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Loudness balance between electric and acoustic stimulation

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Binaural loudness balance between electric and acoustic stimulation is obtained in auditory brainstem implant listeners who had substantial acoustic hearing in one ear. The data are well described by a linear relationship between acoustic decibels and electric microamps. Based upon this linear relationship, we propose an exponential model of loudness growth in electric stimulation. The exponential model predicts that the loudness growth function can be determined solely by the threshold and the uncomfortable loudness level in electric stimulation. This prediction is consistent with previous psychophysical data on loudness functions. Implications of this finding for speech processor designs are discussed.

Loudness balance; Electric stimulation; Loudness function

Introduction

Electric stimulation of the auditory system can partially restore the hearing sensations of deaf listeners. In designing a speech processor for an implant listener, one of the most important factors lies in the proper transformation of acoustic amplitude to electric amplitude. Normal acoustic hearing can process sounds over a range of 120 dB in acoustic amplitude; even speech sounds in a normal conversation can range from 40 to 60 dB. However, implant listeners typically have dynamic ranges of only 6 to 30 dB. Thus, the wide acoustic range must be compressed to a considerably smaller range of electric stimulation to preserve the acoustic amplitude variations that transmit important speech information.

Loudness in electrically stimulated human listeners has been measured quantitatively using rating methods and magnitude estimation techniques (for a review, see Pfingst, 1984). The existing data are not consistent across studies. Some investigators have found that log loudness grows linearly as a function of log current, although some data show two stages, with loudness that grows gradually at low stimulation levels and grows steeply at higher stimulation levels (Clark et al., 1978; House and Edgerton, 1982; Shannon, 1983, 1985; Shannon and Otto, 1990). Muller (1981) found that loudness growth can be described by a power function with an exponent of about 3.5. On the other hand, Mathews (1978), Walker (1978), and Herndon (1981) found that loudness grows linearly as a function of charge.

Eddington et al. (1978) used the method of limits to balance loudness between an electrically and an acoustically stimulated ear in one cochlear implant listener. They found that the perceived loudness, when expressed in dB SPL, increased linearly with electric stimulation amplitude. There has not yet been a widely-accepted quantitative description in implant research of the relation between loudness and electric stimulus level. It is not clear whether the discrepancies among the above-mentioned loudness functions were due to procedural differences or due to individual implant listener differences.

The present study measures loudness balance between electric and acoustic stimulation in auditory brainstem implant (ABI) listeners. These listeners received the implant during first-sided tumor removal and had substantial residual, even normal, hearing in the contralateral ear. The obtained results show a linear relationship in loudness between acoustic decibels and electric amplitude. Based upon this relationship, we propose an exponential loudness growth model in electric stimulation, which is also compared with previous empirical data.

Methods

Subjects

Three subjects with type-2 neurofibromatosis, which is characterized by bilateral acoustic tumors, partici-

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pated in this study. These subjects received the ABI (Eisenberg et al., 1987) during removal of their first-sided tumor, and all had substantial hearing in the contralateral ear at the time of the experiments. These were two females and one male aged 38, 27 and 19 respectively. Subjects ABI 17 and 18 had a percutaneous plug interface and subject ABI 14 had a transcutaneous coil. In the nonimplanted ear, subject ABI 17 had normal hearing (thresholds less than 10 dB HL); subjects ABI 14 and 18 had a 40 to 50 dB flat loss at frequencies from 125 Hz to 8000 Hz (ANSI, 1969). No tone decay was observed in subjects 17 and 18 for a 300-Hz pure tone presented at 5 dB SL to the acoustic ear and lasting 60 s (Olsen and Noffsinger, 1974). All three subjects had previous experience in various psychophysical tasks.

