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Effect of Stimulation Rate on Cochlear Implant Recipients' Thresholds and Maximum Acceptable Loudness Levels

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Abstract

Clinically, speech processor programs are created using electrical thresholds and maximum acceptable loudness levels (MALs) at several different stimulation rates to determine what rate will provide cochlear implant recipients with the best speech recognition when using fast-rate speech coding strategies. This study was designed to determine the difference in thresholds and MALs (expressed in the clinical unit, Current Level [CL]) for pairs of six rates spanning those available with the Nucleus 24 device (i.e., 250 to 2400 pps/ch) using monopolar, 25 μsec/phase stimulation. Test–retest measures of threshold and MAL for each rate were obtained from seven adult Nucleus 24 recipients on each of 11 electrodes. The difference in threshold and in MAL between pairs of rates was dependent on the absolute CL. Below approximately 190 CL, thresholds and MALs decreased with increasing rate; above 210 CL, there was little change in threshold or MAL with increasing rate. Based on these findings, an approach to estimating threshold and MAL from one rate to another is suggested, pending further research.

Key Words: cochlear implant, maximum acceptable loudness level, stimulation rate, threshold

Abbreviations: ACE = advanced combination encoder, CIS = continuous interleaved sampling, CT = computed tomography, CL = current level, FDA = U.S. Food and Drug Administration, MALs = maximum acceptable loudness levels, NRT = neural response telemetry, pps/ch = pulses per second per channel, SPEAK = spectral peak speech coding strategy, WinDPS = Windows programming and diagnostic system

The overall purpose of this study was to determine the effect of stimulation rate on electrical thresholds and maximum acceptable loudness levels (MALs) for recipients of the Nucleus 24 Cochlear Implant System. Research has shown that some recipients' speech understanding improved when the electrical stimulation rate was changed from 250 pulses per second per channel (pps/ch) to a higher rate (between 500 and 2400 pps/ch) (Arndt et al, 1999). For those who performed better with a faster rate, not all performed best with the same rate. To determine which rate was best for each subject, speech processor programs were created for each of several fast rates. Prior to creating these programs, thresholds and MALs were obtained for all electrodes for each rate. Comparison of thresholds and MALs obtained during that study suggested that markedly different stimulation rates (e.g., 250 pps/ch and 1800 pps/ch) are often associated with significantly different thresholds and MALs. In contrast, similar stimulation rates (e.g., 650 and 720 pps/ch) produce essentially the same thresholds and MALs. These findings are consistent with those of earlier studies in which monopolar

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stimulation was used with other cochlear implant systems (e.g., Shannon, 1985). That is, when the rate at which an electrode was stimulated was increased substantially, less current was needed to elicit a threshold response.

Because it takes approximately 45 minutes to obtain thresholds and MALs for all electrodes for one stimulation rate, clinical programming of patients implanted with the Nucleus 24 would be more efficient if guidelines could be developed for estimating the thresholds and MALs from one stimulation rate to those for another rate. To meet this need, the present study was designed to determine the difference in thresholds and in MALs for pairs of six rates that span those available with the Nucleus 24 device (i.e., 250–2400 pps/ch).

METHOD

Subjects

Seven adults implanted with the Nucleus 24 Cochlear Implant System participated (biographic information is given in Table 1). Subjects 1 through 5 had onset of profound sensorineural hearing loss in adulthood; subjects 6 and 7 had onset of profound hearing loss in childhood. All except subject 6 had used hearing aids for a number of years; in addition, subject 7 was implanted with a 3M/House device in the right ear 10 years before it was replaced with the Nucleus device. Subject 6 did not use hearing aids for the following reasons. During childhood and early adolescence, her hearing was either normal or much less impaired in the high than the low frequencies. Consequently, it was impossible to provide appropriate amplification in the low frequencies without distorting high-frequency sound transmission. When she tried hearing aids, she could not understand speech as well with them as without them. She also had severe difficulty tolerating amplified loud sounds. Given this experience, she did not use hearing aids until several months prior to cochlear implantation when she was being evaluated. Coupled with these hearing difficulties, she had onset of optic neuropathy at 3 years of age and is legally blind.

After initially using the spectral peak speech coding strategy (SPEAK) for ≥ 4 months, all except subjects 5 and 7 used two other strategies, the Advanced Combination Encoder (ACE; Arndt et, 1999) and continuous interleaved sampling (CIS; Wilson et al, 1995), as part of a U.S. Food and Drug Administration (FDA)-approved clinical investigation of the efficacy of each strategy. The average stimulation rate with SPEAK is 250 pps/ch; higher rates (between 500 and 2400 pps/ch) were used with the ACE and CIS strategies (Arndt et al, 1999). Information about the strategy and stimulation rate that subjects were using on their speech processors at the time of this study is shown in Table 2. All devices were programmed in a monopolar stimulation mode with 25 μsec/phase, biphasic pulses. Each subject's score on the consonant-vowel nucleus-consonant (CNC) word test (Peterson and Lehiste, 1962) presented at 70 dB SPL using these parameters in the speech processor program is given in Table 2.

