Pitch Scaling and Speech Understanding by Patients Who Use the Ineraid Cochlear Implant

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ABSTRACT

Pitch scaling was assessed for 10 normal-hearing listeners and 8 patients who use the Ineraid multichannel cochlear implant. For two patients who were excellent users of the prosthesis, pitch increased over a wide range of frequencies (100 Hz to 2333–3000 Hz). For three patients who were above average users of the prosthesis, pitch increased with frequency over a smaller range (100 Hz to 1200–2300 Hz). For three patients who demonstrated poor word recognition ability, pitch increased with frequency over a very small range (100 Hz to 600–1000 Hz). These results suggest that differences in speech understanding among patients who use the Ineraid may be accounted for, in part, by the range of pitch available through the implant.

IN A RECENT REPORT, we described the word identification ability of patients who use the Ineraid multichannel cochlear implant (Dorman et al, 1989b). Test scores ranged from 0 to 60% correct for monosyllabic words and from 0 to 100% correct for spondee words. In this report we describe a factor which may account for some of the differences in performance. That factor is the range of pitch available to the patient through his/her implant.

Speech signals from a male speaker are composed of frequencies over the range approximately 100 to 7000 Hz. Over the lower half of this frequency range, the greater the range of frequencies heard by a listener, the better the speech intelligibility. For example, French and Steinberg (1947) reported approximately 25% intelligibility for syllables low-pass filtered at 1000 Hz; 50% intelligibility for syllables low-pass filtered at 1500 Hz, and 90% intelligibility for syllables low-pass filtered at 3300 Hz.

We suppose that the general relationship between signal bandwidth and speech intelligibility that holds for normal listeners also holds for listeners fitted with a multichannel cochlear implant. That is to say, listeners who can identify only a limited range of pitch through their implant should not recognize speech as well as patients who can identify a wide range of pitch.

For patients who use a multichannel cochlear implant, signal frequency is encoded into the sensation of pitch by rate and rate/place codes. Psychophysical studies using single electrode systems indicate that rate pitch, that is, the pitch which results from neural elements discharging in synchrony to the time wave form of a signal, increases with frequency up to approximately 300 Hz for some patients and up to 1250 Hz for others (Hochmair-Desoyer et al, 1983; Townshend et al, 1987). With multiple electrode systems the potential range of pitch is greater because when signals greater than 300 Hz are presented to basal electrodes they are heard as higher in pitch than signals presented to more apical electrodes (Eddington, 1980).

In this report we describe two experiments which assessed (1) the range of pitch that can be scaled by patients who use the Ineraid implant and (2) the relationship between pitch range and speech understanding. Experiment I was conducted during 1986 by the second author. Experiment II was conducted 3 years later.

EXPERIMENT 1

METHOD

Subjects

Six normal-hearing adults and five adults who use the Ineraid implant served as subjects. All of the normal-hearing listeners passed an auditory screening test at 20 dB HL for frequencies of 0.5, 1, 2, and 4 kHz.

Biographical data on the implanted patients are shown in Table 1. Patients 1 and 2 posted some of the highest scores

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Table 1. Biographical information on implant patients.

Patient	Age	Length of Deafness	Percent Correct Spondee Words	Percent Correct Monosyllables	Percent Correct 12 Vowels
1	32	8	100	52	79
2	21	1	88	48	65
3	58	1	78	36	63
4	50	28	70	28	49
5	55	19	28	2	35
6	55	10	42	16	60
7	48	5	28	0	15
8	66	24	38	22	29

on tests of word and vowel identification of patients who use the Ineraid prosthesis. They were classified as excellent users of the device. Patients 3 and 4 posted above average scores on the vowel and word identification tests [the median score for 50 patients on the Spondee Recognition Test was 44% correct; the median score for the Monosyllabic Word Recognition Test was 14% (Dorman et al, 1989b)]. Patient 5 posted below average scores on the vowel and word recognition tests. Our "clinical" evaluation of the four patients, based on the patients' everyday functioning, was consistent with the grouping of the patients into categories of excellent, above average, and below average.