Stimuli

For subjects ABI 17 and 18 with a plug interface, electric stimulation was delivered through an optically-isolated constant-current source (Vurek et al., 1981). The maximum output was 1000 microamps and was periodically calibrated to ensure accuracy. For subject ABI 14, the coil was directly driven by a Crown D-75 amplifier. For this subject, the calibration was achieved by placing a plastic spacer of the patient's skin thickness between the external coil and the internal coil. The maximum output was then adjusted to 10 volts peak-to-peak into a 1-kΩ load connected to the internal coil. The sinusoidal stimuli were generated digitally and output at a 10 kHz rate on a 12-bit D/A converter (Data Translation DT2801-A). A 5 kHz low-pass filter (6 dB/octave slope) was used to smooth the waveforms. The electric stimulus was a series of 300 ms duration bursts presented once per second.

Acoustic stimulation was provided by an audiometer (Grason-Stadler model 1701) and was delivered to the subject through a TDH-49 headphone. The audiometer was calibrated before data collection, and the acoustic level was presented as dB HL (ANSI, 1969). The acoustic stimulus was also a sinusoidal waveform and was presented continuously to the subject.

Stimulus frequency for subjects ABI 17 and ABI 18 was 300 Hz; for subject ABI 14, it was 1000 Hz due to the inefficient low-frequency transmission of the coil delivery system.

Procedure

Thresholds and uncomfortable loudness levels of both acoustic and electric stimulation were obtained first in each subject to set the lower and upper limits of stimulation (Shannon and Otto, 1990). An acoustic sinusoidal standard stimulus was presented continuously to the subject during each of the following three loudness balance trials. The acoustic stimulus was turned off between trials. The subject was instructed to bracket the point of equal loudness by first adjusting the electric stimulus to the level that was just-noticeably louder than the acoustic stimulus, then to the level that was just-noticeably softer, and then to the point of subjective equality. The subject controlled the electric level by moving his or her finger up or down a touch sensitive surface (Koala pad). For subject ABI 17, a reversed procedure was also used to obtain the balanced acoustic levels while the electric level was fixed. The acoustic stimulus level was presented across the entire dynamic range with a step of either 5 or 10 dB. The presentation order of these fixed levels was randomized. Each loudness balance judgment took about 10 s. Each data point is an average of two such judgments.

Result

Fig. 1 shows the loudness balance data between electric and acoustic stimulation in the three ABI subjects. The filled circles represent the point of subjective equality between the electric and acoustic levels. The filled squares, in the upper panel only (ABI 17), also represent the point of subjective equality in the condition in which the electric level was fixed and the patient adjusted acoustic level to match. Note the consistency between the two procedures with either acoustic or electric level fixed. The open, inverted triangles represent the just-noticeably louder point, the open triangles represent the just-noticeably softer point. The vertical dashed line on each panel represents the acoustic threshold of each individual subject.

Fig. 1 shows a nearly linear relationship between acoustic decibels and electric microamps or millivolts. Linear regression fits to the data show that the slopes are 7.93, 3.96 μA, and 8.98 mV per decibel, the intercepts are -71.52, 73.75 μA, and 151.86 mV, and the Pearson coefficients are 0.98, 0.97, and 0.99 for subjects ABI 17, 18 and 14, respectively. The coefficients of determination are also calculated to measure the goodness of fit (Barrett, 1974) and high values identical to the Pearson coefficients are obtained.

Because of the absolute differences in threshold and dynamic range, it is difficult to directly compare the loudness growth among these subjects. We calculate the relative percent loudness growth such that the lowest levels are normalized to be 5% and the highest levels are normalized to 95% of the dynamic range. Fig. 2 shows relative loudness growth between electrically and acoustically stimulated ears in the three ABI listeners (open symbols). The x-axis represents relative acoustic level in terms of percent acoustic dynamic range (computed in dB), and the y-axis represents relative electric level in percent electric dynamic range (computed in microamp or millivolt). There is a linear relation between relative electric and acoustic loudness growth among these three subjects (the coefficient of determination, $R = 0.98$). The slope is 0.96 and the intercept is -3.29 in the linear regression function.

