Fourth Quarterly Progress Report

June 27 through September 27, 1986

NIH Contract NO1-NS-5-2396

Speech Processors for Auditory Prostheses

Prepared by

Blake S. Wilson, Charles C. Finley and Dewey T. Lawson

Neuroscience Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

CONTENTS

I. Introduction

The purpose of this project is to design and evaluate speech processors for auditory prostheses. Ideally, the processors will extract (or preserve) from speech those parameters that are essential for intelligibility and then appropriately encode these parameters for electrical stimulation of the auditory nerve. Work in the present quarter included the following:

1. Continued evaluation of alternative processing strategies with patient MH, including (a) further studies of idealized versions of the processing strategy used in the Melbourne/Nucleus device, (b) new studies of interleaved-pulses processors whose outputs are coupled to monopolar (as opposed to radial bipolar) electrodes in the implanted electrode array, and (c) studies of processing strategies designed to make channel-specific percepts more distinct than those evoked with "standard" interleaved-pulses or compressed-analog-outputs strategies;

2. Continued psychophysical investigations of the bases and characteristics of loudness and pitch perception in implant patients;

3. Development and testing of new computer programs to support and extend the above psychophysical and speech-perception studies;

4. Continued development of a portable, real-time processor for implementing various multichannel coding strategies;

5. Collaboration with the team at the University of California at San Francisco in the specification of performance characteristics for a new, 8-channel transcutaneous transmission system;

6. Further development of finite-element models of electric field patterns in the implanted ear; and

7. Presentation of project results at the IUPS Satellite Symposium on Advances in Auditory Neuroscience and the Annual Meeting of the American Academy of Otolaryngologists.

In this report we will describe our studies of idealized versions of the processing strategy used in the Melbourne/Nucleus device and outline our plans for the next quarter. Detailed descriptions of the remaining activities indicated in points 1 through 6 above will be presented in future reports. Finally, we want to mention that in this quarter we had very pleasant and productive visits from Hugh McDermott of the University of Melbourne, Jim Patrick of Nucleus Ltd., and Don Eddington of the Eaton-Peabody Laboratory.

II. Evaluation of Idealized "Australian" Processors

The two most-widely used processing strategies for multichannel auditory prostheses are the compressed-analog-outputs strategy, used in the UCSF/Storz and Utah/MIT/Symbion devices, and the "F0/F2" strategy of the Melbourne/Nucleus device (Clark et al., 1983, 1984a and 1984b; Clark and Tong, 1982; Millar et al., 1984; Patrick et al., 1985). The F0/F2 strategy is designed to represent detected approximations to the speech parameters F0 and F2 by (a) selecting a pair of electrodes in a multichannel array according to the frequency of detected F2, where the position of the selected pair corresponds to the tonotopic ranking of pairs across the electrode array, and (b) delivering to the selected pair pulsatile stimuli at a rate proportional to the detected F0. The amplitudes of the pulses are computed with a loudness mapping function (similar but not identical to our logarithmic mapping law described on page 13 of QPR 2, NIH project N01-NS-5-2396) to reflect either the amplitude of the detected second formant (see, e.g., Clark et al., 1983) or the overall envelope of the wide-band speech signal (Clark et al., 1984b). Finally, balanced biphasic pulses are used, and the typical duration of these pulses is 0.2 msec/phase.

To evaluate the potential of the basic coding strategy used in the Australian processor, we decided to use idealized versions of this strategy in which highly-accurate extractions of speech parameters were obtained. In particular, for extractions of F0 and v/uv boundaries we used our previous, semi-automated measurements of these parameters for all tokens of the vowel- and consonant-confusion tests (see pages 28 and 29 of QPR 2, NIH project N01-NS-5-2396, for a complete description of the procedure). Next, detection of the spectral peak in the F2 band was accomplished by sensing the RMS energies in logarithmically-spaced "sub bands" spanning the F2 range. The sub band with the greatest RMS energy in each time frame of ongoing speech was used to select the electrode pair to which the stimulus pulses were to be delivered. Finally, for unvoiced segments a "jittered" representation was used. The range and mean of the instantaneous frequencies of jittered pulses were made to approximate the range and mean of instantaneous frequencies used in the actual Australian processor.

The tested variations of idealized Australian processors included the following:

1. A six-channel processor using radial bipolar pairs, with the frequency band represented by electrode channel selection covering the range from 800 to 4000 Hz (i.e., the "F2 band"), and with the amplitudes of stimulus pulses derived from wide-band (50 - 4000 Hz) RMS energies;

2. A processor identical to the one described in point 1 above, except that the frequency band represented by electrode channel selection was expanded to cover the range from 400 to 4500 Hz;

3. A processor identical to the one described in point 1 above, except that the amplitudes of the stimulus pulses were derived from F2-band (800 - 4000 Hz) RMS energies; and

4. A seven-channel processor using longitudinal bipolar pairs, with the frequency band represented by electrode channel selection covering the range from 800 to 4000 Hz, and with the amplitudes of stimulus pulses derived from the RMS energies in this band.

These variations were selected to evaluate possible differences in performance produced by manipulations in (a) the range of frequencies represented by electrode channel selection; (b) the bandwidth of energies represented by the amplitudes of stimulus pulses; and (c) the configuration used to couple the outputs of the speech processor to the electrode array. The last manipulation was thought to be important because a "longitudinal bipolar" configuration is used in the Melbourne/Nucleus prosthesis. Inasmuch as the electric fields produced by the "radial bipolar" configuration of the UCSF electrode array are sharper (i.e., more spatially selective) than the fields produced by the longitudinal bipolar configurations of either the UCSF or Melbourne electrode arrays (Merzenich and White, 1977; van den Honert and Stypulkowski, 1985), we expected that performance might be affected with changes in the coupling configuration.

The results for all tested variations of idealized Australian processors are presented in Table 1. Also presented in Table 1 are the results from a variation of the "6-of-6-channels," interleaved-pulses processors with explicit coding of F0 and v/uv boundaries (see QPR 2, pp. 28-34, for a full description of such processors). In this variation the frequency range of channel bandpasses was reduced from the wide-band representation used in previous interleaved-pulses processors (from approximately 400 to 4500 Hz) to the "F2 band" representation used in the Australian processors (i.e., from 800 to 4000 Hz). The purpose of including this last strategy was to evaluate the idea that a "dense," interleaved-pulses representation of the spectrum in the F2 band might be superior to the sparse representation of the spectral peak in this band with the Australian processor.