Table 1 Biographic Information

Subject	*Age at Implant (Yr)*	*Implant Use (Mo)*	*Implant Ear*	*Number of Rings Inserted*	*Age at Onset of HL (Yr)*	*Age at Onset of Profound HL (Yr)*	*Etiology*
1	80	15	RE	24	50	RE: 80 LE: 50	Otosclerosis
2	73	15	RE	25	18	RE: 72 LE: 45	Unknown
3	66	13	RE	24	38	RE: 66 LE: 42	Meniere's disease
4	73	14	LE	27	20	RE: 59 LE: 72	Unknown
5	76	12	LE	24	8	AU: 64	Genetic, noise
6	32	13	RE	25	8	AU: 14	Usher's syndrome
7	21	5	RE	27	Birth	RE: birth LE: 8	Unknown

Implant = cochlear implantation, number of rings inserted = number of electrodes (22) and supporting rings (10) that the surgeon reported inserted during cochlear implantation, HL = hearing loss, RE = right ear, LE = left ear, AU = both ears.

Table 2 Speech Coding Strategy, Stimulation Rate, Number of Maxima in Speech Processor Programs Subjects Used in Everyday Life, and CNC Word Scores Using These Programs

Subject	*Speech Coding Strategy*	*Stimulation Rate (pps/ch)*	*Number of Maxima (per Cycle)*	*CNC Word Score (% Correct)*
1	SPEAK	250	6	66
2	SPEAK	250	6	24
3	ACE	650	8	66
4	ACE	720	12	38
5	SPEAK	250	6	24
6	ACE	720	6	8
7	SPEAK	250	6	2

pps/ch = pulses per second/channel, SPEAK = spectral peak strategy, ACE = advanced combination encoder strategy, CNC = consonant-vowel nucleus-consonant.

Equipment/Test Environment

The Nucleus 24 Cochlear Implant System used for this study consists of an internal device (CI24M), a wearable speech processor (SPrint™), and a Windows programming and diagnostic system (WinDPS). The internal device includes a receiver/stimulator connected to an array of 22 intracochlear electrodes and 2 extracochlear electrodes (a plate electrode on the implant package and a ball electrode on a lead that is placed under the temporalis muscle during surgery). For this study, the intracochlear electrodes were stimulated in a monopolar configuration and the extracochlear electrodes were connected together as the ground electrode. Thresholds and MALs were obtained with a 200-MHz Pentium computer system and programming interface (Processor Control Interface), WinDPS software, and each subject's own SPrint speech processor. The study was conducted in one of two quiet offices, each with identical computer systems.

Test Procedures

Threshold Estimation

Detection threshold for each electrode was obtained with a single 500-msec biphasic pulse train presented at each level with an ascending adaptive procedure (Carhart and Jerger, 1959) using a keystroke on the computer keyboard. Initial search for threshold was made with 5-level increments and 10-level decrements, then final estimation was made with 2-level increments and 4-level decrements. Detection threshold was the lowest level during an ascent that sound was detected three times. At this threshold, a set of two, three, four, or five pulse trains was presented. If the subject correctly counted the number of pulse trains in each of three sets, this level was the counted threshold (Skinner et al, 1995). If one of the three sets was miscounted, the level was raised in 2-level steps until the number of pulse trains in all three sets was correctly counted. This level was the counted threshold. For each stimulation rate, thresholds were obtained on 11 electrodes starting with the most apical and progressing in order to the most basal.

Maximum Acceptable Loudness Level

The MAL on each electrode was obtained with repeated 500-msec, biphasic pulse trains (500 msec on/500 msec off). The level was slowly increased by the investigator with the stimulus control knob from below threshold to the level judged as MAL (i.e., the loudness between loud and very loud that would be acceptable to listen to for a few minutes). Only one ascent was made on each electrode at each session (Skinner et al, 1995). For each stimulation rate, MALs were obtained on the same electrodes in the same order as for threshold.

Stimulation Rates and Electrodes

Six stimulation rates were evaluated: 250, 600, 900, 1200, 1800, and 2400 pps/ch. These rates span the range available with the Nucleus 24 device and are associated with different sound percepts. The interphase gap between the negative and positive phases of the biphasic, square-wave stimulation was 45 μsec for 250 pps/ch and 8 μsec for the other five rates. These interphase gaps are the same used in the clinical software for creating speech processor programs for the SPEAK, ACE, and CIS strategies.

As shown in Table 3, 11 electrodes evenly spaced across the array were selected for stimulation for subjects 1 and 4 through 7; electrode 22 was the most apical and 2 was the most basal electrode selected. Because subjects 2 and 3 had difficulty tolerating high-pitched sound when electrodes 4 through 2 (subject 2) and electrodes 3 and 2 (subject 3) were stimulated, other basal electrodes were selected for a total of 11.

Evaluation Schedule

Subjects participated in four 2-hour weekly sessions. During each session, thresholds and MALs were obtained for three of the six stimulation rates on the 11 electrodes. Each rate was presented during session 1 or 2 and again during session 3 or 4. This schedule provided test–retest measures for threshold and MAL on the 11 electrodes for each rate. The testing order of the six stimulation rates was pseudorandomized across subjects and sessions.

Inadvertently, testing on electrode 2 was conducted for subjects 1 and 4 at 250 pps/ch only on the second test day. For the first test day, the threshold at 250 pps/ch for electrode 2 was estimated for each of these two subjects by averaging the difference in threshold (in current level [CL]) between 250 and 600 pps/ch across the other 10 electrodes on that day and applying that difference (in CL) to the threshold at 600 pps/ch on electrode 2. The same procedure was used to estimate the data point at MAL for each subject.