We replotted the loudness balance data of Eddington et al. (1978) in the same fashion. The filled circles are relative electric and acoustic stimulation levels on electrodes 1 and 2 (session 1) and calculated from Fig. 17(A) of Eddington et al. (1978) by visual inspection. The linear regression fits to the replotted data yield almost same values as those obtained in the present ABI listeners ($R = 0.99$, slope $= 0.95$, and intercept $=$ 4.06). This similarity suggests that a linear relationship between acoustic decibels and electric microamps holds

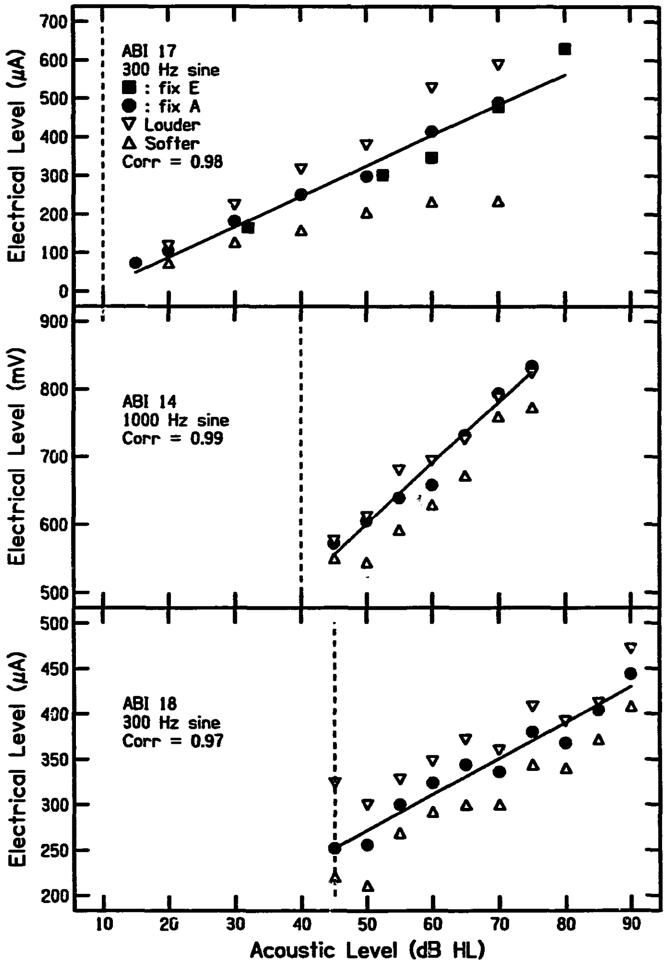

Fig. 1. Loudness balance between electric and acoustic stimulation in three auditory brainstem implant (ABI) listeners. The filled circles represent the point of subjective equality between electric level in microamps (upper and lower panels) or millivolts (middle panel) and acoustic level in dB HL. The filled squares in upper panel only represent the point of subjective equality in the condition in which the electric level was fixed and the patient adjusted acoustic level to match. The open inverted triangles represent the just-noticeably louder point, the open triangles represent the just-noticeably softer point. The vertical dashed line on each panel represents the acoustic threshold of each individual subject.