The best variation of the idealized Australian processors was the one in which six channels of radial-bipolar stimulation were used, with the frequency band represented by electrode channel selection covering the range from 800 to 4000 Hz, and with the amplitudes of stimulus pulses derived from the RMS energies in this band (variation 3 in the list on the previous page). The scores for vowel recognition with this processor were good (24/25 with lipreading and 18/25 without lipreading) and the scores for consonant recognition were fair (16/24 with lipreading and 9/24 without lipreading). In all, these scores closely approximated the scores obtained with our "2-of-6-channels," interleaved-pulses processor (i.e., 24/25 and 22/25 for vowels with and without lipreading, and 14/24 and 9/24 for consonants with and without lipreading; see QPR 2, NIH project N01-NS-5-2396, for further details on the performance of interleaved-pulses processors).

To suggest an explanation for this similarity of results between the best variation of the idealized Australian processors and the "2-of-6-channels," interleaved-pulses processor, we note that both of these processors provide relatively-sparse representations of speech spectra (i.e., only one or two channels represent spectral maxima on each update frame for both processors). Previous comparisons of "2-of-6" and "6-of-6" interleaved-pulses processors indicate, however, that while sparse representations of speech spectra may be adequate for transmitting information on vowels, such representations are inadequate for transmitting complete information on consonants. Indeed, this idea is further supported

Table 1

Results from Tests to Evaluate Several Variations of "Idealized" Australian Processors

	VOWELS*		CONSONANTS**		total
processor variation	w. lips	w.o. lips	w. lips	w.o. lips	% correct
Australian processor, pulse amplitudes reflect wide-band RMS energies	21/25	12/25	18/24	11/24	63
same as above, except that the entire F1 + F2 band is spanned, as opposed to F2 only	23/25	16/25	14/24	2/24	56
Australian processor, pulse amplitudes reflect RMS levels of F2 band	24/25	18/25	16/24	9/24	68
Australian processor, pulse amplitudes reflect RMS levels of F2 band, pulses delivered to 7 longitudinal pairs of bipolar electrodes	21/25	20/25	14/24	5/24	61
6-channel, interleaved-pulses processor with explicit coding of F0 and v/uv boundaries, and with channel outputs representing the F2 band only	24/25	21/25	20/24	9/24	76

---

*Chance is 5/25

**Chance is 3/24

by the results obtained with the present "6-of-6-channels," interleaved-pulses processor where the channel outputs represented the F2 band only (see Table 1). The overall performance of this last processor is substantially higher than the overall performance of the best variation of the idealized Australian processors (76% vs. 68%), and the greatest improvement for the "6-of-6-channels" processor is in the category of consonant recognition with lipreading (20/24 vs. 16/24). Moreover, the percepts elicited by the "6-of-6-channels" processor sounded much more natural and speechlike than the percepts elicited with the best Australian processor. The differences in quantitative and qualitative performance for these two classes of speech processors indicate that a high-resolution representation of speech spectra may be essential for natural-sounding percepts and for good recognition of consonants.

The overall scores for the remaining variations of Australian processors were substantially lower than the overall score for the best variation. However, the scores for consonant recognition were somewhat higher (and consequently the scores for vowel recognition lower) with the variation in which the intensities of stimulus pulses reflected wide-band RMS energies rather than the RMS energies in the F2 band. This improvement may have resulted from a better representation of the envelope of the speech signal, a feature known to be important for recognition of consonants (see, e.g., Soli _et al._, 1986). The decline in scores for vowel recognition may have resulted from the "convoluted" representation of formant amplitudes. Specifically, while the position of the spectral peak in the F2 band is represented, the amplitude of this peak is not. Instead, the envelope of the entire speech signal is coded and this envelope level is only indirectly related to the amplitude of F2.

Finally, the manipulations of increasing the range of frequencies represented by channel selection (from 800 - 4000 Hz to 400 - 4500 Hz, see the first two entries in Table 1) or coupling the outputs of the best variation of the idealized Australian processors to longitudinal bipolar pairs (see fourth entry in Table 1) both produce large decreases in overall performance. One possibility for the drop in performance when the range of frequencies represented by channel selection was increased is that the resolution for coding the position of the spectral peak was degraded with this manipulation. Because most of the consonants in our confusion matrix have peaks in the high-band region, this lowered resolution for coding such peaks may have produced highly-similar representations of tokens at the electrode array. Indeed, the score for consonant recognition with lipreading for the the "wide-band" processor was no different than the score obtained on a previous occasion for lipreading alone, and the score for consonant recognition without lipreading was at a chance level.

The decrease in performance found with the longitudinal coupling configuration might simply reflect the relatively-low spatial resolution of electrical excitation with longitudinal bipolar pairs. Even though the number of channels was increased from 6 to 7 in our manipulation of changing the coupling from radial bipolar to longitudinal bipolar, this increase was apparently inadequate to offset the presumably "blurred" representation of spectral peaks with the longitudinal coupling configuration. The addition of many more channels of closely-spaced, longitudinal bipolar pairs may have improved performance. In this regard we note that the Melbourne electrode array has 22 longitudinal bipolar pairs spaced 0.75 mm apart, while the UCSF array has either 8 radial bipolar pairs spaced 2.0 mm apart or 7 longitudinal bipolar pairs also spaced 2.0 mm apart. Our best simulation of the Melbourne electrode array was therefore to use the 7 longitudinal bipolar pairs spaced 2.0 mm apart. It may be that much better results could be obtained in patients implanted with the Melbourne array for favorable cases in which most of the 21 "electrode channels" could be usefully exploited.

In conclusion, we first note that the performance of the Australian processor, as implemented in our idealizations of the real-time processor and electrode array used in the actual device, is moderately good when ranked with the other processors we have evaluated. Specifically, as shown in Table 2, the overall percent correct score of the best variation of idealized Australian processors is substantially lower than the score for the best variation of interleaved-pulses processors, but also significantly higher than the score for the best variation of compressed-analog-outputs processors. Our findings collectively indicate that non-simultaneous stimulation with a relatively-dense representation of the speech spectrum produces superior results for patients who have psychophysical

Table 2. Best results to date from various major classes of processors, Patient MH.

processor class	VOWELS* w. lips	VOWELS* w.o. lips	CONSONANTS** w. lips	CONSONANTS** w.o. lips	total % correct
Compressed analog outputs, 4 channels	20/25	8/25	13/24	7/24	49
4-channel, interleaved-pulses processor	21/25	12/25	17/24	10/24	61
same as above, except that F0 and v/uv boundaries are explicitly coded	22/25	18/25	19/24	11/24	71
6-channel, interleaved-pulses processor	24/25	23/25	20/24	14/24	83
same as above, except that F0 and v/uv boundaries are explicitly coded	24/25	24/25	22/24	17/24	89
Idealized Australian processor	24/25	18/25	16/24	9/24	68

