

Effects of pulse rate on threshold and dynamic range in Clarion cochlear-implant users^{a)} (L)

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The effects of pulse rate on absolute threshold (THS), maximum acceptable loudness (MAL), and dynamic range (DR) were evaluated in 15 Clarion cochlear implant users. A wider range of pulse rates was assessed than in previous studies, and subjects with both standard and perimodiolar electrode arrays were tested. THS and MAL decreased with pulse rate, and DR increased with pulse rate, for pulse rates between 200 and 6500 pulses per second (pps). However, slopes of THS-vs-pulse rate and MAL-vs-pulse rate functions became shallower above 3250 pps. Subjects with standard electrode arrays had similar THSs as subjects with perimodiolar electrode arrays at all pulse rates. In contrast, subjects with standard arrays had significantly higher MALs and larger DRs than subjects with perimodiolar arrays, and these differences became larger with increasing pulse rate. © 2004 Acoustical Society of America. [DOI: 10.1121/1.1701895]

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I. INTRODUCTION

Cochlear implants have undergone several important changes over the past decade, one of which is the use of increasingly faster rates of pulsatile stimulation: Whereas early devices used pulse rates in the range of 250 pps/channel, contemporary devices are capable of stimulating at rates greater than 5000 pps/channel (Advanced Bionics, 2003). Previous studies have shown that increasing pulse rate reduces electrical threshold and increases electrical dynamic range in both human cochlear implant listeners (Simmons, 1966; Shannon, 1985; 1989; Vandali *et al.*, 2000; Skinner *et al.*, 2000) and animal models (Pfungst *et al.*, 1980; Black *et al.*, 1983; Pfungst *et al.*, 1993; 1995; Miller *et al.*, 1997). In general, these studies have indicated that electrical thresholds decrease -2 to -4 dB per doubling of pulse rate and that most comfortable loudness levels (MCLs) or maximum acceptable loudness levels (MALs) decrease more gradually (-0.8 to -1.2 dB/doubling of pulse rate).¹ However, previous studies were limited to pulse rates of 3000 pps and only a few subjects were tested at rates above 2400 pps. Thus, it is not known whether threshold continues to decrease and dynamic range continues to increase with pulse rate over the entire range of pulse rates available in newer devices.

The design of the implanted electrode array is also known to affect electrical thresholds and dynamic ranges. At low pulse rates (<1000 pps), the perimodiolar arrays used in contemporary cochlear implants require substantially less current to generate comfortable (or maximal) loudness levels than the standard arrays used in earlier devices (Osberger *et al.*, 1999; Young and Grohne, 2001; Donaldson *et al.*, 2001; Lesinski-Shiedat *et al.*, 2000; Lenarz *et al.*, 2001; Xu and Pfungst, 2002; Parkinson *et al.*, 2002; and Hay-McCutcheon *et al.*, 2002). There is much less difference in

current levels needed to reach detection threshold; as a result, dynamic ranges are smaller for perimodiolar electrode arrays than for standard arrays. Because comparisons between perimodiolar and standard electrode arrays have not been made at pulse rates above 1000 pps, it is not known whether differences in their operating ranges are maintained at the higher pulse rates now in common clinical usage.

The present study was designed to extend previous results by evaluating electrical thresholds and dynamic ranges at higher pulse rates. The first goal was to determine whether the effects of increasing pulse rate observed for pulse rates less than 3000 pps (decreases in threshold and increases in dynamic range) were also observable at higher pulse rates (up to 6500 pps). The second goal was to determine whether previously observed differences in the current requirements of standard versus perimodiolar electrode arrays were constant across a wide range of pulse rates.

II. METHODS

Subjects were 15 postlingually deafened adults with a Clarion version 1.2 cochlear implant. Eight subjects had a standard electrode array (Spiral electrode array [SPRL]) and seven subjects had a perimodiolar electrode array (HiFocus electrode array with electrode positioning system [HF+EPS]). Subjects had used their devices for 5 months to 4 years prior to participating in the study. Although average duration of implant use was significantly longer for SPRL subjects (2.5 years) than for HF+EPS subjects (1.0 years), average word recognition scores were similar for the two groups (NU-6, SPRL=51.7%, HF+EPS=48.3%). Three individual electrodes distributed across the electrode array were evaluated in each subject (one each from the apical, middle, and basal third of the array).

