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Hearing Research 202 (2005) 55–62
HEARING RESEARCH
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Loudness growth in cochlear implants: effect of stimulation rate and electrode configuration

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Received 22 April 2004; accepted 12 October 2004
Available online 21 November 2004

Abstract

In cochlear implant speech processor design, acoustic amplitudes are mapped to electric currents with the intention of preserving loudness relationships across electrodes. Many parameters may affect the growth of loudness with electrical stimulation. The present study measured the effects of stimulation rate and electrode configuration on loudness growth in six Nucleus-22 cochlear implant users. Loudness balance functions were measured for stimuli that differed in terms of stimulation rate, electrode configuration and electrode location; a 2-alternative, forced-choice adaptive procedure (double-staircase) was used. First, subjects adaptively adjusted the amplitude of a 100-pulse-per-second (pps) pulse train to match the loudness of a 1000-pps standard pulse train. For a range of reference stimulation levels, the loudness of the 100-pps stimulus was matched to that of the 1000-pps standard stimulus; loudness balancing was performed for three electrode pairs [(20,22), (1,3), (1,22)]. The results showed that the loudness balance functions between the 100- and 1000-pps stimulation rates were highly subject-dependent. Some subjects' loudness balance functions were logarithmic, while others' were nearly linear. Loudness balance functions were also measured across electrode locations [(20,22) vs. (1,3)] for two stimulation rates (100, 1000 pps). Results showed that the loudness balance functions between the apical and basal electrode pairs highly depended on the stimulation rate. For all subjects, at the 1000-pps rate, the loudness balance functions between the two electrode locations were nearly linear; however, at the 100-pps rate, the loudness balance function was highly nonlinear in two out of six subjects. These results suggest that, for some cochlear implant patients, low-frequency stimulation may be processed differently at different electrode locations; for these patients, acoustic-to-electric amplitude mapping may need to be sensitive to this place-dependent processing when relatively low stimulation rates are used.

Keywords: Cochlear implants; Loudness balance; Loudness growth; Stimulation rate; Electrode configuration; Amplitude mapping

1. Introduction

Modern multi-channel cochlear implants (CIs) provide hearing sensation to profoundly deaf patients by directly stimulating the remaining auditory nerves. A major concern in CI speech processor design is the proper transformation of acoustic amplitudes to electric currents delivered to each electrode. Acoustic amplitudes in normal conversation can vary over a 30-dB range. However, for CI users, the dynamic range of electrical current between detection threshold and comfortably loud stimulation is typically only 6–15 dB. If the acoustic-to-electric amplitude mapping fails to maintain appropriate loudness growth within each electrode, important speech cues may be lost. Previous experiments in which CI patients' acoustic-to-electric amplitude mapping was varied have shown that the best speech recognition performance occurred when a normal loudness growth function was restored; distortions to the normal loudness growth function resulted in a moderate, but significant drop in perception performance (Shannon et al., 1992; Boëx et al., 1995, 1997; Fu and Shannon, 1998).

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doi:10.1016/j.heares.2004.10.004

One straightforward approach to estimate the appropriate acoustic-to-electric amplitude mapping is to directly compare the loudness growth function of acoustic hearing to that of electric hearing. In normal acoustic hearing, the function relating loudness to acoustic amplitude has a long history. In the widely accepted model of loudness in acoustic hearing, Steven's Power Law (Stevens, 1955), loudness grows in proportion to the stimulus amplitude (A) raised to a power (p – the exponent of the acoustic power law – is 0.6). With electrical stimulation of the tympanic membrane, Stevens and colleagues (Stevens, 1937, 1959) found loudness grew much more quickly ($p = 3.5$). Müller (1981) found that loudness growth for electrical stimulation via CIs could also be described by a power function, where p was approximately 3.5. Fu and Shannon (1998) measured loudness growth functions in Nucleus-22 CI patients and found that the loudness growth functions for all measured electrodes were well fit by a power function with a mean exponent of 2.72. One suggestion from these studies is that loudness with electric stimulation of the cochlea grows much more quickly than normal.