---

*Chance is 5/25

**Chance is 3/24

manifestations of poor nerve survival. For the particular patient described in this report, the spectral representation with the Australian processors was apparently too sparse to support good recognition of consonants. We note, however, that the processing strategy used in the Melbourne/Nucleus prosthesis has recently been modified to include a representation of the first formant (F1). In this "F0/F1/F2" processor separate pairs of electrodes are updated on each stimulus cycle to reflect the frequency positions and intensities of F1 and F2 (McDermott, 1986). Tests with this new processing strategy demonstrate that recognition of both consonants and vowels is significantly improved with the additional coding of F1. Moreover, after a short period of learning and accommodation to the new processing strategy (on the order of one month), patients report that the percepts evoked with the F0/F1/F2 processor sound more natural and speech-like than the percepts evoked with the F0/F2 processor. These results, of higher scores on objective tests of speech recognition and of improved "naturalness" of speech percepts, are fully consistent with the present findings of improved performance with progressively more-dense representations of speech spectra with non-simultaneous stimuli. Our findings further indicate that (a) explicit extraction of formant frequencies is not essential to good performance and (b) a somewhat more-dense representation of speech spectra than that used in the Fo/F1/F2 strategy might produce additional gains in performance, especially for consonants. Finally, we note that excellent performance has been reported for some patients using compressed-analog-outputs processors (see, e.g., Eddington, 1980 and Schindler *et al.*, in press). This performance may reflect a favorable pattern of nerve survival inasmuch as our patients with poor nerve survival do not obtain good results with compressed-analog-outputs processors. Until we can evaluate the performance of interleaved-pulses processors and idealized Australian processors in patients with good nerve survival, we will not know whether such processors are inferior or superior to compressed-analog-outputs processors for these fortunate patients. For the present, though, it seems clear that good performance in at least some patients with poor nerve survival can be obtained with (a) the use of non-simultaneous stimuli, to realize a substantial "release" from temporal channel interactions, and (b) a high rate of channel updates, to improve the temporal and spectral resolutions of represented speech sounds.

III. Plans for the Next Quarter

The major activity of the next quarter will be continued testing of patient MH. We expect to complete our work on the development of a portable processor for her to use away from the laboratory, and expect to continue psychophysical and speech-perception studies. In addition, we plan to evaluate the performance of interleaved-pulses, idealized Australian and compressed-analog-outputs processors with most of the subtests of the Minimal Auditory Capabilities battery (the "MAC" test) and with some of the supplementary tests to this battery developed by the implant team at the University of Iowa. Finally, we expect to resume our studies of electric field patterns in the implanted ear (first done with patient SG) and to begin new investigations aimed at the measurement and interpretation of intracochlear evoked potentials.

In addition to the above tests with patient MH, a patient implanted elsewhere with the single-channel, 3M/Vienna device will be visiting our laboratory for evaluation of alternative processing strategies. None of his scores is above chance with his present processor, and our hope is that an alternative strategy will produce a better result. The alternative strategies will include (a) single-channel variations of the "Breeuwer/Plomp processor" described on pages 12-15 of our second QPR for this project; (b) variations of the "F0" strategies used for single-channel stimulation by the English group; and (c) various "hybrid" strategies designed to code F0 and F2 on a single channel of stimulation by ringing a filter, whose center frequency is proportional to F2, with a pulse train whose frequency is proportional to F0.

IV. References

Clark, G.M., Crosby, P.A., Dowell, R.C., Kuzma, J.A., Money, D.K., Patrick, J.F., Seligman, P.M. and Tong, Y.C., The preliminary clinical trial of a multichannel cochlear implant hearing prosthesis, J. Acoust. Soc. Am., 74 (1983) 1911-1914.

Clark, G.M. and Tong, Y.C., A multiple-channel cochlear implant: A summary of results for two patients. Arch. Otolaryngol., 108 (1982) 214-217.

Clark, G.M., Tong, Y.C. and Dowell, R.C., Comparisons of two cochlear implant speech-processing strategies, Ann. Otol., 93 (1984a) 127-131.

Clark, G.M., Tong, Y.C., Patrick, J.F., Seligman, P.M., Crosby, P.A., Kuzma, J.A. and Money, D.K., A multi-channel hearing prosthesis for profound-to-total hearing loss, J. Med. Eng. Technol., 8 (1984b) 3-8.

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

McDermott, H.J., Speech processors for auditory prostheses, presented at the 17th Annual Neural Prosthesis Workshop, Bethesda, MD, Oct. 15-17, 1986.

Merzenich, M.M. and White, M., Cochlear implants: The interface problem. In F.T. Hambrecht and J.B. Reswick (Eds.), Functional Electrical Stimulation: Applications in Neural Prostheses, Marcel Dekker, New York, 1977, pp. 321-340.

Millar, J.B., Tong, Y.C. and Clark, G.M., Speech processing for cochlear implant prostheses, J. Speech and Hearing Res., 27 (1984) 280-296.

Patrick, J.F., Seligman, P., Tong, Y.C. and Clark, G.M., Speech processing method and apparatus, U.S. Patent 4,515,158 (May 7, 1985).

Schindler, R.A., Kessler, D.K., Rebscher, S.J. and Yanda, J., The University of California, San Francisco/Storz cochlear implant program, Otolaryngologic Clin. N. Amer., in press.

Soli, S.D., Arabie, P. and Carroll, J.D., Discrete representation of perceptual structure underlying consonant confusions, J. Acoust. Soc. Am., 79 (1986) 826-837.

van den Honert, C. and Stypulkowski, P., Spatial mapping of electrical excitation patterns within the cochlea derived from single fiber responses, ARO Abstr., 8th Midwinter Res. Conf., 1985, p. 106.

Appendix 1

Summary of Reporting Activity for the Period of June 27 through September 27, 1986, NIH Contract NO1-NS-5-2396

The following major presentations were made in the present reporting period:

Wilson, BS: Ensemble models of neural discharge patterns evoked by intracochlear electrical stimulation. Invited speaker presentation at the IUPS Satellite Symposium on Advances in Auditory Neuroscience, San Francisco, CA, July 8-11, 1986.

Finley, CC and BS Wilson: Field patterns in the electrically-stimulated human cochlea, IUPS Satellite Symposium on Advances in Auditory Neuroscience, San Francisco, CA, July 8-11, 1986.

Wilson, BS: Processing strategies for cochlear implants. Invited faculty lecture for the special course on cochlear implants at the Annual Meeting of the American College of Otolaryngologists, San Antonio, TX, Sept. 18-19, 1986.