Data Analysis

Data analysis was based on values in CL, the clinical unit used with the Nucleus 24 programming system. Unlike the Nucleus 22 internal device, there is negligible variation in the electrical amplitude output of the Nucleus 24 receiver/stimulator from one device to the next. The range of clinical levels is from 1 to 255; current delivered at a CL of 1 is nominally 10 μA with logarithmic increments of 2 percent between steps (e.g., between 1 and 2 and between 254 and 255). Because there is little variation in electrical amplitude output among devices, analysis of group data across subjects can be made in CL without adjusting values with a calibration table. Furthermore, it is meaningful to clinicians to report the results in clinical units.

Factorial analyses of variance were conducted for threshold and MAL values to determine if there were significant differences among subjects, stimulation rates, and electrodes. All effects, including subjects, were considered fixed. Post hoc multiple comparisons were made among the six rates using the Studentized range statistic of the post hoc Tukey HSD test.

RESULTS

Effect of Stimulation Rate on Threshold

Group mean thresholds across electrodes and subjects decreased as stimulation rate increased. The values were 170, 167, 162, 157, 148, and 144 CLs for stimulation rates of 250, 600, 900, 1200, 1800, and 2400 pps/ch, respectively. Results of the analysis of variance for threshold are shown on the left side of Table 4. This analysis showed significant subject, rate, and electrode main effects. The post hoc Tukey HSD results confirmed that data sets for each rate formed a homogeneous subset; multiple comparisons of the difference in threshold between pairs of rates are shown in Figure 1. All of the differences between pairs of rates were significant at the <0.001 level; these mean differences ranged from 3 to 26 CLs. In our clinical experience, Nucleus implant recipients often hear a difference in the loudness of the perceived sound when changes of three or more levels are made in the minimum stimulation levels in a speech processor program.

Table 3 Electrodes Selected for Each Subject for Stimulation

Subject	*Electrodes*										
1	22	20	18	16	14	12	10	8	6	4	2
2	22	20	18	16	14	12	10	8	7	6	5
3	22	20	18	16	14	12	10	8	6	5	4
4	22	20	18	16	14	12	10	8	6	4	2
5	22	20	18	16	14	12	10	8	6	4	2
6	22	20	18	16	14	12	10	8	6	4	2
7	22	20	18	16	14	12	10	8	6	4	2

Table 4 Analysis of Variance for Thresholds and Maximum Acceptable Loudness Levels (MALs) across Electrodes and Stimulation Rates

	Threshold				*MAL*			
Source	*df*	*MS*	*F*	*p*	*df*	*MS*	*F*	*p*
1. Subject (S)	6	88,577.14	4912.00	<.001	6	106,357.64	1974.42	<.001
2. Rate (R)	5	16,765.97	929.75	<.001	5	5058.93	93.91	<.001
3. Electrode (E)	10	1177.53	65.30	<.001	10	95.92	1.78	.062
4. S × R	30	702.51	38.96	<.001	30	981.17	18.21	<.001
5. S × E	60	880.14	48.81	<.001	60	645.64	11.99	<.001
6. R × E	50	29.31	1.62	.006	50	10.04	.19	1.00
7. S × R × E	300	18.98	1.05	.310	300	13.08	.24	1.00
8. Error	462	18.03			462	53.87		

As shown in the analysis of variance results in Table 4, there were subject by electrode, subject by rate, and rate by electrode interactions. The subject by electrode interaction was expected because there are differences among subjects in nerve survival rates along the length of the cochlea as well as differences in the longitudinal and cross-sectional position of each electrode within the cochlear canal. To explore the subject by rate interaction, each subject's mean threshold across electrodes was plotted as a function of rate as shown by the symbols connected by solid lines in the left panel of Figure 2. There was a monotonic decrease in threshold with increase in stimulation rate from 250 to 2400 pps/ch for subjects 1, 2, 5, and 7, whereas for subjects 4 and 6, threshold at 250 pps/ch was lower than at 600 pps/ch. Subject 3's threshold for these two rates was the same. Unlike the other subjects, all of subject 6's thresholds between 600 and 2400 pps/ch were high and showed little variation (i.e., 213–210 CL). Based

Rate (pps/ch)	600	900	1200	1800	2400
250 vs	2.6 / 0.000	7.1 / 0.000	12.4 / 0.000	21.5 / 0.000	26.1 / 0.000
600 vs		4.6 / 0.000	9.9 / 0.000	18.9 / 0.000	23.5 / 0.000
900 vs			5.3 / 0.000	14.4 / 0.000	18.9 / 0.000
1200 vs				9.1 / 0.000	13.6 / 0.000
1800 vs					4.6 / 0.000

Figure 1 Multiple comparisons of the difference in group mean threshold level (CL) across electrodes for pairs of stimulation rates between 250 and 2400 pps/ch are shown in the upper diagonal box. In the lower diagonal box below each value is the significance level for each threshold difference value (post hoc Tukey HSD test).

on these data, the difference in threshold across rates appears dependent on the absolute value of threshold. That is, substantially less current is necessary to reach threshold at 2400 pps/ch compared to 600 pps/ch for absolute values less than approximately 190 CL, whereas for CLs around 210, there is little variation in level between 600 and 2400 pps/ch. For all of these rates, the pulse width was 25 μsec/phase and the interphase gap was 8 μsec. For 250 pps/ch, the pulse width remained the same, but the interphase gap was much longer (45 μsec). Shepherd and Javel (1999) have shown that lengthening the interphase gap is associated with more sensitive thresholds, particularly for pulse widths of shorter duration than 100 μsec/phase. Their results are consistent with those from subjects 4 and 6 for whom less current was required to reach threshold at 250 pps/ch than at 600 pps/ch. For these two subjects, thresholds for both rates were at CLs above 170. This dependence of threshold at different stimulation rates on absolute CL was an unexpected result.