Little is known of the etiology of deafness of the five patients. For all patients hearing loss was progressive.

Materials

The patients were tested with a battery of subtests selected from the revised MAC battery (Owens, Kessler, Raggio, & Schubert, 1985). The Spondee Recognition Test was composed of 25 words. The Monosyllabic Word Test was composed of 50 words (from the NU 6 list). The Everyday CID Sentence Test consisted of one of four lists of 10 sentences. In each list, 50 words were scored as "key" words.

The Spondee Recognition Test and the Monosyllabic Word Test were administered via tape recorder and loudspeaker at 70 dB SPL. The CID Sentences were administered live voice at the same level. No feedback of correct answers was given for any test in the battery.

A vowel recognition test was composed of the words, "beet, bit, bait, bet, bat, bought, but, boot, Bert, bout, bite, boat" which had been synthesized using the KLATT algorithm (see Dorman, Dankowski, McCandless, & Smith, 1989). All signals had the same length and fundamental frequency contour. The peak SPL, measured at the patient's input microphone, varied less than 1.5 dB across the signals.

Implant Design

The Ineraid implant consists of (1) six monopolar electrodes implanted in the scala tympani with remote reference; (2) a percutaneous pedestal to which the electrode wires are attached, and (3) 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. The four, most apical, electrodes are activated in most patients. Given the depth of insertion of the electrodes and their spacing, we suppose that the band-passed input to each electrode is at least a half-octave or more lower in frequency than the corresponding place of cochlear stimulation.

Each electrode is driven by an analog signal derived from the input signal after the operation of an AGC circuit and band-pass filtering. The AGC circuit has a very rapid attack time and a relatively slow release time. The center frequencies of the filters for channels 1 to 4 (most apical to most basal electrodes) are 0.5, 1, 2, and 3.4 kHz. The filters roll off at 6 dB/octave.

Stimuli

Pure-tone signals of 100 to 3000 Hz in 50 Hz increments through 1300 Hz and in 100 Hz increments from 1300 Hz through 3000 Hz were generated by a Wavetek signal generator under computer control. The output of the signal generator was directed to a headphone (David Clark H3050) customized to fit over the microphone of the patient's portable signal processor.

Procedure

First, all signals were balanced in loudness to a 1 kHz reference tone. Loudness balancing was achieved in the following manner. Each subject set the 1 kHz signal to a comfortable level. Next, pairs of signals consisting of the reference tone and one of the other signals were presented. The subjects were told to use keys on a computer terminal to increase or decrease the level of the second signal until the loudness of that signal was equal to that of the first or reference signal.

The subjects were then presented the lowest frequency signal followed by the highest frequency signal ad libitum. Next, the subjects were told that they would hear signals that varied in frequency between the lowest and the highest frequency and were instructed to assign a number ranging from 1 to 100 to those signals.

The test frequencies were presented in random order. Each stimulus was presented to each listener only once.

RESULTS AND DISCUSSION

Normal-Hearing Listeners

The group mean performance of the normal listeners is shown in Figure 1. The error bars in the figure indicate ±1 SD. The data were fit by a straight line with $r = 0.96$. Thus, under the conditions of this experiment, stimulus frequency and estimates of pitch were related in a linear fashion.

Implant Patients: Reliability

Post hoc inspection of the data from the implant patients indicated that the patients did not form a

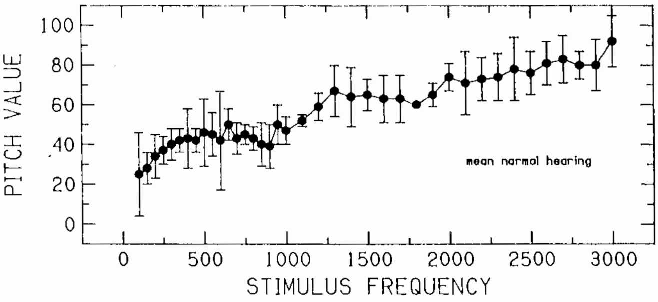

Figure 1. Mean pitch value as a function of frequency for six normal-hearing listeners.

homogenous group. Thus, each patient's data will be described individually.