In addition to these presentations, the following paper has been accepted for presentation at the next national meeting of the Triological Society:

Wilson, BS, CC Finley, JC Farmer, Jr., BA Weber, DT Lawson, R Wolford, PD Kenan, MW White, MM Merzenich and RA Schindler: Comparative studies of speech-processing strategies for cochlear implants, to be presented at the 90th Annual Meeting of the Triological Society, Denver, CO, April 28-30, 1987.

Selected abstracts of the presentations just listed are shown on the remaining pages of this Appendix.

Comparative Studies of Speech-Processing Strategies for Cochlear Implants

BS Wilson, CC Finley, JC Farmer, Jr., BA Weber, DT Lawson, R Wolford and PD Kenan (Center for the Severly Hearing Impaired, Duke University Medical Center, Durham, NC and Research Triangle Institute, Research Triangle Park, NC); MW White, MM Merzenich and RA Schindler (Coleman and Epstein Labs and Dept. of Otolaryngology, University of California at San Francisco, San Francisco, CA).

In recent studies of two implant patients fitted with percutaneous cables, our teams at UCSF and Duke have evaluated 14 major classes of speech-processing strategies for multichannel auditory prostheses. The performance of each strategy was measured with tests of vowel and consonant confusions, with and without lipreading. The processing strategies included the compressed-analog-outputs strategy of the present UCSF/Storz prosthesis: interleaved-pulses processors in which the amplitudes of non-simultaneous pulses code the levels of RMS energies in logarithmically-spaced bands across the spectrum of the first and second formants of speech; and idealized versions of the processing strategy used in the present Melbourne/Nucleus device. For these two patients, both implanted with the UCSF electrode array and both with various psychophysical manifestations of poor nerve survival, speech recognition scores were significantly higher with the interleaved-pulses processors than with all alternative strategies (performance of the Australian processor was not evaluated with the first patient). Moreover, the percepts elicited by the interleaved-pulses processors were always described by both patients as being more natural and speechlike than the percepts elicited with the other processors. We believe the two most-important ingredients for the superior performance of the interleaved-pulses processors are (1) use of non-simultaneous stimuli, to obtain a substantial "release" from temporal channel interactions, and (2) a high rate of channel updates, to improve the temporal and spectral resolutions of represented speech sounds. These elements are not combined in any commercially-available auditory prosthesis; indeed, both these patients with poor nerve survival would have had only a poor-to-moderate outcome with a "standard" clinical device. Because our studied population of patients is small, we do not know at this time whether one processing strategy will emerge as superior for all patients. It may be that a completely different class of processors would work best for more-fortunate patients with good nerve survival. For example, the excellent results from approximately half of the patients in the UCSF series strongly indicate that a compressed-analog-outputs strategy may be as good as or better than an interleaved-pulses strategy for cases in which nerve survival is good. We are anxious to test such a patient to evaluate this hypothesis. In the interim, however, the major lessons to us are that (1) different processing strategies can produce widely-different outcomes for individual patients; (2) interleaved-pulses processors are far superior to other processors for at least two patients with poor nerve survival; (3) processors other than the interleaved-pulses processors may be superior for patients with good nerve survival; and (4) therefore it is important not to have an "adopted religion" for a single strategy of speech processing for auditory prostheses.

[This work was supported by NIH contracts N01-NS-2356 and N01-NS-5-2396.]

'61

Ensemble Models of Neural Discharge Patterns Evoked by Intracochlear Electrical Stimulation

Blake S. Wilson and Charles C. Finley

Neuroscience Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

SUMMARY

Models of the ensemble response of the auditory nerve for intracochlear electrical stimulation can be constructed by coupling a mathematical description of electric field patterns in the ear with a mathematical description of neural responses elicited by such fields. In this presentation we will describe three classes of ensemble models and then apply the simplest of these to predict responses to transient stimuli. This last model consists of an exponential-falloff model of the electric field and a strength-duration model of neural responses. The results suggest, in part, that control of the fine temporal structure of discharges in the electrically-evoked neural volley may provide improved coding of fundamental attributes of the auditory stimulus such as frequency and intensity. In addition, the model illustrates effects of (1) manipulation of pulse parameters on neural response fields; (2) simultaneous stimulation of adjacent channels in a multichannel electrode array; and (3) a heterogeneous neural population on response fields elicited by bipolar and monopolar stimulation. Finally, model results suggest ways in which good performance might be obtained in certain "star" patients with single-channel devices or with multichannel devices using monopolar electrodes.

[This work was supported by NIH contracts N01-NS-2356 and N01-NS-2396-5]

FIELD PATTERNS IN THE ELECTRICALLY-STIMULATED HUMAN COCHLEA.

C.C. Finley and B.S. Wilson, Neuroscience Program Office, Research Triangle Institute, North Carolina, U.S.A.

Knowledge of field patterns within the electrically-stimulated cochlea may provide a basis for improved designs of auditory prostheses. In particular, by knowing the basic mechanisms that govern and limit control of excitation, steps may be taken to reduce channel interactions, eliminate spurious pain stimulation, and/or reduce covariation of pitch and loudness percepts, to name a few. We have employed two approaches to address the question of field patterns in the human cochlea.

One approach is the development of a finite-difference mathematical model to predict the field generated by a specified stimulus. The model is described and predictions for a simple stimulus are presented.

The other approach is the direct recording of field patterns in the human cochlea in patients implanted with a percutaneous cable. Sinusoidal, subthreshold stimuli are applied and the resulting artifact potentials at non-stimulated electrodes are recorded. Initial results are presented.

Finally, comparision of the model predictions and the measured results are made. Initial results suggest good correlation between the two approaches.

Fifth Quarterly Progress Report

September 26 through December 26, 1986

NIH Contract N01-NS-5-2396

Speech Processors for Auditory Prostheses

Prepared by

Blake S. Wilson, Charles C. Finley and Dewey T. Lawson

Neuroscience Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

1.

