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Encoding loudness by electric stimulation of the auditory nerve

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ELECTRIC charge has long been hypothesized to be the effective stimulus variable that determines loudness evoked by directly stimulating the auditory nerve. This 'equal-charge, equal-loudness' hypothesis predicts that stimulus amplitude and duration can be traded linearly to produce equal loudness. Loudness sensations from threshold to maximum loudness were measured systematically as a function of stimulus amplitude and duration in cochlear implant listeners. The measured data do not support the equal-charge, equal-loudness hypothesis: an increment in stimulus amplitude produces a significantly louder sensation than the same change in stimulus duration. Instead of the linear equal-charge model, a power-function model successfully predicts the measured data and should be used to encode loudness in electric hearing. *NeuroReport* 9: 1845–1848 © 1998 Rapid Science Ltd.

Key words: Auditory nerve; Cochlear implant; Electric stimulation; Loudness

Introduction

The encoding of sensory information is a fundamental issue in neuroscience and has been studied traditionally by two different approaches. The psychophysical approach treats the sensory system as a black box and measures the system's input–output function.[1,2] Alternatively, the physiological approach opens up the 'black box' by directly recording the electric activity in the sensory nerve and infers the information represented in the nerve spike train.[3–5] Here we combine both approaches to address the issue of loudness coding by measuring perceptual responses to electric stimulation of the auditory nerve in human cochlear implant users.

The cochlear implant can provide functional hearing to deaf people with a surgically inserted array of extracellular electrodes in the damaged sensory end organ, the cochlea, which directly stimulate the auditory nerve with electric currents.[6–9] The cochlear implant can also serve as a unique research tool to separate the roles of the ear and the brain in sensory information coding. Our earlier results from cochlear implant users suggested a phenomenological model for loudness coding, in which the enormous sound intensity range (100–120 dB) is first compressed in the auditory periphery to allow effective transmission of the intensity information via the auditory nerves of narrow dynamic ranges (20–40 dB), followed by an exponential expansion in the brain to recover the compressed intensity information.[10–12] While the clinical use of the cochlear implant is increasing exponentially, the perceptual study of electric stimulation of the auditory nerve is still in its infancy; many assumptions are made without substantiating evidence.

The present study focuses on a widely assumed but never formally tested hypothesis in electric hearing: electric charge is the effective stimulus variable that encodes loudness. Previously, analog electric waveforms and monophasic pulses were used to stimulate the auditory nerve,[7,13] but modern auditory prostheses use a charge-balanced, biphasic pulse train to drive a voltage-controlled current source in order to prevent abnormal tissue growth and toxicity caused by long-term electric stimulation.[14] In these devices, either pulse amplitude or pulse duration can be modulated to follow the amplitude variations in environmental sounds, including speech. There has been a long-standing view that it is possible to trade off pulse amplitude for pulse duration and maintain equal loudness providing total charge is constant[9] (charge is the product of pulse amplitude and pulse duration). To date, the equal-charge, equal-loudness hypothesis has not been tested, despite the fact that commercial cochlear implant devices (e.g. Nucleus 22) have used this model to program their loudness mapping functions. Here we provide the first systematic measurement on loudness balance functions between pulse amplitude and pulse duration to test directly this equal-charge, equal-loudness hypothesis.

Materials and Methods

Subjects: Four post-lingually deafened adults (two males and two females), all users of the Nucleus cochlear implant, participated in this research. All subjects could use the telephone with their cochlear implant alone and were experienced in psychophysical experiments. The experiments were conducted with the consent of each subject and received approval from the Institutional Review Board.