The rate by electrode interaction was explored by plotting the mean threshold across subjects for nominal electrode position from apex to base in the cochlea as a function of rate (Fig. 3). The contours for each rate across electrodes are approximately parallel to each other except for the 250 pps/ch contour. In contrast, the 250 pps/ch contour has a different shape with the mean thresholds for the most apical electrode, and two most basal electrodes essentially the same as those at 600 pps/ch. To confirm that the rate by electrode interaction was related to the difference in the shape of the 250 pps/ch contour, analysis of variance of the threshold data was obtained, omitting data for 250 pps/ch. This analysis indicated that there was no significant rate by electrode interaction ($F [40, 385] = .710$, $p = .908$) for stimulation rates of 600 through

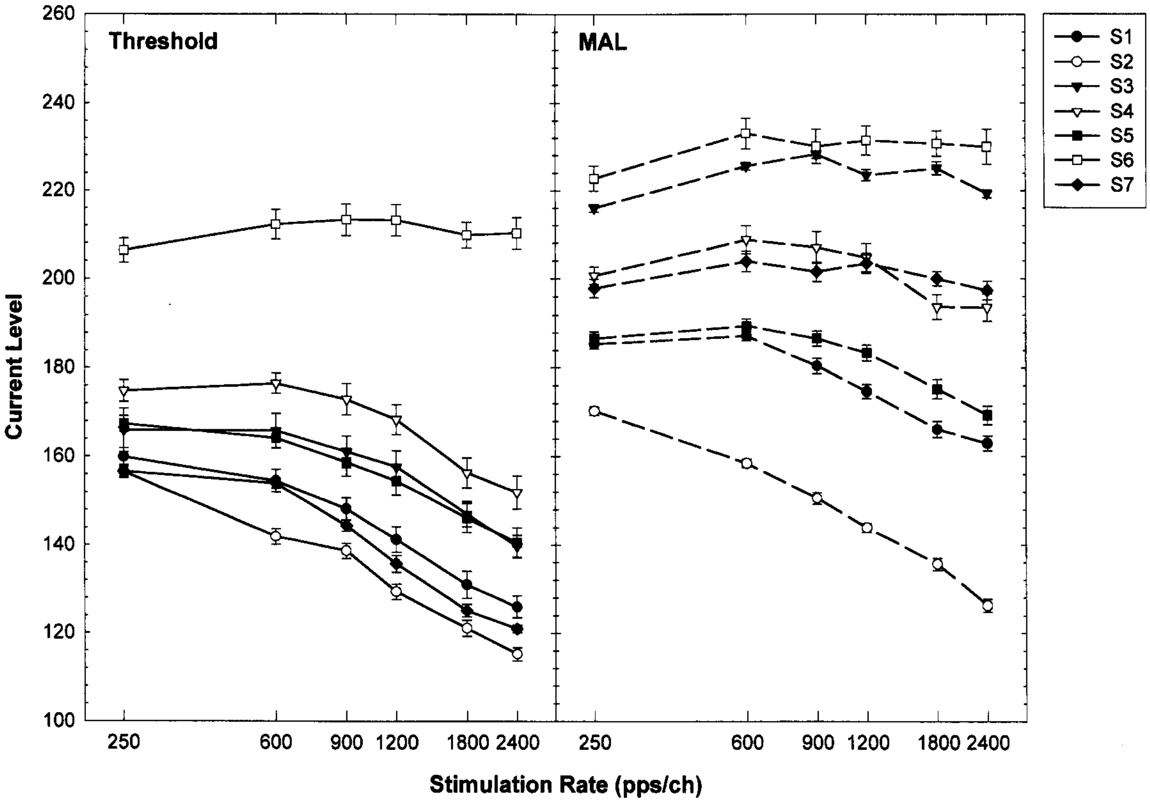

Figure 2 *A*, Individual subjects' mean threshold (CL) across electrodes for six stimulation rates between 250 and 2400 pps/ch. Error bars are ±1 standard error of the mean. *B*, Individual subjects' mean MAL (CL) across electrodes for six stimulation rates between 250 and 2400 pps/ch. Error bars are ±1 standard error of the mean.

2400 pps/ch. For stimulation rates of 600 through 1800 pps/ch, the contours are approximately equidistant as a function of difference in rate between adjacent rates (i.e., average differences between 4.6 and 5.3 CL for a change of 300 pps/ch as shown in Fig. 1). The distance between the 1800 and 2400 pps/ch contours is less (i.e., an average difference of 4.6 CL for a change of 600 pps/ch).

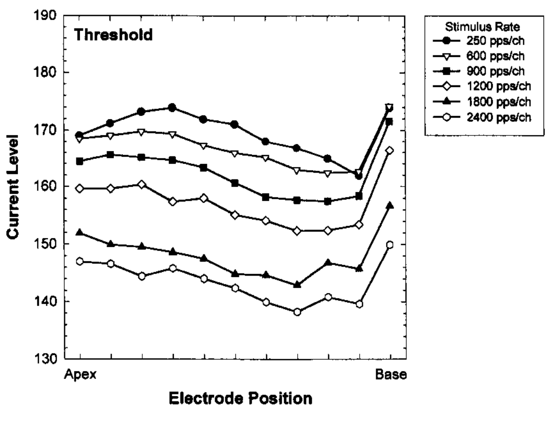

Figure 3 Each contour is the mean threshold (CL) across subjects for one stimulation rate plotted as a function of nominal electrode position from apex to base in the cochlea.