Experiments were controlled by a personal computer (PC) running the Clarion SCLIN '98 FOR WINDOWS software (Advanced Bionics Corporation, 1996–97), and a second PC running custom software that controlled a research interface

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provided by Advanced Bionics Corporation for the Clarion C-I intracochlear stimulator (ICS). Stimuli were 200-ms pulse trains comprised of 77- μ s/phase, cathodic-first, biphasic pulses with no interphase gap. Pulse rates were 200, 500, 1000, 1625, 2600, 3250, and 6500 pps. Electrode coupling was monopolar, with the active, intracochlear electrode referenced to a return electrode on the case of the ICS. Nominal current amplitudes specified in the clinical and research stimulation software were translated to calibrated amplitudes using a set of tables developed in our laboratory. These tables compensated for nonlinearities in the current source that were functions of electrode impedance and pulse rate. Electrical impedances for the three test electrodes were measured at the beginning and end of each data collection session using the SCLIN software. Impedance measures typically varied less than $\pm 10\%$ across sessions. The average value of impedance measures obtained at all test sessions was used to compute the calibrated amplitudes for a given electrode.

Data collection for each test electrode spanned two, 2-h research sessions. The middle electrode was tested first, followed by the apical and basal electrodes. In each session, THS and MAL were measured using the SCLIN software with an ascending method of adjustment procedure. Additional threshold estimates were subsequently obtained with a three-interval, forced choice adaptive procedure that used a three-down, one-up stepping rule to estimate the current amplitude corresponding to 79.4%-correct detection (Levitt, 1971). The three listening intervals for each trial were cued visually on a video monitor, and the signal was presented in one interval, selected at random. The subject used a computer mouse to indicate the interval thought to contain the sound. Correct-answer feedback was given immediately after each response. Current amplitudes corresponding to the final eight reversals of each adaptive track were averaged to obtain a single threshold estimate. Adaptive thresholds were obtained in sets where a given set included one threshold estimate at each pulse rate, collected in increasing order of pulse rate. Final values for THS and MAL at each pulse rate were computed by averaging the combined data obtained in the two research sessions (4–6 adaptive threshold estimates and 2 MAL estimates). Dynamic range (DR) was computed by subtracting the final THS from the final MAL at each pulse rate.

III. RESULTS AND DISCUSSION

The left panel of Fig. 1 shows the mean data for THS and MAL as a function of pulse rate for subjects with the SPRL and HF+EPS electrode arrays. Although some individual subjects showed differences in THS or MAL across test electrodes (apical, middle, basal), there were no systematic effects of electrode site on average THS or MAL for either group. Thus, the mean data shown in Fig. 1 were obtained by first collapsing the data across test electrodes for each subject, and then averaging the data across subjects in each group. Error bars in the figure represent standard errors of the means.

It is apparent from Fig. 1 that mean THSs for SPRL and HF+EPS subjects are similar at all pulse rates. This result is consistent with findings of Lesinski-Shiedat *et al.* (2000) and Lenarz *et al.* (2001), who compared standard and perimodi-

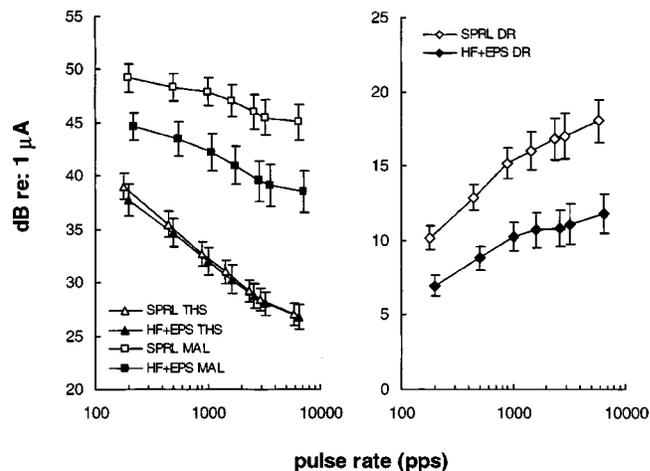


FIG. 1. Left panel: Mean detection threshold (THS) and maximum acceptable loudness level (MAL) as a function of pulse rate, for Clarion subjects with standard (SPRL) and perimodiolar (HF+EPS) electrode arrays. Right panel: Mean dynamic range (DR) for the same groups. Error bars represent ± 1 s.e. of the mean.

olar electrode arrays for the Clarion device at fixed pulse rates. Other studies conducted at fixed pulse rates have shown slightly lower thresholds for perimodiolar arrays than for standard arrays (Osberger *et al.*, 1999; Young and Grohne, 2001; Donaldson *et al.*, 2001; Xu and Pfungst, 2002; Parkinson *et al.*, 2002; Saunders *et al.*, 2002).

Linear functions provided good fits to individual THS-vs-pulse rate functions in log–log coordinates (dB re: 1 μ A vs log pulse rate). Slopes of THS-vs-pulse rate functions were nearly invariant across subjects in both the SPRL and HF+EPS groups, with a mean value of -2.4 dB/doubling. This slope is within the range (-2 - to -4 -dB/doubling) of slopes reported in earlier studies (Simmons, 1966; Shannon, 1985; 1989; Vandali *et al.*, 2000; Skinner *et al.*, 2000).

