustments were made by measuring the hearing thresholds with different modes of stimulation for three patients (see Table below). The mean adjustments from the table were −24 levels for bipolar, + 12 levels for bipolar-plus-two, and + 18 levels for bipolar-plus-three. To adjust common ground thresholds, the adjustments were + 26 levels for basal, −7 levels for middle, and −2 levels for apical electrodes. The adjustment was added to the measured thresholds to calculate the approximate equivalent threshold in bipolar-plus-one mode. Note that a fixed difference on the current level scale corresponds to a fixed ratio of actual current values. In the group reported, eight patients used common ground, four used bipolar, six used bipolar-plus-two, and one used bipolar-plus-three stimulation.

The assumption above is a crude one and is not valid for comfortable levels. It is *not recommended* that this adjustment be used in setting patient stimulation levels in different modes.

THRESHOLD CURRENT LEVEL DIFFERENCES RELATIVE TO BIPOLAR-PLUS-ONE STIMULATION FOR THREE PATIENTS

	Basal Electrode			*Middle Electrode*			*Apical Electrode*		
Mode	*Pt 16*	*Pt 36*	*Pt 67*	*Pt 16*	*Pt 36*	*Pt 67*	*Pt 16*	*Pt 36*	*Pt 67*
Common ground	−34	−18	—	11	11	− 2	− 5	14	− 4
Bipolar	24	32	—	30	—	—	26	7	—
Bipolar-plus-two	− 5	−22	—	− 7	− 5	−42	−12	− 4	−10
Bipolar-plus-three	−17	−37	—	−26	− 5	—	−16	−10	−11

Patient numbers refer to list of all patients implanted in Melbourne, and have been used in previous publications. Normal stimulation modes were bipolar-plus-one for patients 16 and 36, and common ground for patient 67. Basal electrodes produced unpleasant sensation for patient 67, and no hearing threshold was measurable in bipolar-plus-one mode. Hearing thresholds were not reached in bipolar mode for middle electrodes of patients 36 and 67 or apical electrode of patient 67, even at highest level of stimulation.

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