CONTENTS

I. Introduction

The purpose of this project is to design and evaluate speech processors for auditory prostheses. Ideally, the processors will extract (or preserve) from speech those parameters that are essential for intelligibility and then appropriately encode these parameters for electrical stimulation of the auditory nerve. Work in the present quarter included the following:

1. Continued psychophysical investigations of the bases and characteristics of loudness and pitch perception in implant patients;

2. Initiation of a new series of studies with six patients implanted with the 4-channel UCSF/Storz auditory prosthesis, to compare the performance of each patient's compressed-analog-outputs processor (the UCSF/Storz processor) with the performance of the interleaved-pulses processors developed in this project (see QPRs 2 and 4, NIH project N01-NS-5-2396);

3. Evaluation of alternative processing strategies for a patient implanted with the single-channel, extracochlear 3M/Vienna auditory prosthesis;

4. Development and testing of new computer programs to support and extend the above psychophysical and speech-perception studies;

5. Continued development of hardware and software for implementing various multichannel and single-channel coding strategies in portable, real-time processors;

6. Continued collaboration with the team at the University of California at San Francisco on the specification of performance characteristics for a new, 8-channel transcutaneous transmission system; and

7. Presentation of project results in a site visit for NIH representatives and in various conferences and symposia (see Appendix 1).

In this report we will describe recent psychophysical studies on loudness and pitch perception with cochlear implants. Detailed descriptions of the remaining activities indicated in points 2 through 6 above will be presented in future reports.

II. Studies of Loudness and Pitch Perception with Cochlear Implants

The fundamental dimensions of auditory perception for steady-state stimuli are loudness, pitch and timbre. Temporal variations of these three percepts convey the information and meaning coded in speech and other complex sounds. Not surprisingly, then, a basic problem in the design of speech processors for auditory prostheses is to provide means for exploiting and controlling the full range of loudness, pitch and timbre percepts available to implant recipients. A first step toward solution of this problem is to characterize the percepts obtained under various conditions of steady-state electrical stimulation. In the present studies, we used the method of magnitude estimation to ask our patient MH to report her judgments of loudness and pitch under conditions of (1) bipolar coupling of pulse-train stimuli to different radially-oriented pairs of electrodes in the UCSF array; (2) monopolar coupling of these stimuli to the "lateral" electrodes in this array; and (3) different frequencies of pulsatile stimulation within bipolar and monopolar "electrode channels." Among many other findings, the results demonstrate striking differences in the patterns of loudness and pitch judgments for bipolar and monopolar stimulation. These results, along with implications for the design of speech processors, will be presented in this report.

Methods

All studies were conducted with our present cable patient (MH). Her case history is outlined in our second quarterly progress report for this project. Briefly, she was implanted with the UCSF electrode array in February, 1986, and a percutaneous cable was fitted at the time of surgery to allow subsequent direct access to the intracochlear electrodes. She has participated in an extensive series of psychophysical and speech-perception studies since mid-March, 1986. Results of the psychophysical studies to date strongly indicate that she has sparse survival of neuronal elements in her implanted ear (see QPR 2, NIH project N01-NS-5-2396, pp. 4-5).

Although MH represents one case on the poor-nerve-survival end of the spectrum of implant patients, her percutaneous cable provides a unique opportunity to evaluate differences in the percepts produced by bipolar and monopolar coupling configurations. Specifically, stimuli can be delivered to the offset radial bipolar pairs of the UCSF electrode array for spatially-selective excitation of remaining neural elements (Merzenich and White, 1977; van den Honert and Stypulkowski, 1985), or stimuli can be delivered between an intracochlear electrode and remote reference electrode for broad, "monopolar" excitation of the nerve. To our knowledge only one other study has been performed to compare percepts obtained under conditions of bipolar and monopolar stimulation (Shannon, 1983). The present study adds a case to Shannon's three patients, and extends the previous study by increasing the number of tested conditions.

The basic paradigm used for all studies reported here was that of magnitude estimation. In response to each stimulus presentation, MH was asked to report simultaneously her judgments of loudness and pitch by placing an electronic pointer at the appropriate location on a bit pad with labeled loudness and pitch coordinates. The appearance of the labeled bit pad was similar to that shown in the graph of Fig. 2. Loudness estimates ranged between zero and five, and pitch estimates ranged between zero and ten. The pitch estimates were later normalized to values between zero and one for the purpose of graphing the results. Finally, a box labeled "did not hear" was provided on the bit pad so that the subject could identify stimuli as inaudible.

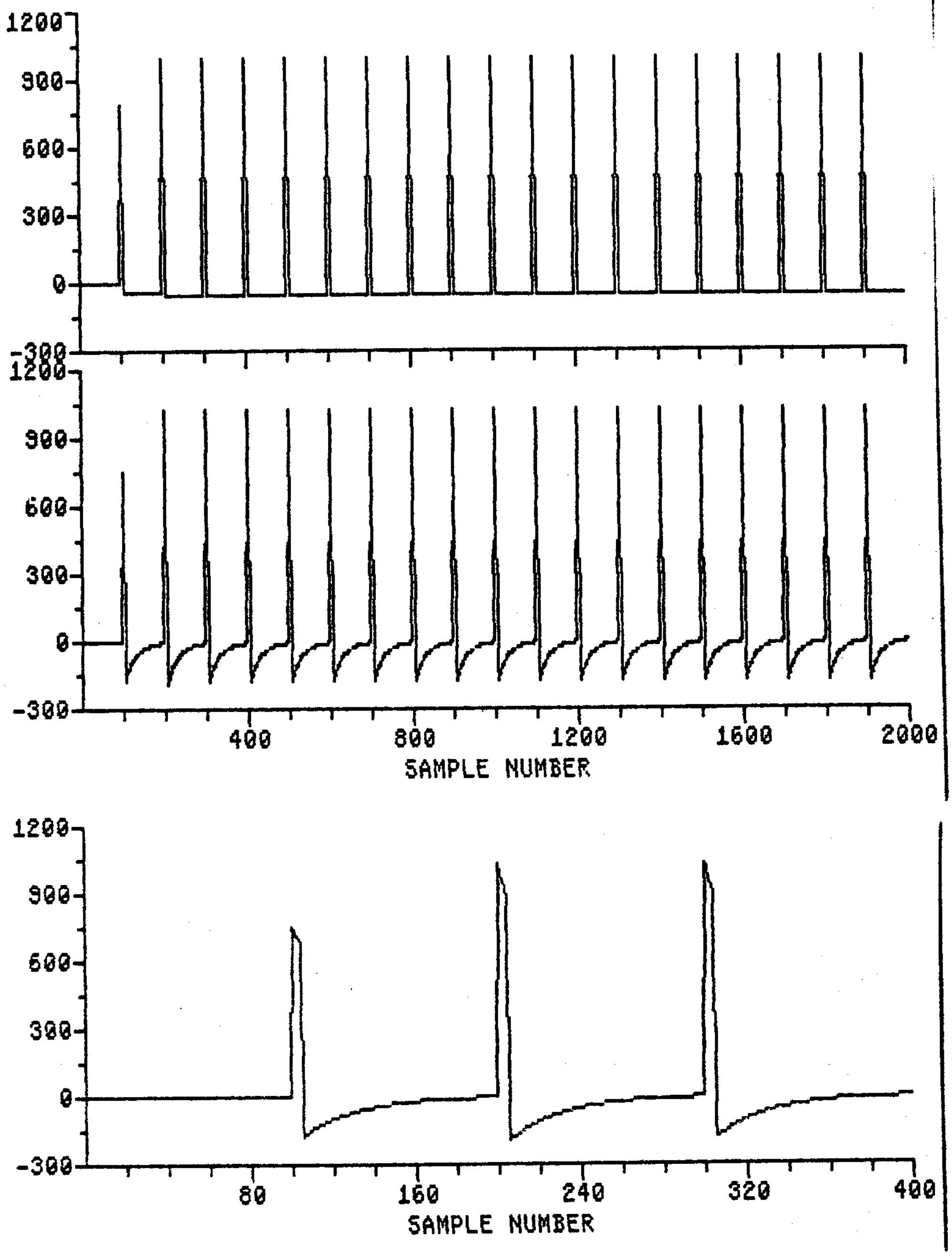
At the beginning of the studies MH was instructed to report her loudness judgments on the scale of zero to five, where a "0" judgment corresponded to a "just audible" percept and a "5" judgment corresponded to a percept at "maximum comfortable loudness." During the course of testing MH remarked that she would assign a "1" to "soft sounds," a "3" to "moderately-loud sounds," and a "4" to "loud sounds." MH was encouraged to make as finely-graded judgments as she could, and she generally gave her reports in quarter-interval steps (e.g., "2 and 3/4").