Effect of Stimulation Rate on MAL

Unlike the monotonic decrease in thresholds with increasing stimulation rate, group mean MAL increased from 250 to 600 pps/ch and decreased from 600 pps/ch to 2400 pps/ch. The values were 197, 201, 198, 195, 190, and 186 CL at 250, 600, 900, 1200, 1800, and 2400 pps/ch, respectively. The increase in group mean MAL from 250 to 600 pps/ch at CLs above 190 agrees with the same increase in threshold for subjects 4 and 6 at CLs above 170. The more sensitive MAL at the 250 pps/ch rate is related to the longer interphase gap (45 μsec) than that at 600 pps/ch (8 μsec). Results of the analysis of variance for MAL are shown at the right side of Table 4; there were significant subject and rate main effects. The post hoc Tukey HSD multiple comparisons of the difference in MAL level between pairs of rates are shown in Figure 4. There was a significant difference between pairs of rates except for 250 ver-

Rate (pps/ch)	600	900	1200	1800	2400
250 vs	-3.8 / 0.000	-0.7 / 0.965	2.1 / 0.126	7.6 / 0.000	11.6 / 0.000
600 vs		3.2 / 0.002	5.9 / 0.000	11.5 / 0.000	15.4 / 0.000
900 vs			2.8 / 0.012	8.3 / 0.000	12.2 / 0.000
1200 vs				5.5 / 0.000	9.5 / 0.000
1800 vs					3.9 / 0.000

Figure 4 Multiple comparisons of the difference in group mean MAL level (CL) across electrodes for pairs of stimulation rates between 250 and 2400 pps/ch are shown in the upper diagonal box. In the lower diagonal box below each value is the significance level for each MAL difference value (post hoc Tukey HSD test).

sus 900 pps/ch and 250 versus 1200 pps/ch. This lack of significant difference in group mean MALs between 250 and 900 pps/ch as well as between 250 and 1200 pps/ch appears related to the interaction of the much longer interphase gap of 45 μsec for the slower stimulation rate of 250 pps/ch and the much shorter interphase gap of 8 μsec for the higher stimulation rates of 900 and 1200 pps/ch. The significantly different pairs of group mean MALs differed by three or more levels. As described for threshold, a change of three levels or more in the maximum stimulation levels in a speech processor program is often noticed as a change in loudness by implant recipients.

There were significant subject by electrode and subject by rate interactions at MAL. The subject by electrode interaction was expected because there are intersubject differences in patterns of nerve survival and electrode position along the length of the cochlea. The subject by rate interaction at MAL appears to be similar to that at threshold. If subjects' threshold contours in the left panel of Figure 2 are compared with their MAL contours in the right panel, the change in shape as a function of increasing CL is very similar for the same absolute level. Subject 2, who had the lowest MAL levels, was the only one whose MALs decreased monotonically from 250 to 2400 pps/ch. All of the others had lower MALs at 250 pps/ch than at 600 pps/ch because of the longer interphase gap at 250 pps/ch and CLs above approximately 190. Subjects 3, 4, 6, and 7, who had MALs at CLs above 190, had substantially less decrease in MAL between 600 and 2400 pps/ch than the other subjects whose MALs were at CLs below 190. These results suggest that the subject by rate interaction is related to the absolute value of mean MAL, which differs among subjects.

DISCUSSION

An important finding in this study was dependence of the difference in threshold and MAL for stimulation rates between 250 and 2400 pps/ch on the absolute CL value. To determine whether this result was representative of other Nucleus 24 recipients' difference in threshold and MAL with rate, data from the present study were compared with data from two other studies. In all three studies, subjects were implanted with the same model of internal device and used the SPrint speech processor programmed in a monopolar stimulation mode with 25 μsec/phase stimuli. In the study by Vandali et al (1999), threshold and MAL data were obtained at 250, 807, and 1615 pps/ch and then modified, if necessary, to specify the minimum and maximum stimulation levels (i.e., T and C levels) in speech processor programs. These programs were used for the evaluation of speech recognition using the three different rates. Unlike the present study, the interphase gap at 250 and 807 pps/ch was 25 μsec, whereas the gap at 1615 pps/ch was 8 μsec. The minimum and maximum stimulation levels in these programs were evaluated again at the end of the 21-week study. Each subject's mean minimum and maximum stimulation levels across the two evaluation periods and all active electrodes in the speech processor programs are plotted in the left panel of Figure 5. Because the interphase gap was the same at 250 and 807 pps/ch, the mean minimum and maximum stimulation levels at 807 pps/ch were at more sensitive CLs than at 250 pps/ch. However, the mean maximum stimulation levels for subjects A, B, and C were higher at 1615 pps/ch than at 807 pps/ch because these were above a CL of 190 and the interphase gap was shorter for the 1615 pps/ch rate.