Because each stimulus was presented only once to a patient, there could be no estimate of variance for the pitch of each stimulus. To obtain an indication of variability in pitch assignment, we have plotted, in Figures 2 to 4, the pitch of adjacent stimuli along the frequency continuum as if the two stimuli were repetitions of the same stimulus. Thus, for example, the pitch values of the 100 Hz stimulus and the 150 Hz stimulus are plotted on the same point on the x axis.

Visual inspection of Figures 2 to 4 suggests that estimates of pitch were reasonably reliable. The estimates appear sufficiently reliable to allow inferences about differences in pitch scaling among patients.

Differences Among Implant Patients

Patients 1 and 2 were classified as being excellent users of the prosthesis. Their data, shown in Figure 2, suggests that pitch increased with frequency over the range 100 to 3000 Hz. Straight lines were fit to the data from each patient with $r = 0.94$ in each case. This outcome suggests that, for these two patients, as for the mean normal patient, pitch and frequency were related in a linear fashion. We do not infer from these data that patients 1 and 2 had normal pitch perception. Rather, we view the data as indicating only that pitch increased with frequency over the range of frequencies tested.

Patients 3 and 4 were classified as above average users of the prosthesis. Patient 3's data, shown in Figure 3, suggests that pitch increased with frequency over the range 100 to approximately 1500 to 2000 Hz. For patient 4 (Fig. 3, *bottom*), there appears to be a maximum in pitch estimate near 1500 Hz with perhaps another maximum near 3000 Hz.

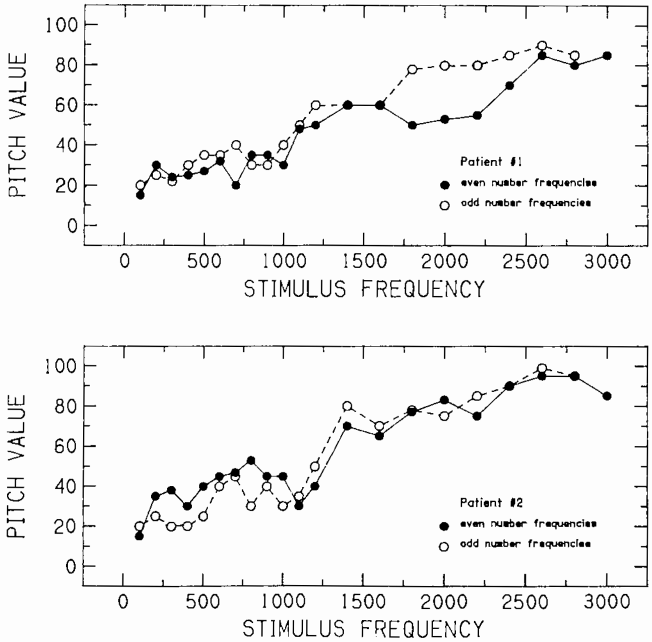

Figure 2. Pitch as a function of frequency for two implant patients who were classified as excellent users of the prosthesis.