For the assignment of numbers to pitch judgments, MH was instructed to think of a piano keyboard and to assign a "0" for an extremely-low pitch beyond the left end of the keyboard and a "10" for an extremely-high pitch beyond the right end of the keyboard. MH played piano as a child (she lost her hearing at age 27) and seemed to have no difficulty with this scale. However, like other cochlear-implant patients, MH remarked that her percepts did not have the "pure tone" quality of sounds she remembered from the piano and other musical instruments.

The stimuli used in the present studies were trains of charge-balanced, "monophasic-like" pulses. The derivation of such stimuli is illustrated in Fig. 1. First, a 300 msec train of true monophasic pulses is generated. Then the charge in each pulse (the product of intensity and duration) is calculated and the time between the offset of the pulse and the onset of the following pulse is used for a compensation phase to balance charge. The compensation phase has the same charge as the leading phase, but is opposite in polarity and longer in duration. A typical waveform for this "software balanced" pulse trian is shown in the top panel of Fig. 1. Next, to ensure further that the net charge delivered to the electrodes is exactly zero, the stimulus isolation unit (see QPR 2, NIH project N01-NS-2356) has two stages of high-pass filtering. The first stage is in the signal path leading to the constant-current driver, and the second stage is in the capacitive coupling of both sides of the constant-current output to the selected pair of electrodes in the implanted electrode array. The corner frequency of these two stages of filtering approximates 60 Hz. Typical waveforms of stimuli at the electrodes, after high-pass filtering at 60 Hz, are shown in the bottom two panels of Fig. 1.

"Monophasic-like" pulse trains of the form illustrated in Fig. 1 were used in the present studies because such stimuli have been found to be more useful than intensity- and duration-balanced biphasic pulses in speech processors for MH (see QPR 2, NIH project N01-NS-2396). In particular, monophasic-like stimuli (of one polarity) have a lower threshold and wider dynamic range than intensity- and duration-balanced pulses. Moreover, intensity- and duration-balanced pulses elicit pain percepts at relatively-low thresholds on some of MH's channels of bipolar stimulation. Under certain conditions of pulse duration and channel selection, intensity- and duration-balanced pulses can elicit mild pain percepts at thresholds below the thresholds of auditory percepts. Therefore, to relate the results of the present psychophysical studies to the design of speech processors for MH, we decided to use "monophasic-like" pulse trains in the psychophysical studies. We plan to use intensity- and duration-balanced pulses and sinusoidal stimuli (on channels where pain can be avoided) in future studies.

Finally, the "monophasic-like" stimuli just described were delivered to MH's implanted electrode array via a connector box and the percutaneous