In a study by Skinner et al (2000), threshold and MAL data were obtained at 720 and 1800 pps/ch as a basis for creating speech processor programs before evaluating speech recognition at the two rates. The interphase gap for both rates was 8 μsec. Threshold and MAL data were obtained again near the end of the 14-week study. Each subject's mean threshold and MAL data across the two evaluation periods and all active electrodes are plotted in the right panel of Figure 5. For both of these studies, the trends are the same as in the present study. That is,

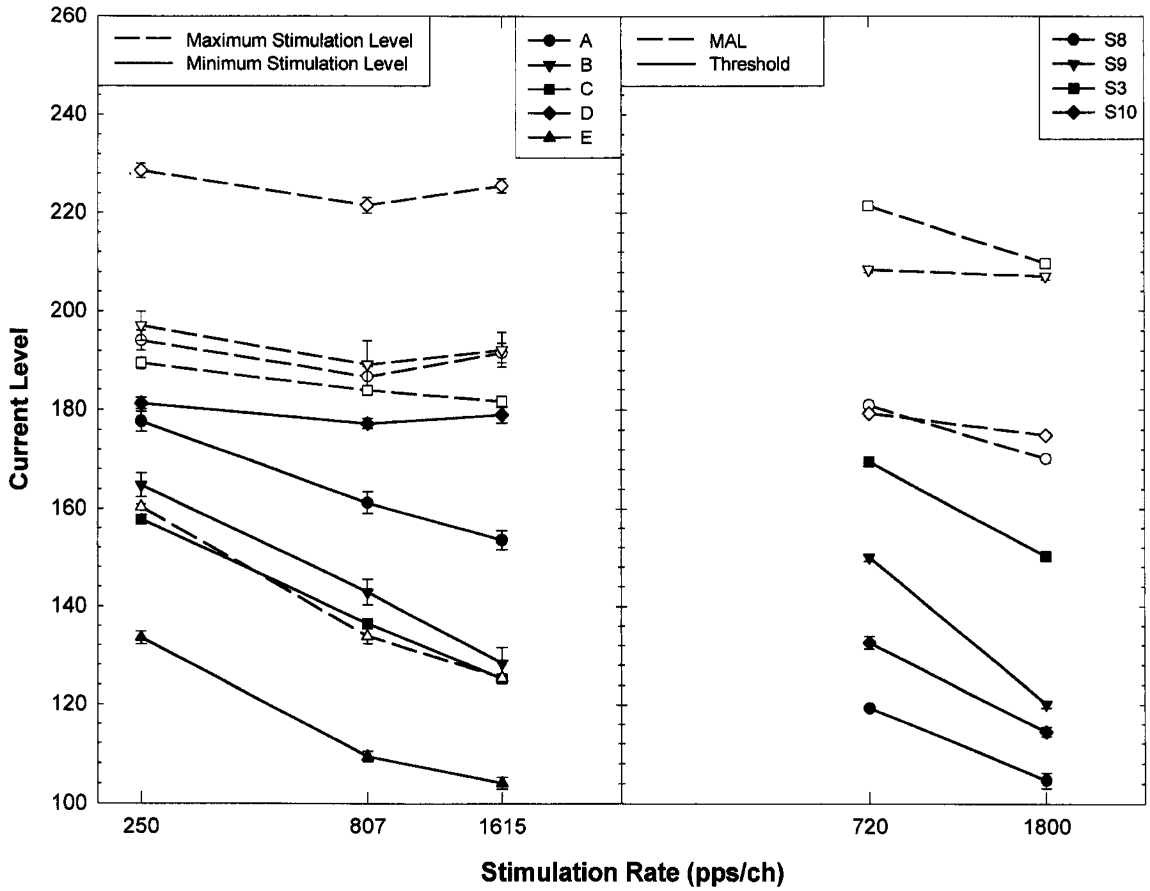

Figure 5 *A*, Individual subjects' mean minimum and mean maximum stimulation levels used in the speech processor programs across all active electrodes for three stimulation rates between 250 and 1615 pps/ch as a function of CL. Error bars are ±1 standard error of the mean. These data were obtained at the Cooperative Research Centre for Cochlear Implant, Speech and Hearing Research, East Melbourne, Australia and plotted with the permission of Vandali et al (2000). *B*, Individual subjects' mean thresholds and MALs across all active electrodes for two stimulation rates, 720 and 1800 pps/ch as a function of CL from a study by Skinner et al (2000). Subject 3 is the same person who participated in the present study. Error bars are ±1 standard error of the mean.

there were substantially lower thresholds at the higher rates (e.g., 1615 and 1800 pps/ch) than at the lower rates (e.g., 250 and 720 pps/ch) for absolute values less than approximately 190 CL; for CLs higher than 190, there was much less change in these values between the lower and the higher rates. Although the number of subjects across these three studies is small, the close agreement among them is of considerable interest.