Stimuli: A cochlear implant typically consists of an external speech processor, an external radio-frequency transmitting antenna, an internally implanted receiver and an electrode array. The Nucleus device has 22 intracochlear ring-shaped electrodes with 0.75 mm spacing between electrodes and can reach a typical insertion depth of 20 mm into the cochlea. A custom-made research interface was used to control all electric stimulus parameters in the experiments.[15] A bipolar stimulation mode was used, in which both the stimulating electrode and the return electrode were inside the cochlea. Four electrode pairs, (1,3) (9,11) (20,22) (1,22), were selected in an attempt to stimulate the basal, middle, apical, and the entire region of the cochlea, respectively. A biphasic train of 200 ms at a rate of either 100 or 1000 Hz was applied to these electrode pairs. The pulse amplitude (in μA) was presented ranging from 25 to 1500 μA with about 3% resolution. The pulse duration was varied from 10 to 4000 μs/phase for the 100 Hz biphasic pulse train, and from 10 to 450 μs/phase for the 1000 Hz pulse train. The time resolution was 0.4 μs for the pulse duration change.

Procedures: Electric dynamic range was measured with a procedure combining the method of limits and Bekesy's tracking method.[16,17] The lower boundary of the dynamic range, the threshold level that evokes just audible hearing, was estimated from averaging an ascending sequence from inaudible to just audible and a descending sequence from clearly audible to just inaudible. The upper boundary of the dynamic range, the electric level that results in maximum acceptable loudness level, was estimated from the ascending sequence only. Loudness balance between pulse amplitude and pulse duration was obtained using an adaptive, double-staircase procedure that independently tracks the 21% and 79% points on the psychometric function.[18,19]

Results

We first measured the hearing threshold and the maximum comfortable loudness as a function of pulse amplitude and duration. This amplitude *vs* duration relationship has been referred as the strength–duration function, particularly at the threshold level.[20] Assuming that the equal-charge, equal-loudness hypotheses were valid, equal loudness sensation would be achieved as long as the electric charge is kept constant: $A \times D = k$, where A is pulse amplitude, D is pulse duration, and k is a constant. This linear trade-off or constant-charge model would predict a straight line with a slope of –1 on a log-log scale for equal loudness functions.

Figure 1 depicts threshold and maximum acceptable loudness data obtained for the 100 Hz pulse train from a typical cochlear implant user. Linear regression analysis was performed for both the threshold and the maximum loudness data on the log-log scale. The prediction of the equal-charge, equal-loudness hypothesis is also plotted. Because all subjects show similar data patterns, the slope values are averaged across subjects for four electrode configurations and two stimulus rate conditions (Table 1).

The most notable result is that neither the threshold function nor the maximum loudness function abides by the equal-charge, equal-loudness hypothesis for all subjects and under all experimental conditions. Both the threshold and maximum loudness data can be well described by a power-function model: $A = kD^{\alpha}$, resulting in a slope (the exponent α on a log-log scale) shallower than –1 and a high regression coefficient ($r > 0.90$ for all experimental

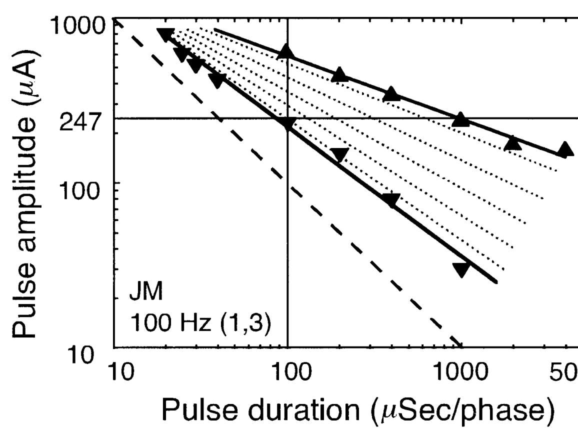

FIG. 1. Strength–duration functions or equal-loudness curves in electric stimulation of the auditory nerve (subject: JM). The x-axis is pulse duration in μs/phase and the y-axis is pulse amplitude in μA for a biphasic electric pulse train. The triangles are threshold data and the inverted triangles are the maximum loudness data. The bottom thick line is a power function that best fits the threshold data (exponent = –0.79, r = 0.99) and the top thick line is a power function that best fits the maximum loudness data (exponent = –0.38, r = 0.99). The dashed line represents the prediction of the equal-charge, equal-loudness hypothesis (exponent = –1). The five dotted lines represent hypothetical equal-loudness curves at 10%, 30%, 50%, 70% and 90% dynamic range. The loudness balance function between a fixed-duration stimulus (thin vertical line) and a fixed-amplitude stimulus (thin horizontal line) can be predicted by the intercepts of the horizontal line and the equal-loudness curves (see Discussion).