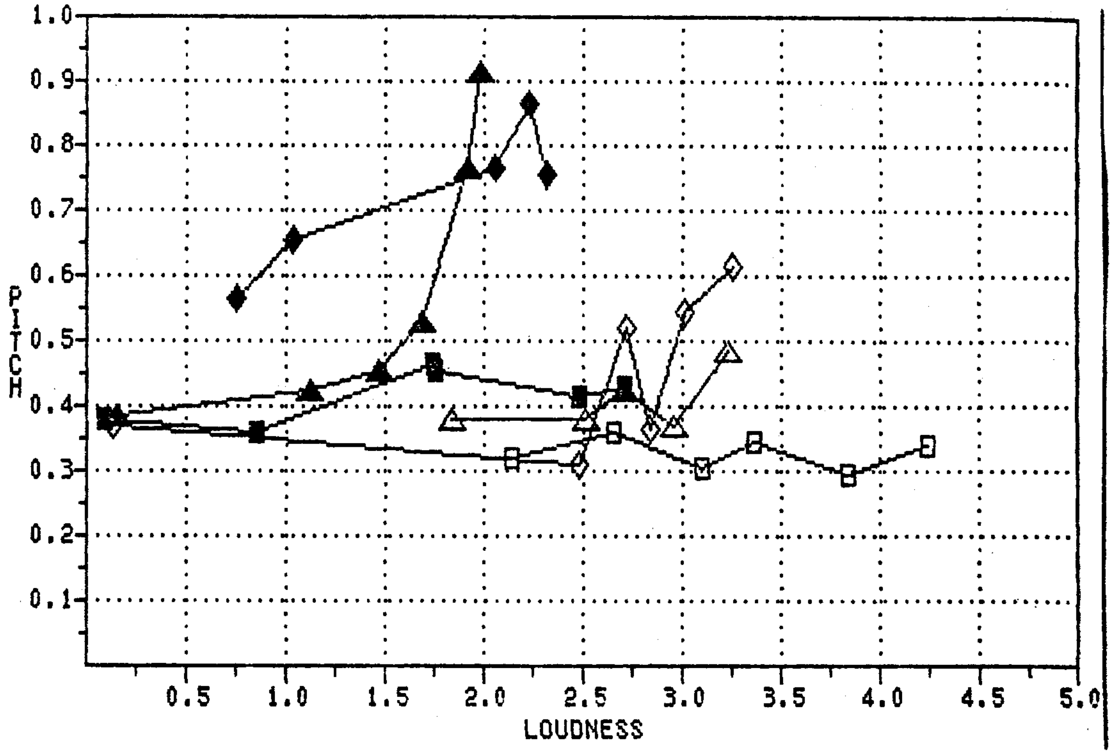
Derivation of "Monophasic-Like" Stimuli

Fig. 1. Waveforms of "monophasic-like," charge-balanced pulses. Top panel shows a train of pulses presented at the rate of 100 Hz, with each pulse consisting of a 0.5 msec leading phase and a 9.5 msec following phase of opposite polarity. Charge balancing is achieved by making the absolute values of the product of intensity and duration equal for both phases. This balancing is done in software. Charge balancing is further ensured by high-pass filtering the stimuli (at approximately 60 Hz) prior to delivery at the electrodes; this filtering is done in the stimulus-isolation unit. The effect of high-pass filtering on stimulus waveforms is shown in the middle panel. Finally, the bottom panel shows the filtered waveforms on an expanded time scale.

cable. The connector box provided a labeled jack for each of the 16 electrodes in the intracochlear array and one additional reference electrode implanted in the middle ear. The labels for the intracochlear electrodes were arranged in ascending order from apex to base, so that the apical-most electrode in the array was labeled as electrode 1 and the basal-most electrode in the array was labeled as electrode 16. In this study constant-current outputs were coupled to the "offset radial" bipolar pairs of the UCSF array (Loeb et al., 1983) in one configuration (e.g., to pair 1-2) and to the "lateral" electrodes and the remote reference electrode in another configuration (e.g., to pair 1/Ref). These coupling configurations are referred to as "bipolar" and "monopolar" respectively in the remainder of this report.

Bipolar Stimulation

Average judgments of loudness and pitch for bipolar stimulation using 100 Hz pulse trains are shown in Fig. 2; all conditions of the experiment are presented in the figure caption. In general, a complicated pattern of loudness and pitch judgments is evident. Prominent features of this pattern include (1) a clustering of pitch judgments for the apical four channels for loudnesses below 3.0; (2) strong covariances between loudness and pitch for the basal two channels; (3) higher judgments of pitch for channel 5 than for channel 6 over most of the measured range; and (4) a widening range of pitch judgments with increases in loudness, mainly due to the covariances of loudness and pitch on channels 5 and 6. The pattern in Fig. 2 is far from the ideal pattern for the independent coding of loudness and pitch according intensity and site of stimulation. In the ideal situation stimulation of a given channel would always produce the same pitch for all loudnesses, and the pitch elicited by stimulation of any one channel would be distinct from the pitches elicited by stimulation of any of the remaining channels (i.e., the ideal pattern would be one of horizontal lines on the loudness-pitch plane, where each line is separated from its nearest neighbors by at least one standard-error-of-the-mean of pitch judgments for that channel). Obviously, the representation of loudness and pitch for MH is much more complicated than the ideal pattern.



Judgments of Loudness and Pitch, Bipolar Pairs, 100 Hz

Fig. 2. Judgments of loudness and pitch for 300 msec bursts of "monophasic-like" pulses presented to different bipolar pairs of electrodes in the UCSF electrode array. The pulse repetition frequency was 100 Hz, and the initial phase of each pulse was 0.5 msec in duration (see Fig. 1). The judgments of loudness and pitch were obtained using the method of magnitude estimation; both the intensities of stimulation within channels and the channel to which each stimulus was delivered were randomized across presentations. Six linear steps of intensity between a minimum current (for the leading phase of each pulse) and a maximum current were used for each channel. The electrode assignments, symbol, minimum current and maximum current used for each of the six channels of stimulation are tabulated below:

Ch	pair	symbol	min uA	max uA
1	1-2	□	98	500
2	5-6	◇	125	1000
3	7-8	△	98	1000
4	11-12	■	195	1000
5	13-14	◆	62	250
6	15-16	▲	98	195

Finally, the number of trials per condition was six, producing a total of 216 presentations for the test. Standard deviations for loudness and pitch, along with the number of responses for each condition (not all stimuli were heard, especially at the lowest intensity levels), are presented in Table 1 of Appendix 2.

The complexity of pitch and loudness judgments for MH is further illustrated in Fig. 3 and Table 1. Fig. 3 shows the averages and standard deviations of pitch judgments across channels for bipolar stimulation at 100 Hz. The curves for the different symbols in Fig. 3 indicate pitch judgments for different ranges of loudnesses. These curves highlight several interesting features of the data first presented in Fig. 2. One such feature is the observation that discrimination of channels on the basis of pitch is a strong function of loudness. For "soft" loudnesses between 0.5 and 1.5, none of the channels can be discriminated from each other on the basis of absolute pitch judgments. However, for higher loudnesses (and for the combined condition of all loudnesses), the analysis presented in Table 1 suggests that four cochlear regions can be discriminated. In Table 1 the channels are ranked according to ascending judgments of average pitch, and the adjacent pitch rankings are compared for discriminable differences using a two-tailed t test.* The comparisons indicate that (1) the pitches elicited by stimulation of channel 1 are discriminable from the pitches elicited by stimulation of the other channels; (2) the pitches elicited by stimulation of channels 2, 3 and 4 are not discriminable from each other; and (3) the pitches elicited by stimulation of channels 5 and 6 are discriminable from each other and from all other channels.

In summary, the results presented in Figs. 2 and 3 indicate that the <u>place</u> of stimulation (i.e., channel) is not a strong predictor of pitch for MH. For low loudnesses stimuli delivered to different channels do not elicit statistically-different pitch percepts, and at moderate and higher loudnesses the distinction of four regions of cochlear excitation is mainly attributable to strong covariances between loudness and pitch on the basal two channels. In fact, if all channels exhibited the same covariance between loudness and pitch, then no opportunity would exist for coding pitch by place of stimulation.

---

*Because the multiple conditions of channel number should be included in the comparisons, a full statistical treatment of these data would require an analysis-of-the-variance (ANOVA) procedure. However, for the present purpose a series of simple t tests provides a useful indication of channel discriminations.