Figure 1 illustrates that mean MALs were 4 to 7 dB higher for subjects with the SPRL array than for subjects with the HF+EPS array. This result is also similar to data previously reported at fixed pulse rates (Lesinski-Shiedat *et al.*, 2000; Lenarz *et al.*, 2001). A two-way (group \times pulse rate) repeated-measures ANOVA confirmed a significant main effect of group [$F(1,78) = 6.20$, $p < 0.05$] and also indicated that group differences in MAL increased slightly with pulse rate [$F(6,78) = 3.92$, $p < 0.01$, for the interaction component]. *Post hoc* tests showed that the group differences in MAL were statistically significant for pulse rates of 1000 pps and higher (Tukey test, $p < 0.05$), and approached significance at 200 and 500 pps (Tukey test, $p = 0.093$ and $p = 0.067$, respectively).

Individual MAL-vs-pulse rate functions were also well fit by linear functions in log–log coordinates. Even though mean MALs were considerably different for SPRL and HF+EPS subjects, the slopes of MAL-vs-pulse rate functions were similar across groups. The slopes of these functions (mean = -1.2 dB/doubling) were substantially shallower than the slopes of THS-vs-pulse rate functions, and were similar to corresponding slopes for MAL and MCL indicated by the data of Skinner *et al.* (2000) and Vandali *et al.* (2000), respectively.

Although THS-vs-pulse rate and MAL-vs-pulse rate functions were fit with a single linear function between 200 and 6500 pps, some individual functions of both types showed a reduction in slope between 3250 and 6500 pps. These reductions in slope are also evident in the mean data (Fig. 1). Thus, although the effects of pulse rate observed at lower rates appear to be operative at pulse rates as high as 6500 pps in some subjects, there is also some evidence of saturation above 3250 pps. Evaluation of pulse rates higher than 6500 pps would be necessary to determine the pulse rates at which complete saturation occurs.

The right panel of Fig. 1 shows the average DR as a function of pulse rate for SPRL and HF+EPS subjects. Higher MALs led to substantially larger DRs for SPRL subjects (mean=15.2 dB across pulse rates) as compared to HF+EPS subjects (mean=9.3 dB across pulse rates). A two-way repeated-measures ANOVA confirmed that the main effect of group was significant [$F(1,78)=14.80, p<0.05$] and a significant group×pulse rate interaction showed that differences between groups increased with pulse rate [$F(6,78)=4.62, p<0.001$]. *Post hoc* tests indicated that group differences in DR were significant at all pulse rates (Tukey test, $p<0.05$).

IV. CONCLUSIONS

- (1) The effects of pulse rate on THS, MAL, and DR are qualitatively similar at pulse rates above 3000 pps as at lower pulse rates: both THS and MAL improve with pulse rate. However, average rates of improvement are reduced above 3250 pps, suggesting a partial saturation of the underlying mechanisms at very high pulse rates. Further evaluation of pulse rate effects above 6500 pps is needed to determine the pulse rates at which complete saturation occurs.
- (2) Clarion cochlear implant subjects with standard (SPRL) and perimodiolar (HF+EPS) electrode arrays have similar thresholds over a wide range of pulse rates (200–6500 pps).
- (3) Clarion subjects with standard (SPRL) electrode arrays have significantly higher MALs than those with perimodiolar (HF+EPS) electrode arrays, and these differences increase with increasing pulse rate. As a result, differences in DR also increase with pulse rate.
- (4) Slopes of MAL-vs-pulse rate functions are similar for Clarion subjects with standard (SPRL) and perimodiolar (HF+EPS) electrode arrays, even though average MALs are significantly different between groups.

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¹Only two studies reported data for MCL or MAL as a function of pulse rate: We estimated a slope of -1.2 dB/doubling from the MAL data of Skinner *et al.* (2000) for pulse rates between 600 and 2400 pps, and estimated a slope of -0.8 dB/doubling from the MCL data of Vandali *et al.* (2000) for pulse rates between 250 and 1615 pps.

Advanced Bionics Corporation (2003). "New methodology for fitting cochlear implants," HiResolution Sound Technology Workshops, Valencia, CA.

Advanced Bionics Corporation (1996–97). SCLIN '98 FOR WINDOWS [cochlear implant programming software]. Sylmar, CA.

Black, R. C., Steel, A. C., and Clark, G. M. (1983). "Amplitude and pulse rate difference limens for electrical stimulation of the cochlea following graded degeneration of the auditory nerve," *Acta Oto-Laryngol.* **95**, 27–33.