The results from these three studies suggest that there is temporal integration with increasing stimulation rate between 600 and 2400 pps/ch that is consistent with prior studies of threshold and growth of loudness (e.g., Shannon, 1985). However, for CLs over 190, there appears to be an interaction between temporal integration and recovery from neural refractoriness as shown in the much smaller difference in threshold or MAL with increasing stimulation rate than at lower CLs. It appears that the possible effect of temporal integration may be counteracted by long recovery times from high levels of stimulation. The fastest rate of stimulation (i.e., 2400 pps/ch) also may be associated with long recovery times that interact with temporal integration as shown by the data in Figures 1 and 3. As shown in these figures, the mean threshold differences for 300 pps/ch increments in stimulation rate from 600 to 1800 pps/ch are between 4.5 and 5.3 CLs, whereas the mean threshold difference for the 600 pps/ch increment between 1800 and 2400 pps/ch is 4.6 CLs. That is, the mean threshold difference between 1800 and 2400 pps/ch is approximately one half that for differences of

600 pps/ch in the lower rates of stimulation. Chatterjee (1999) has reported interaction between temporal integration and recovery from neural refractoriness for bipolar stimulation in Nucleus 22 recipients in forward masking experiments. She found that the shape of the recovery function was most strongly influenced by masker duration and that there were large intersubject differences in the amount of interaction between temporal integration and recovery from stimulation. When the thresholds and MALs at 250 pps/ch are compared with those at higher rates, there appears to be a complex interaction between the effects of interphase gap duration, temporal integration, and refractoriness, particularly as CL increases (see Fig. 2).

As shown in Figure 3, the CLs at threshold across subjects for each rate were highest for the most basal electrode tested; in addition, there was a trend for threshold values to be lower for the other, more basal electrodes than the more apical electrodes. It is possible that the different threshold values across electrodes for a single rate are related to the position of the active electrodes in relation to the surviving neurons. Because the Nucleus 24 electrode array has the same design as the Nucleus 22 array, observations by Ketten et al (1998) about the trajectory of the Nucleus 22 array in 20 recipients from their spiral computed tomography (CT) scans seem relevant. This trajectory followed a general course across subjects. From the cochleostomy to the bend at the end of the lower basal turn, the array was often near the middle of the cochlear canal. Above this bend, the array was against the outer bony wall to the most apical electrode inserted. In many recipients, there was a kink in the array in the lower basal turn (see Fig. 7 in Ketten et al, 1998). Based on these observations, it is likely that the more apical electrodes in the upper basal turn were further from the surviving neurons than the more basal electrodes in the lower basal turn for the Nucleus 24 recipients in the present study. In addition, the electrode(s) in the kinked portion of the array were probably further from the neurons than electrodes adjacent to them. Based on animal studies by Shepherd et al (1990) and Merzenich et al (1978) using longitudinal or radial bipolar stimulation, it is expected that the closer the electrodes are to the surviving neurons, the lower the CLs required to reach threshold. This relation has been confirmed for monopolar stimulation in recent animal studies by Finley and Niparko (personal communication, 1999). Because postoperative spiral CT scans were obtained for the subjects in the present study, the position of their electrodes in relation to their thresholds and MALs will be evaluated in future research. It is not clear why the threshold contour across electrodes for 250 pps/ch (see Fig. 3), which is at the highest absolute CL, differs in shape from those at the other rates. The decrease in threshold values occurs at each end of the active electrodes in the array. It is possible that modeling the electrical field from the spiral CT data from individual subjects will shed some light on this issue.

Although evaluation of speech recognition at the six stimulation rates was not included in the research design of this study, subjects' speech recognition abilities (as represented by their CNC scores at their most recent evaluation; see Table 2) do not appear related to CL at threshold (see Fig. 2). For example, the most sensitive thresholds are for subjects 1, 2, and 7. Subject 7 was prelinguistically deaf, and her CNC word score was 2 percent. Of the postlinguistically deaf subjects, subject 2 had one of the lowest (24%) and subject 1 had one of the highest scores (66%). This apparent lack of relation between speech recognition and threshold occurred for subjects in the studies by Vandali et al (in press) and Skinner et al (2000). Chatterjee (1999) also found that subjects who had rapid recovery from stimulation at threshold in the forward masking experiments were not necessarily the ones with the best speech recognition.

It is clear that no single conversion value can be used to predict threshold and MAL values from one stimulation rate to another across Nucleus 24 recipients who use the monopolar mode with 25 μsec/phase pulse duration. Furthermore, the difference in shape between the 250 pps/ch contour for nominal electrode positions and contours for the other rates (see Fig. 3) suggests that application of conversion values across electrodes should be used for pairs of rates between 600 and 2400 pps/ch. Most important, the conversion value will differ for thresholds and MALs below and above a CL of approximately 190. Because the difference values between pairs of rates in Figures 1 and 4 are across all CLs, these values are probably less than would be obtained at CLs below 190 and greater than would be obtained at CLs above 190.

Now that the ACE strategy is clinically available and preferred by the majority (60%) of the 62 subjects in the study by Arndt et al (1999), it seems appropriate to initially stimulate Nucleus 24 recipients with this strategy at an intermediate rate (e.g., 900 pps/ch) to obtain thresholds and MALs for creation of the first speech processor program. Later, threshold and MAL on three electrodes (e.g., electrodes 21, 12, and 4) at another rate (e.g., 1800 pps/ch) can be obtained to determine the difference in threshold and in MAL on the three electrodes between the two rates. The mean difference in threshold for one adjacent pair (e.g., electrodes 21 and 12) can be applied to the 900 pps/ch thresholds for electrodes in between this pair; the same procedure would be followed using the other adjacent pair of electrodes (e.g., electrodes 12 and 4). Estimation of MAL at 1800 pps/ch would be done in the same way. To evaluate which electrodes might be chosen for testing at other rates, threshold data for rates between 600 and 2400 pps/ch obtained from subjects in the present study were analyzed. For each subject and each electrode, the following calculations were made. The difference between the threshold at 900 and 600 pps/ch on one electrode was calculated (e.g., electrode 5; difference 0.5 CL). Then this difference was added to the 900 pps/ch thresholds on the other 10 electrodes to obtain the estimated thresholds at 600 pps/ch. The absolute difference between each of these estimated thresholds and the obtained thresholds was calculated; these differences represented the error of the estimated thresholds. This process was repeated using each of the other rates (i.e., 1200, 1800, and 2400 pps/ch) on the same electrode and then for each of the other 10 electrodes for 600, 1200, 1800 and 2400 pps/ch. For each subject, average differences between estimated and obtained thresholds were calculated for each rate (across electrodes) and for each electrode (across rates), then these data were averaged across subjects to obtain group data. The group mean threshold difference was approximately three CLs across all pairs of stimulation rates for each of the 11 electrodes. Consequently, it is suggested that the electrodes chosen clinically for this conversion from one rate to another should be "good" electrodes. That is, when they are electrically stimulated, the electrodes have reasonably low impedance, are in compliance, and provide the recipient with acceptable sound quality. Because the estimated error is approximately three CLs, it is important to present stimulation at threshold at the new rate on all electrodes, starting with an electrode that includes a measured threshold, and determine whether the loudness is balanced across all active electrodes. If the loudness is not balanced, then changes in the level need to be made until it is. The same procedure then can be done at MAL.