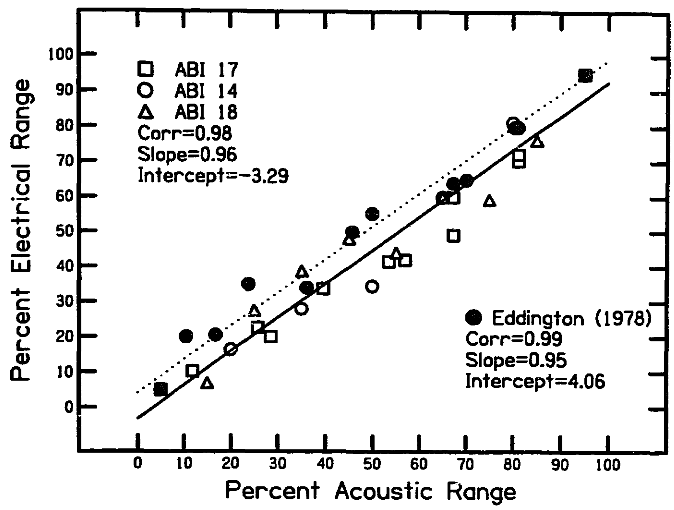

Fig. 2. Normalized loudness balance between electric and acoustic stimulation. The percent acoustic range is normalized in decibels and the percent electric range is normalized in microamps or millivolts. The open symbols represent data of ABI listeners in the present study; the filled circles represent data of a cochlear implant (CI) listener from Eddington et al. (1978). The solid line is a linear regression fit to the ABI data and the dotted line is to the CI data.

true in both cochlear and auditory brainstem implant listeners.

Several interesting subjective perceptions were reported by the subjects during these loudness balances. First, subject ABI 17 reported a loudness 'entrainment' phenomenon in which a wide range of electric levels appeared to be the same loudness as a constant acoustic stimulus. Subject ABI 17 noted that when the loudness was changing in the electrically stimulated ear, the loudness of the acoustic stimulus, presented at fixed level, also appeared to be changing. This phenomenon was strongest when both the electric and acoustic stimuli were low frequency and at high levels. As a consequence of this loudness entrainment phenomenon, the judged range of equal electric loudness was much larger at high levels (upper panel). However, the other two subjects reported no such effect when balancing loudness. Second, all subjects reported that at high loudness levels, the sound image appeared to be fused between electrically and acoustically stimulated ears. At low loudness levels, the electric and acoustic stimulation evoked two different sensations and the acoustic stimulation appeared to have a 'clearer' sound quality.

Discussion

Loudness function in electric stimulation

The most widely-accepted loudness model in acoustic stimulation relates loudness to a power function of the stimulus amplitude, i.e, loudness (L) grows in proportion to the stimulus amplitude (A) raised to a power (p) (Stevens, 1955):

$$L = KA^p \tag{1}$$

Fig. 2 suggests that there is a linear relationship between normalized electric level and normalized acoustic level. Furthermore, it shows that this linear relationship has a slope close to 1 and an intercept to 0, which implies that the following equation holds:

$$\frac{E - Eo}{Eu - Eo} = \frac{20 \log A - 20 \log Ao}{20 \log Au - 20 \log Ao} \tag{2}$$

where Eo and Eu, Ao and Au are stimulus amplitudes that produce threshold and uncomfortable loudness levels in electric and acoustic stimulation, respectively. E is electric level in terms of either microamps or millivolts, and 20 log A is acoustic level in decibels.

Combining equation (1) and (2), we obtain the loudness growth function in electric stimulation:

$$L = KA_o^p(A_u/A_o)^p \frac{E - E_o}{E_u - E_o} \tag{3}$$

Equation (3) predicts that loudness grows exponentially as a function of electric stimulation level. Note that the derivation of this exponential function is based upon two assumptions: Stevens's power law and the linear relation between acoustic decibels and electric microamps. Consider two important implications in equation (3). First, there are no free parameters in equation (3). The parameters K, p, Au, and Ao are constants determined by acoustic stimulation, whereas the parameters Eo and Eu are the threshold and the uncomfortable loudness level in electric stimulation. This means that loudness growth is solely determined by electric dynamic range, which acts as a scaling factor that controls the steepness of the loudness growth function. In other words, the larger the electric dynamic range, the lower the slope of loudness growth. This is consistent with the observation of many investigators that the gradual tail portion in electric loudness function near threshold increases with the dynamic range of electric stimulation (Clark et al., 1978; Muller, 1981; House and Edgerton, 1982; Shannon, 1983; Pfingst, 1984; Shannon, 1985; Shannon and Otto, 1990). Second, equation (3) implies that there is no loudness recruitment in electric stimulation, as electric threshold (combined with electric uncomfortable level) acts like a scaling factor. Further investigation is required to validate this implication.