Table 1. Averaged slopes of the strength–duration function at threshold (left column) and the maximum acceptable loudness (right column). The maximum loudness data for electrodes (20,22) could not be obtained because the required current exceeded the hardware limit.

	Threshold (Hz)		Maximum loudness (Hz)	
Electrodes	100	1000	100	1000
(1,3)	–0.67	–0.70	–0.41	–0.52
(9,11)	–0.76	–0.73	–0.40	–0.41
(20,22)	–0.84	–0.74	–0.22	N/A
(1,22)	–0.72	–0.66	–0.45	–0.56
Average	–0.75	–0.71	–0.37	–0.50

conditions). Specifically, the slope of the threshold function averaged over all subjects and electrodes is –0.75 (s.d. 0.14) for the 100 Hz pulse train condition and –0.71 (s.d. 0.09) for the 1000 Hz condition; the averaged slope of the maximum loudness function is even flatter at –0.37 (s.d. 0.11) for the 100 Hz condition and –0.50 (s.d. 0.17) for the 1000 Hz condition. A three-way analysis of variance indicates a significant difference in the slope between the threshold and the maximum loudness measures ($F(df = 1) = 49.3$, $p < 0.001$), but no significant difference ($p > 0.1$) across pulse rates or electrode configurations.

Figure 2 shows individual loudness balance functions between pulse amplitude and pulse duration at 100 Hz (top panel) and 1000 Hz (bottom panel) rates. If pulse amplitude can be traded linearly for pulse duration to achieve equal loudness, then loudness should grow in the same fashion as a function of either pulse amplitude or pulse duration (i.e. slope = 1, represented as the diagonal dashed line). It is clear that all subjects' loudness balance functions have a slope shallower than 1, deviating severely from the equal-charge, equal-loudness hypothesis.