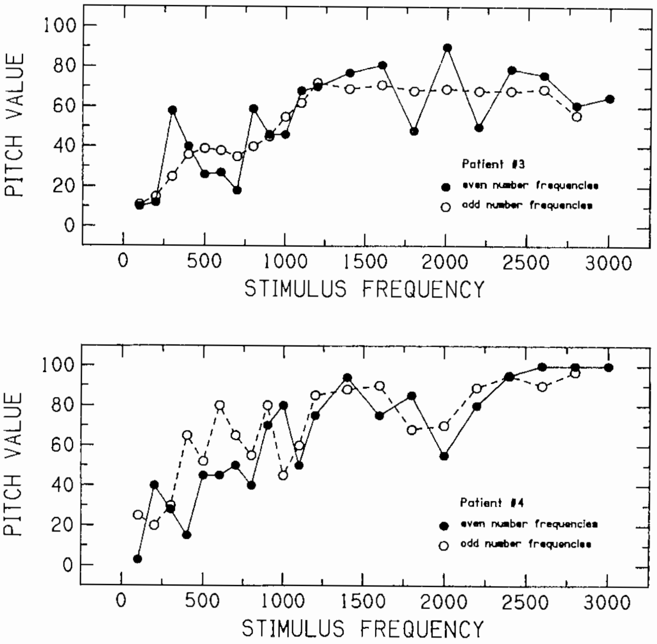

Figure 3. Pitch as a function of frequency for two patients who were classified as above average users of the prosthesis.

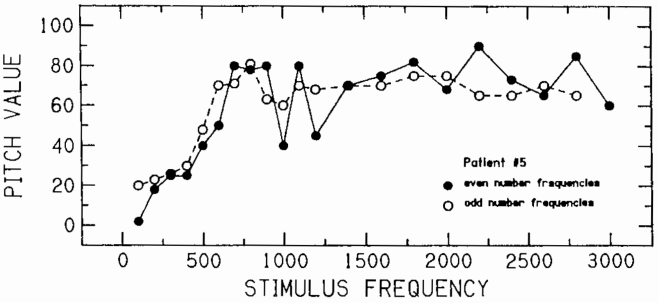

Figure 4. Pitch as a function of frequency for a patient who demonstrated poor vowel and word recognition.

Patient 5 evidenced poor vowel and word recognition scores. Visual inspection of Figure 4 suggests that pitch reached asymptote near 700 Hz.

Although we did not assess the difference limen for pitch for our patients, and, thus, do not have an estimate of frequency resolution, the range of pitch identified by patients 1 to 4 is consistent with excellent and above average speech understanding. The very restricted range of pitch identified by patient 5 is consistent with poor speech understanding. The range of pitch available to this patient is similar to that available to patients with a single channel implant. It is not surprising to find that the patient's word recognition scores are similar to those of many patients fitted with single channel implants.

Although our sample of implant patients was small and the pitch scaling task difficult, the data were orderly and suggest that the range of pitch identified by a listener is related to speech recognition.

EXPERIMENT 2

In experiment 2 we assessed the relationship between stimulus frequency and pitch for two patients who had been tested in experiment 1 and for three new patients. Two aspects of our experimental procedures were changed from those of experiment 1. The stimulus range was extended to 4000 Hz and each stimulus was presented five times so that we could obtain, for each patient, an estimate of the mean pitch value. Our goals were (1) to assess the replicability of the data collected in experiment 1, and (2) to determine whether the data from the new patients would fit into the patterns of results found in experiment 1.

METHOD

Subjects

Four normal-hearing listeners and five implant patients were tested. Patients 1 and 3 were from the group tested in experiment 1. The biographical data for patients 6, 7, and 8 are shown in Table 1. We categorized patient 6 as an above average user of the prosthesis even though her word recognition scores were near the median scores for the word tests and were similar to those of patient 8 who we categorized as a poor user of the prosthesis. Patient 6 was categorized as above average on the basis of her vowel recognition score (60% correct) and on our repeated observation that patient 6 uses the telephone exceptionally well. Patient 8 was categorized as a poor user on the basis of her vowel score (29% correct) and our observation of her everyday functioning. Patient 7, like patient 5 in experiment 1, evidenced relatively poor word recognition scores. The categorization of all patients was accomplished before the pitch scaling data were collected.

The etiology of deafness was known for only one of the three new patients. Patient 8 lost the hearing in each ear following surgery for insertion of a stapes replacement.