Predictions of loudness model relating to previous data

Fig. 3 shows previous psychophysical loudness growth data and predictions of the present exponential loudness model. Data from Tong et al. (1979), Shannon (1985), and Hochmair-Desoyer and Burian (1985) are obtained by visual inspection of their original figures. Muller's (1981) data are calculated using a power function with an exponent of 3.5. In calculation, a typical acoustic dynamic range, as expressed in 20*LOG (Au/Ao), is chosen as 90 dB and the exponent of acoustic power law, p, is 0.6. The model predictions are generally consistent with the empirical data. Particularly, it is noted that the upper portion of the loudness growth function (> 10%) has almost the same shape on these coordinates and is independent of the dynamic range. On the other hand, the lower portion of loudness growth (< 10%) varies greatly with the dynamic range. The larger the dynamic range, the longer the tail of the loudness growth function (e.g., triangles in Shannon [1985]). This suggests that there is no need to assume a two-stage loudness growth function because the tail merely reflects the scaling effect of electric dynamic range.

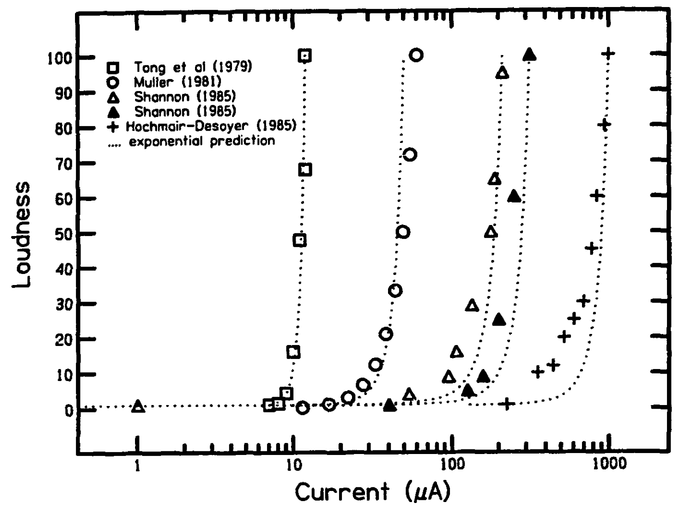

Fig. 3. Comparison of exponential loudness growth model and empirical psychophysical data. The dotted lines are predictions of the proposed exponential loudness model, whereas various symbols are psychophysical loudness data obtained in previous studies.

Although the present simple model hypothesizes an exponential loudness growth in electric stimulation, it is not now clear why the large dynamic range results in a long tail at low levels. We speculate that the tail of loudness growth function is related to the survival of high-spontaneous rate (high-SR) neurons. Zeng et al. (1991) suggest that high-SR neurons are responsible for absolute threshold detection, whereas low-SR neurons are responsible for suprathreshold loudness coding. In other words, more survival of high-SR neurons could produce a lower threshold and thus a larger dynamic range, but does not contribute much to loudness growth.

Implications for Speech Processing Strategy

If the proposed loudness function is valid, equation (2) indicates that the proper acoustic-to-electric intensity mapping in a speech processor is a logarithmic transformation. This is consistent with the concept that the cochlea normally provides a logarithmic compression. With electric stimulation, we need to perform logarithmic compression externally to compensate for the missing cochlear function. Equation (2) also indicates that both threshold and dynamic range should be considered to further accommodate the individual differences and parametric dependences in electric stimulation. Basically, in designing a speech processor for a specific implant listener using a specific stimulus paradigm, threshold of the stimulus in the subject functions as a DC offset and the dynamic range functions as a gain control. Such a processing strategy has been implemented in several implant research laboratories (Wilson et al., 1991; Shannon et al., 1992), and a substantial degree of success in improving speech recognition has been achieved. The present study may provide a theoretical basis for this success.

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