In summary, a clinically efficient procedure for estimating threshold and MAL values from one stimulation rate to another is necessary for comparing and selecting a rate that will provide the best access to sound for an individual. The results of this study and two other studies suggest that the difference in threshold and MAL as a function of stimulation rate is dependent on the absolute CL of these values. Further research with larger numbers of subjects is needed to confirm that this application of conversion value for pairs of rates between 600 and 2400 pps/ch is consistent with measured thresholds and MALs at these rates. In addition, conversion values from 250 pps/ch to the higher rates should be based on research directed at understanding why electrode-specific differences at 250 pps/ch compared to the higher rates were observed for the subjects in this study. It is suggested that this research include the 80 pps/ch rate used in neural response telemetry (NRT; e.g., Abbas et al, 1999) to estimate threshold and obtain growth functions. Because it will be valuable to combine the NRT data with behavioral data to create initial speech processor programs for infants as suggested by Brown et al (in press), it is important to have more information about the difference in threshold and MAL for 80 pps/ch and higher stimulation rates.

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REFERENCES

Abbas PJ, Brown CJ, Shallop JK, Firszt JB, Hughes ML, Hong SH, Staller SJ. (1999). Summary of results using the Nucleus CI24M implant to record the electrically evoked compound action potential. *Ear Hear* 20:45–59.

Arndt PL, Staller S, Arcarola J, Ebinger K. (1999). *Within-Subject Comparison of Advanced Coding Strategies in the Nucleus 24 Cochlear Implant.* Englewood, CO: Cochlear Corporation.

Brown C, Hughes M, Luk B, Abbas P, Wolaver A, Gervais J. (in press). The relationship between EAP and EABR thresholds and the levels used to program the Nucleus CI24M speech processor: data from adults. *Ear Hear.*

Carhart R, Jerger J. (1959). Preferred method for clinical determination of pure tone thresholds. *J Speech Hear Disord* 14:330–345.

Chatterjee M. (1999). Temporal mechanisms underlying recovery from forward masking in multielectrode implant listeners. *J Acoust Soc Am* 105:1853–1863.

Ketten DR, Skinner MW, Wang G, Vannier MW, Gates GA, Neely JG. (1998). In vivo measures of cochlear length and insertion depth of Nucleus cochlear implant arrays. *Ann Otol Rhinol Laryngol* 107 (Part 2), Suppl 175:1–16.

Merzenich MM, Leake-Jones P, Vivion M, White MW, Silverman M. (1978). *Development of Multichannel Electrodes for an Auditory Prosthesis.* 4th Quarterly Progress Report (June 1–August 31, 1978). National Institutes of Health contract no. N01-N5-7-2367.

Peterson G, Lehiste I. (1962). Revised CNC lists for auditory tests. *J Speech Hear Disord* 27:62–70.

Shannon RV. (1985). Threshold and loudness functions for pulsatile stimulation of cochlear implants. *Hear Res* 18:135–143.

Shepherd RK, Javel E. (1999). Electrical stimulation of the auditory nerve: II. Effect of stimulus waveshape on single fibre response properties. *Hear Res* 130:171–188.

Shepherd RK, Maffi CL, Hatsushika S, Javel E, Tong VC, Clark GM. (1990). Temporal and spatial coding in auditory prostheses. In: Rowe M, Aitkin L, eds. *Information Processing in Mammalian Auditory and Tactile Systems.* New York: Wiley-Liss, 281–293.

Skinner MW, Holden LK, Demorest ME, Holden TA. (1995). Use of test–retest measures to evaluate performance stability in adults with cochlear implants. *Ear Hear* 16:187–197.

Skinner MW, Holden LK, Holden TA, Demorest ME. (2000). *Comparison of Speech Recognition by Nucleus 24 Cochlear Implant Recipients Using the ACE Speech Coding Strategy with Two Stimulation Rates.* Research in progress.

Vandali AE, Whitford LA, Plant KL, Clark GM. (in press). *Speech Perception as a Function of Electrical Stimulation Rate: Using the Nucleus 24 Cochlear Implant System.*

Wilson BS, Lawson DT, Finley CC, Wolford RD. (1995). New processing strategies in cochlear implantation. *Am J Otol* 16:669–675.