Donaldson, G. S., Peters, M. D., Ellis, M. R., Friedman, B. J., Levine, S. C., and Rimell, F. L. (2001). "Effects of the Clarion Electrode Positioning System on auditory thresholds and comfortable loudness levels in pediatric patients with cochlear implants," *Arch. Otolaryngol. Head Neck Surg.* **127**, 956–960.

Hay-McCutcheon, M. J., Brown, C. J., Schmidt Clay, K., and Seyle, K. (2002). "A comparison of EAP and EABR thresholds in Nucleus CI24R cochlear implant recipients," 25th Annual Midwinter Research Meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, FL.

Lenarz, T., Tasche, C., Frohne-Buechner, C., Buechner, A., Illg, A., Strauss-Schier, A., and Battmer, R.-D. (2001). "Comparison of different Clarion and Nucleus electrode systems within matched-pairs groups," 2001 Conference on Implantable Auditory Prostheses, Pacific Grove, CA.

Lesinski-Schiedat, A., Goldring, J. E., Gupta, S., Battmer, R.-D., Frohne, C., Weber, B. P., and Lenarz, T. (2000). "Evaluation of Clarion Electrode Positioning System with the preformed and Hifocus electrode," CI2000: The 6th International Cochlear Implant Conference, Miami Beach, FL.

Levitt, H. (1971). "Transformed up-down methods in psychoacoustics," *J. Acoust. Soc. Am.* **49**, 467–477.

Miller, A. L., Morris, D. J., and Pfungst, B. E. (1997). "Interactions between pulse separation and pulse polarity order in cochlear implants," *Hear. Res.* **109**, 21–33.

Osberger, M. J., Koch, D., Fisher, L., and Zimmerman-Phillips, S. (1999). "Clinical results in patients implanted with the Clarion electrode positioning system," 1999 Conference on Implantable Auditory Prostheses, Pacific Grove, CA.

Parkinson, A. J., Arcaroli, J., Staller, S. J., Arndt, P. L., Cosgriff, A., and Ebinger, K. (2002). "The Nucleus 24 Contour cochlear implant system: Adult clinical trial results," *Ear Hear.* **23**, 41S–48S.

Pfungst, B. E., Spelman, F. A., and Sutton, D. (1980). "Operating ranges for cochlear implants," *Ann. Otol. Rhinol. Laryngol. Suppl.* **66**(89), 1–4.

Pfungst, B. E., and Morris, D. J. (1993). "Stimulus features affecting psychophysical detection thresholds for electrical stimulation of the cochlea. II. Frequency and interpulse interval," *J. Acoust. Soc. Am.* **94**, 1287–1294.

Pfungst, B. E., Morris, D. J., and Miller, A. L. (1995). "Effects of electrode configuration on threshold functions for electrical stimulation of the cochlea," *Hear. Res.* **85**, 76–84.

Saunders, E., Cohen, L., Aschendorff, A., Shapiro, W., Knight, M., Stecker, M., Richter, B., Waltzman, S., Tykocinski, M., Roland, T., Laszig, R., and Cowan, R. (2002). "Threshold, comfortable level and impedance changes as a function of electrode-modiolar distance," *Ear Hear.* **23**, 28S–40S.

Shannon, R. V. (1985). "Threshold and loudness functions for pulsatile stimulation of cochlear implants," *Hear. Res.* **18**, 135–143.

Shannon, R. V. (1989). "A model of threshold for pulsatile electrical stimulation of cochlear implants," *Hear. Res.* **40**, 197–204.

Simmons, F. B. (1966). "Electrical stimulation of the auditory nerve in man," *Arch. Otolaryngol.* **84**, 24–76.

Skinner, M. W., Holden, L. K., Holden, T. A., and Demorest, M. E. (2000). "Effect of stimulation rate on cochlear implant recipients' thresholds and maximum acceptable loudness levels," *J. Am. Acad. Audiol.* **11**, 203–213.

Vandali, A. E., Whitford, L. A., Plant, K. L., and Clark, G. M. (2000). "Speech perception as a function of electrical stimulation rate: Using the

Nucleus 24 Cochlear implant system,” *Ear Hear.* **21**, 608–624.
Xu, L., and Pfungst, B. E. (2002). “Variation in thresholds and comfort levels across cochlear implant stimulation sites: Effects of electrode configuration and stimulus level,” 25th Midwinter Research Meeting, Asso-

ciation for Research in Otolaryngology, St. Petersburg Beach, FL.
Young, N. M., and Grohne, K. M. (2001). “Comparison of pediatric Clarion recipients with and without the electrode positioner,” *Otol. Neurotol.* **22**, 195–199.