The pitch of electrically presented sinusoids

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A patient who uses the Ineraid cochlear implant, and who has hearing thresholds less than 50 dB HL for frequencies under 500 Hz in his nonimplanted ear, was asked to match the pitch of low-frequency signals presented to his two ears. The patient produced pitch matches, for frequencies of 125, 200, and 300 Hz presented to his most apical electrode, that were slightly higher than the reference frequency. When signals of fixed frequency were presented to electrodes located in successively more basal cochlear locations, pitch increased in an orderly fashion—an average of 57 Hz (range =31–87 Hz) for each change in electrode location.

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INTRODUCTION

Most patients who use the Ineraid multichannel cochlear implant report that the pitches of men's and womens' voices sound appropriate. If these verbal reports are accurate, then electrical stimulation must be able to produce low-frequency pitch percepts similar to those produced by normal cochlear mechanisms. In this article we make use of an unusual cochlear implant patient—one with relatively good hearing sensitivity below 500 Hz in his nonimplanted ear—to assess the pitch of electrically presented sinusoids.

Eddington *et al.* (1978a) were among the first to report the results of a pitch matching experiment using electrical and acoustic stimulation. When a 200 pulse/s (pps) electrical signal was presented to the patient's most apical electrode, the signal was matched to an acoustic signal of approximately 1225 Hz in the nonimplanted ear. When a 200-pps signal was applied to a slightly more basal electrode, the signal was matched to an acoustic frequency of approximately 1560 Hz. Eddington *et al.* noted (i) that the patient reported hearing "fuzzy" sounds, not pure tones and (ii) that the pitch matching results were "roughly" consistent with "place" theories of pitch perception; i.e., the electrodes were 20 and 16 mm, respectively, from the round window and thus were near the 1- to 2-kHz place in the cochlea (see Greenwood, 1990, for a discussion of frequency/place maps for the cochlea of several species).

Although patient PH produced pitch matches which were consistent with place theories of pitch perception, it is clear that he, and other early patients (e.g., Eddington *et al.*, 1978b; Simmons, 1966), also could hear periodicity pitch. For example, Eddington *et al.* (1978a) reported that pitch increased for stimuli presented to a given electrode over the range 70–400 pps. Nonetheless, the pitch-matching data between implanted and hearing ears indicated a match to place of stimulation and not to the periodicity of stimulation.

A quite different outcome was reported by Bilger *et al.* (1977). The matching experiment was conducted by presenting a sine stimulus to the hearing ear, and by asking the patient to vary the frequency of a pulse train presented through his House single-channel implant until the electrically elicited pitch matched the acoustically elicited pitch. For frequencies less than 160 Hz, acoustic and electrical stimuli produced similar pitch percepts. However, for frequencies above 160 Hz electrical matches were much lower than the reference frequency. At all events, the electrical matches were more nearly based on rate pitch than on place pitch.

In September 1990 author JLP implanted the Ineraid electrode array in the right cochlea of a patient (MK) who had 0% speech identification scores in both ears. Hearing thresholds in MK's nonimplanted ear were less than 50 dB HL for frequencies under 500 Hz. Given the presence of these reasonably good thresholds, we sought to assess the pitch of electrical stimulation by asking MK to match the pitch of signals in his nonimplanted ear to the pitch of signals in his implanted ear.

I. METHOD

A. Subjects

The patient was 69 years old at the time of testing which was 3 months after surgery. His hearing began to deteriorate bilaterally in 1945 from unknown causes. At the time of surgery, 27 September 1990, he evidenced no speech understanding in either ear at 105 dB HL. At that time the thresholds in his to-be-implanted ear were 30 dB HL at 250 Hz and 75 dB HL at 500 Hz. He had no response to frequencies higher than 500 Hz. In his nonimplanted ear, the threshold at 250 Hz was 25 dB HL; the

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threshold at 500 Hz was 50 dB HL. He had no response to frequencies of 1 kHz and above. MK had tried and rejected hearing aids.

It is important to note that MK reported the pitch of sinusoidal electrical stimulation to have **two** distinct components. One was low frequency and "buzzy." This was the component to which signals in the nonimplanted were matched. The other was described as "much higher in frequency," as "off in the distance" and as "less buzzy—more nearly a tone."

B. Implant design

The Ineraid prosthesis consists of (i) six monopolar electrodes implanted in the scala tympani with remote reference; (ii) a percutaneous pedestal to which the electrode wires are attached and (iii) a portable speech processing and electrode stimulation system (Eddington, 1980). The most apical electrode is located about 22 mm from the round window. The electrodes are spaced at 4-mm intervals.

C. Test signals

The target signals were digitally generated sinusoids at 125, 200, 300, and 400 Hz. The signals were output at a 10-kHz sample rate via a 12 bit D/A converter (Data Translation 2801A). The signals were high-pass filtered at 75 Hz and low-pass filtered at 4800 Hz. The signals were 1 s in duration and had an 8-ms rise/fall time. The signals directed to the patient's electrodes were routed first to a custom-built amplifier, to an optical isolation amplifier, and to a current driver before delivery to the electrodes. The signals did not go through the patient's commercial signal processor.