Stimuli

The stimuli in experiment 2 were generated in the same manner as in experiment 1. To shorten the task, the stimulus frequencies were at ⅓ octave intervals from 125 to 1000 Hz and at ⅙ octave intervals from 1000 to 4000 Hz.

Procedure

As in experiment 1, all signals were balanced in loudness to a 1000 Hz reference tone. The subjects were then presented five repetitions of the lowest frequency signal followed by the highest frequency signal. Next, the subjects were told that they would hear signals that varied in frequency between the lowest and the highest frequency and were instructed to assign a number ranging from 1 to 100 to those signals.

Each stimulus was presented to each listener five times. The test frequencies were presented in random order.

RESULTS

Normal-Hearing Listeners

The results for the four normal-hearing listeners are shown in Figure 5. Each point in this figure (and in the following figures) reflects the geometric mean of the pitch estimates at that frequency. For all four listeners, pitch increased rapidly with frequency over the range 125 to approximately 667 Hz and then more slowly with frequency to 4000 Hz.

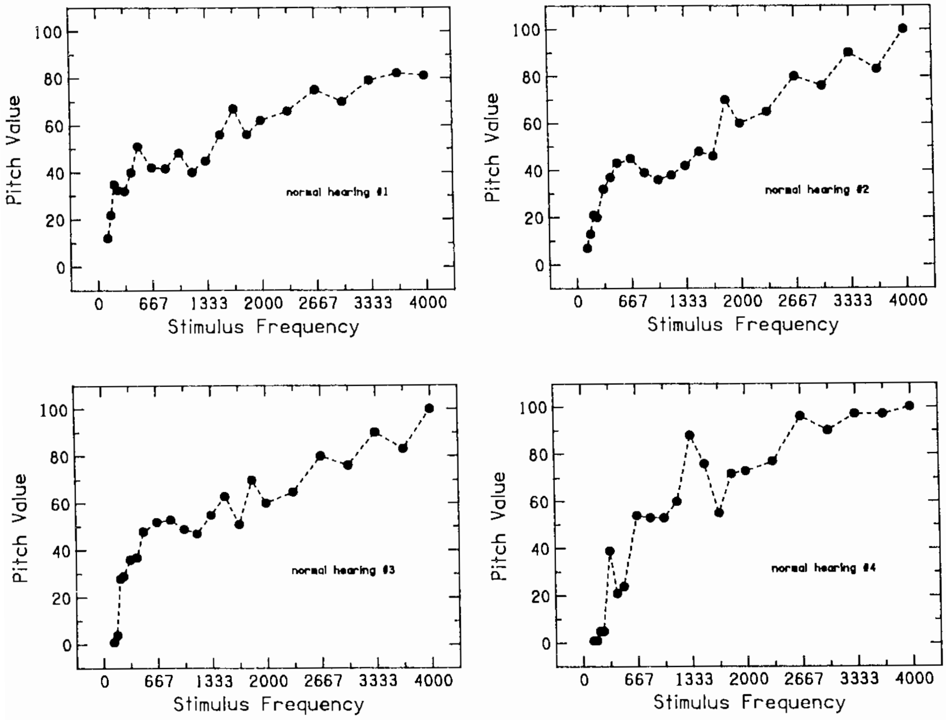

Figure 5. Pitch as a function of frequency for four normal hearing listeners.

In the analysis of our data we made little effort to fit functions or otherwise quantify apparent differences among patients' pitch scaling data. The absence of statistical analysis reflects our belief that the experimental task can provide only a very rough estimate of the range of pitch available to a listener. Future studies using psychophysical tasks which allow finer analyses of pitch scaling should provide better evidence concerning the relationship between pitch range and word recognition among patients who use the Ineraid implant.

We would be surprised if the range of pitch available to patients completely accounted for differences in word recognition. Experiments in progress, which estimate the information available to patients from speech envelope features and which estimate pitch range, should provide an indication of the relative contribution of pitch range to word understanding.

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