With CI patients who have some residual hearing (contralateral to the implanted ear), the appropriate acoustic-to-electric amplitude mapping may be more directly estimated by the loudness balance function between acoustic and electric stimuli. Eddington et al. (1978) balanced loudness between acoustic and electric stimulations in an Ineraid CI patient. They found that acoustic level (in dB SPL) was linearly related to electric amplitude in microamperes (i.e., there was a logarithmic relation between acoustic and electric amplitudes). A similar logarithmic relation was also observed in another Ineraid user (Dorman et al., 1993), and in three auditory brainstem implant (ABI) patients who had substantial acoustic hearing in one ear (Zeng and Shannon, 1992). Zeng and Shannon (1992) argued that this logarithmic acoustic–electric loudness relation was due to the loss of the implanted cochlea's normal logarithmic compression. Based upon this linear relationship between acoustic amplitude (in dB SPL) and electric current (in microamperes), Zeng and Shannon proposed an exponential model of loudness growth in electric stimulation. Their exponential model predicted that the loudness growth in electric stimulation could be determined solely by threshold and uncomfortable loudness levels. They found that predictions with their exponential model were consistent with previous psychophysical data on loudness growth functions in electric hearing. The data from these previous studies suggest that loudness growth in CIs could be described by either a power function or an exponential function.

However, other studies have shown that loudness growth in CIs is also highly dependent on the rate of stimulation (Zeng and Shannon, 1994; Gallego et al., 1999). Zeng and Shannon (1994) compared the loudness growth function of 100- and 1000-pps stimuli in CI listeners, using a loudness-balancing technique. They found that, in contrast to Steven's Power Law (which related loudness and stimulus intensity in normal acoustic hearing), loudness for electric stimulation of the auditory nerve depended on the stimulus frequency. The loudness growth function was exponential for high frequencies and a power function for low frequencies (<300 pps). Gallego et al. (1999) also measured loudness growth functions in CI listeners for 75- and 300-pps stimuli, using a categorical loudness-scaling procedure. The results revealed a significant difference in the loudness growth functions for the two rates, with loudness increasing more steeply with stimulus intensity at the higher stimulation rate. However, when normalized to the dynamic ranges for each rate, loudness was shown to grow similarly for both rates, different from the data reported by Zeng and Shannon (1994).

Because the restoration of normal loudness growth is important for CI users' speech recognition, it is important to understand the effects of stimulation rate on loudness growth. Fu and Shannon (2000) measured vowel recognition scores in six Nucleus-22 CI patients with experimental 4-channel CIS speech processors using either relatively high stimulation rate (500 pps) or low stimulation rate (100 pps). For both rates, the acoustic-to-electric amplitude mapping function was a fixed power function (exponent = 0.2; Fu and Shannon, 1998). Mean vowel recognition scores dropped by 8 percentage points as the stimulation rate was reduced from 500 to 100 pps. Because the amplitude mapping functions were the same for both processors, the difference in performance might have been due to differences the loudness growth between the 100- and 500-pps stimulation rates; if loudness were to grow differently at these rates, the fixed amplitude mapping function might have distorted the amplitude/envelope cues provided by the 100-pps processor. These results suggest that it is important to understand the effects of stimulation rate on loudness growth, and that appropriate adjustments to the amplitude mapping function may be necessary for different stimulation rates.

The effects of stimulation rate on loudness growth may also be valuable to understanding the relationship between CI patients' psychophysical performance and electrically evoked compound action potentials (ECAPs), as measured using neural response telemetry (NRT; Abbas et al., 1999; Brown et al., 2000; Charasse et al., 2004; Franck and Norton, 2001). Charasse et al. (2004) found that the quality and amplitude of the NRT response quickly declined for stimulation rates above 150 pps. Because the stimulation rates used in most speech processing strategies 250 pps or more, it would be useful to know how loudness growth might change as a function of stimulation rate; this way,