D. Procedure

The experimenter first chose an electrode and a frequency for testing (the frequencies and electrodes were tested in pseudorandom order). Then, MK set the amplitude of the electrical signal to a comfortable level. Next, the electrical signal and an acoustic signal were presented sequentially with a 1-s interstimulus interval and MK adjusted the level of the acoustic signal in his hearing ear (by using an amplifier volume control) to be the same loudness as the signal in his implanted ear.

To begin the pitch-matching task, the software program picked at random a starting frequency either higher or lower (+/−90 Hz, except for 125 Hz were the lowest frequency was 100 Hz) than the frequency of the signal in the patient's implanted ear. Then, the signals for the implanted and hearing ears were presented sequentially with a 1-s interstimulus interval. The patient indicated by keypress whether the signal in the hearing ear was lower or higher than the signal in the implanted ear. If, for example, the response was "higher," then the program reduced the frequency of the signal in the hearing ear. The program required two turnarounds; i.e., responses that signals in the hearing ear were higher than and lower than the signal in the implanted ear, before termination. The step size for changing frequency was 50 Hz at the beginning of the procedure, was changed to 25 Hz when the patient reached the first turnaround, and then was changed to 5 Hz following the second turnaround. The matching task was terminated when the patient indicated verbally that the stimulus in the hearing ear was the same pitch as the stimulus in the implanted ear. The task was self paced and MK could listen to any pair of stimuli as many times as he wished. For each signal, two estimates of best match were made. These estimates were separated by at least a half-hour.

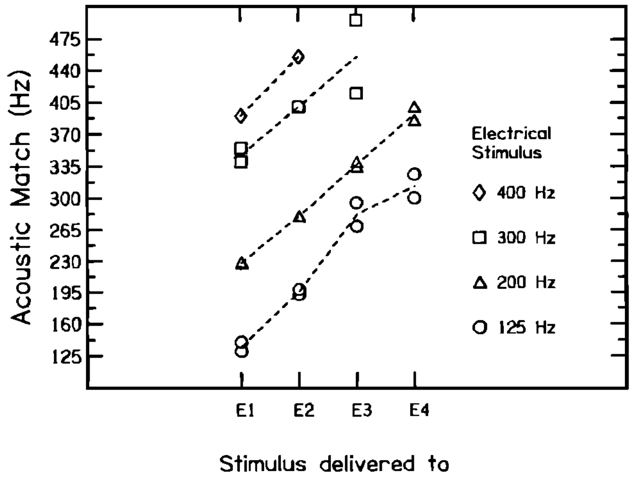

FIG. 1. Pitch matches by patient MK for electrical and acoustic stimulation as a function of the frequency of the electrical stimulus and the stimulating electrode (E1 is the most apical electrode).

II. RESULTS

The results of the pitch matching task are shown in Fig. 1. Both of MK's matches for each target frequency at each electrode are indicated. Although MK verbalized that the task was very difficult, because the target signals (with two perceptual components) sounded qualitatively different than the matching signals (with one perceptual component), the two estimates of a matching pitch were, in most cases, similar. The estimates differed, at most, by 80 Hz (for the 400-Hz signal presented to E3). The majority of estimates differed by less than 15 Hz. In four instances the two estimates were identical (for these instances only one symbol is plotted).

When signals were presented to E1 (the most apical electrode), MK's mean pitch match was 135 Hz to the 125-Hz acoustic stimulus, 228 Hz to the 200-Hz stimulus, 347 Hz to the 300-Hz stimulus and 390 Hz to the 400-Hz stimulus. When the target signals were presented to E2–E4, i.e., electrodes in successively more basal locations, MK's pitch matches increased in frequency. Summed over electrodes, the average change in pitch with a change in electrode location was 57 Hz. The range was 31–87 Hz.

III. DISCUSSION

We indicated in the Introduction that patients fitted with the Ineraid generally report that the pitch of male and female voices is appropriate. MK's pitch matches for sinusoidal stimulation on his most apical electrode are consistent with these reports. For signals of 125 and 200 Hz—frequencies appropriate for male and female voices—MK's average pitch matches were within 10 and 28 Hz, respectively. Thus, for MK, electrical stimulation with a low-frequency sinusoid produces a complex sensation—one component of which is similar in pitch to that produced by acoustic stimulation. Moreover, the low-frequency component of electrically elicited pitch increases in an orderly fashion as more basal electrodes are stimulated.

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Bilger, R., Black, F., Hopkinson, N., Myers, E., Payne, J., and Stenson, N. (1977). "Evaluation of subjects presently fitted with implanted auditory prostheses," Ann. Oto. Rhino. Laryn. 86 (Suppl. 38), 1–176.

Eddington, D. (1980). "Speech discrimination in deaf subjects with cochlear implants," J. Acoust. Soc. Am. 68, 885–891.

Eddington, D., Dobelle, W., Brackmann, D., Mladejousky, M., and Parkin, J. (1978a). "Auditory prosthesis research with multiple channel intracochlear stimulation in man," Ann. Oto. Rhino. Laryn. 87 Suppl., 1–39.

Eddington, D., Dobelle, W., Brackmann, D., Mladejousky, M., and Parkin, J. (1978b). "Place and periodicity pitch by stimulation of multiple scala tympani electrodes in deaf volunteers," Trans. Am. Soc. Art. Intern. Organs 24, 1–5.

Greenwood, D. (1990). "A cochlear frequency position function for several species—29 years later," J. Acoust. Soc. Am. 87, 2592–2605.

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