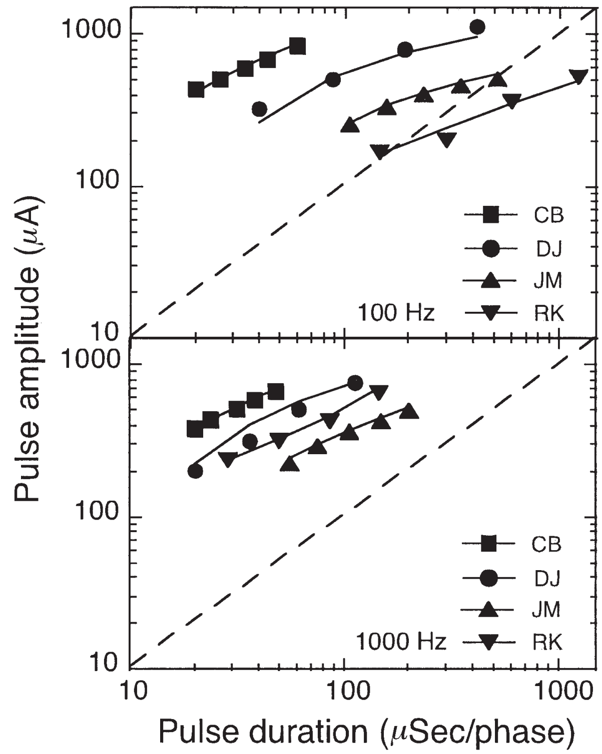

FIG. 2. Measured (symbols) and predicted (solid lines) loudness balance functions for electrodes (1,3). The top panel shows data and prediction obtained at the 100 Hz pulse rate while the bottom panel shows that at the 1000 Hz pulse rate. The dashed diagonal line in both panels represents the prediction of the equal-charge, equal-loudness hypothesis. To obtain these loudness balance functions, amplitude of a fixed-duration pulse train was varied to match loudness of a pulse train with fixed amplitude. For the 100 Hz condition, the fixed amplitude was 562 μA and the fixed duration was 100 μs/phase for subject CB (squares), 1122 μA and 100 μs/phase for DJ (circles), 247 μA and 100 μs/phase for JM (triangles), and 311 μA and 500 μs/phase for RK (inverted triangles), respectively. For the 1000 Hz condition, the fixed amplitude was 708 μA and the fixed duration was 100 μs/phase for subject CB (squares), 1000 μA and 100 μs/phase for DJ (circles), 355 μA and 100 μs/phase for JM (triangles), and 696 μA and 150 μs/phase for RK (inverted triangles), respectively.

Discussion

The measured loudness balance data can be predicted from the threshold and the maximum comfortable loudness data (Fig. 1) if we assume a smooth transition for the equal-loudness curves from the threshold function to the maximum loudness function. For example, let us predict the loudness balance function between the amplitude (A) of a fixed-duration stimulus (the vertical line at 100 μs/phase position in Fig. 1) and the duration (D) of a fixed-amplitude stimulus (the horizontal line at the 247 μA position in Fig. 1). For the amplitude varied from 10% to 90% of the entire dynamic range in 20% steps, the duration needed to balance the loudness of these five amplitudes would be the intercept between the horizontal line and the equal-loudness contours. The predicted function (the solid line across triangles in the top panel of Fig. 2) is in agreement with the measured data.

A closed-form analytic solution can be derived based on the power function describing the threshold and the maximum loudness data. At threshold, the relationship between the electric amplitude (A) in μA and the pulse duration (D) in μs can be described:

$$A = k_t D^{\alpha_t} \quad (1)$$

where k_t and α_t are two constants that determine the intercept and the slope of the threshold function on a log-log plot. Similarly, the maximum loudness function can be written as:

$$A = k_m D^{\alpha_m} \quad (2)$$

where k_m and α_m are two constants that determine the intercept and the slope of the maximum loudness function. The loudness balance function between the amplitude of a fixed-duration stimulus (D_0) and the duration of a fixed-amplitude stimulus (A_0) can be predicted by assuming a smooth change in the slope of the equal-loudness-contour from the threshold function (1) to the maximum loudness function (2):

$$A = k_i D_o^{a_t} \left(\frac{A_o}{k_t D^{\alpha_t}} \right)^{\log([k_m/k_t] D_o^{a_m - a_t}) / \log([k_m/k_t] D^{a_m - a_t})} \quad (3)$$

Figure 2 shows the predicted functions which are consistent with the obtained data. It is also worth noting that Equation (3) contains no free parameters. The four parameters that are needed for prediction can be estimated theoretically from only four measurements with two estimating the slope and intercept of the threshold function and two estimating that of the maximum loudness function. Once these four parameters are estimated, loudness can be determined analytically and unambiguously in the entire amplitude–duration space.

The present data are consistent with previous measures of the psychophysical strength–duration function in electric stimulation of the auditory nerve in cats,[20] monkeys[21] and human subjects.[16] Together these results indicate that the widely assumed equal-charge, equal-loudness model is not valid at either the threshold level or at the suprathreshold level. Moreover, the present data show that all strength–duration functions had a slope shallower than the –1 slope predicted by the equal-charge model: the slope decreased monotonically from the threshold function (–0.7) to the maximum loudness (about –0.5) function. The power–function relationships between pulse amplitude and duration may reflect general biophysical characteristics in the electrode–nerve interface and the stochastic processes underlying neural spike generation and transmission.[20–25] It is thus possible that a similar power-function relationship also exists in perceptual responses to electric stimulation of neurons in other modalities such as vision and touch.

Conclusion

The present report tests a classic hypothesis in functional electrical stimulation: does electric charge determine the magnitude of electrically-evoked perceptual response? Our results show in direct stimulation of auditory nerve that this equal charge, equal loudness hypothesis is not valid; instead a power-function model can account for the observed data. The present model cannot only be used to encode appropriately the loudness of electric stimulation in a cochlear implant, but also be applied to other neural prostheses.

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