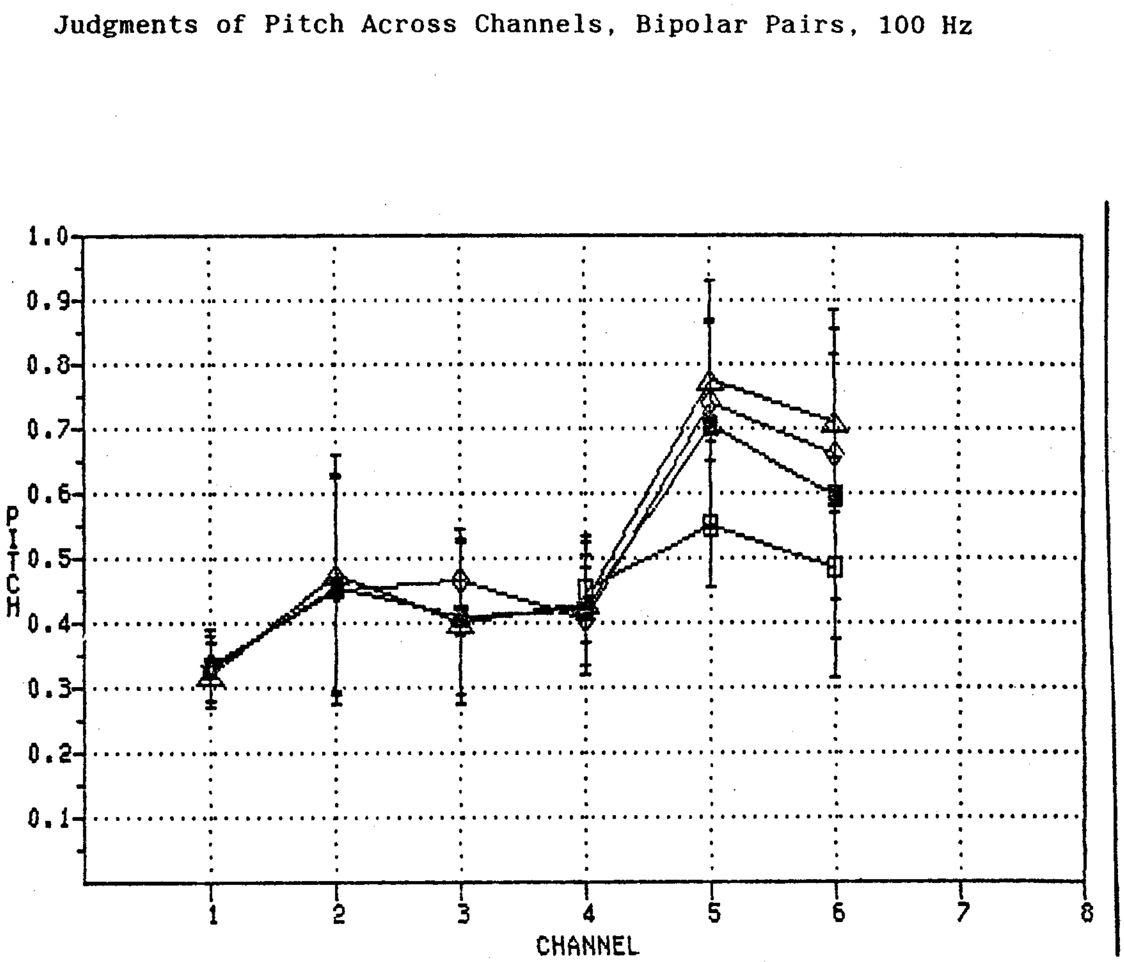


Fig. 3. Averages and standard deviations of pitch judgments across channels for the data shown in Fig. 2. The curves for different symbols refer to pitch judgments for different ranges of loudnesses. The loudness ranges are as follows:

symbol	loudness range
■	all
□	0.5-1.5
◇	1.5-2.5
△	2.5-3.5

Average pitch, standard deviation and number of responses for each condition are presented in Table 2 of Appendix 2.

Table 1. Analysis of pitch judgments across channels, bipolar pairs, 100 Hz, all loudnesses.*

Chan	Pitch	SD	N	T	dF	P
1	.328	.050	36			
3	.408	.155	32	2.93	66	<.01
3	.408	.155	32			
4	.420	.086	34	0.39	64	NS
4	.420	.086	34			
2	.457	.166	35	1.16	67	NS
2	.457	.166	35			
6	.595	.222	33	2.91	66	<.01
6	.595	.222	33			
5	.705	.159	31	2.28	62	<.05

---

*Notes: (1) Abbreviations are Chan for Channel, SD for standard deviation, N for number of trials, T for the value of the student's t statistic, dF for degrees of freedom, and P for the probability value; and (2) channels are ranked according to ascending judgments of pitch.

Although Figs. 2 and 3 demonstrate effects of place and intensity of stimulation on loudness and pitch judgments, they do not show possible effects of frequency of stimulation on these judgments. A general finding for cochlear-implant patients is that judgments of pitch increase with stimulus frequency up to a limit of "pitch saturation" at about 300 Hz (see, e.g., Shannon, 1983; Pfingst and Rush, 1987; Eddington *et al*., 1978a; Simmons, *et al*., 1979). Therefore, to demonstrate possible effects of stimulus frequency on pitch and loudness for bipolar stimulation, we repeated the experiment of Figs. 2 and 3 using the pulse repetition frequency of 300 Hz. We expected that judgments of pitch across the channels would be higher with the stimulation frequency of 300 Hz, and that the patterns of loudness and pitch judgments might be different for the 100 Hz and 300 Hz conditions.

The results of the experiment using 300 Hz stimuli are presented in Figs. 4 and 5. The pattern of loudness and pitch judgments in Fig. 4 appears to be even more complicated than the pattern in Fig. 2 for the 100 Hz condition. In both figures strong covariances between loudness and pitch are found for the basal two channels; however, for the 300 Hz case (Fig. 4) the loudness-pitch curves for these channels are not monotonic. Specifically, pitch rises rapidly with loudness up to a loudness of about 0.7, then a sharp dip in pitch occurs at slightly greater loudnesses, and finally pitch again rises rapidly for loudnesses above 1.0. The pitch judgments at the "dips" in the curves for channels 5 and 6 are significantly different from the neighboring pitch judgments. In addition, a non-significant dip in pitch is found for channel 4 at the same loudness location (i.e., around a loudness of 0.7). In all cases increases in stimulus intensity produced monotonic increases in pitch and slight decreases in loudness in the region of the dip (see Table 3 of Appendix 2). Therefore, the "distortions" in the loudness-pitch curves are a consequence of nonmonotonicities in the loudness-growth functions for the basal three channels.

Another feature of interest in Fig. 4 is the clear covariance between loudness and pitch for channel 2. At loudness levels above 2.5 the pitch judgments for channel 2 are significantly greater than the pitch judgments for channels 3 and 1. The higher pitch judgments for channel 2 compared with those for channel 3 constitute a reversal in the normal tonotopic map of cochlear excitation. A reversal of similar magnitude was found for the

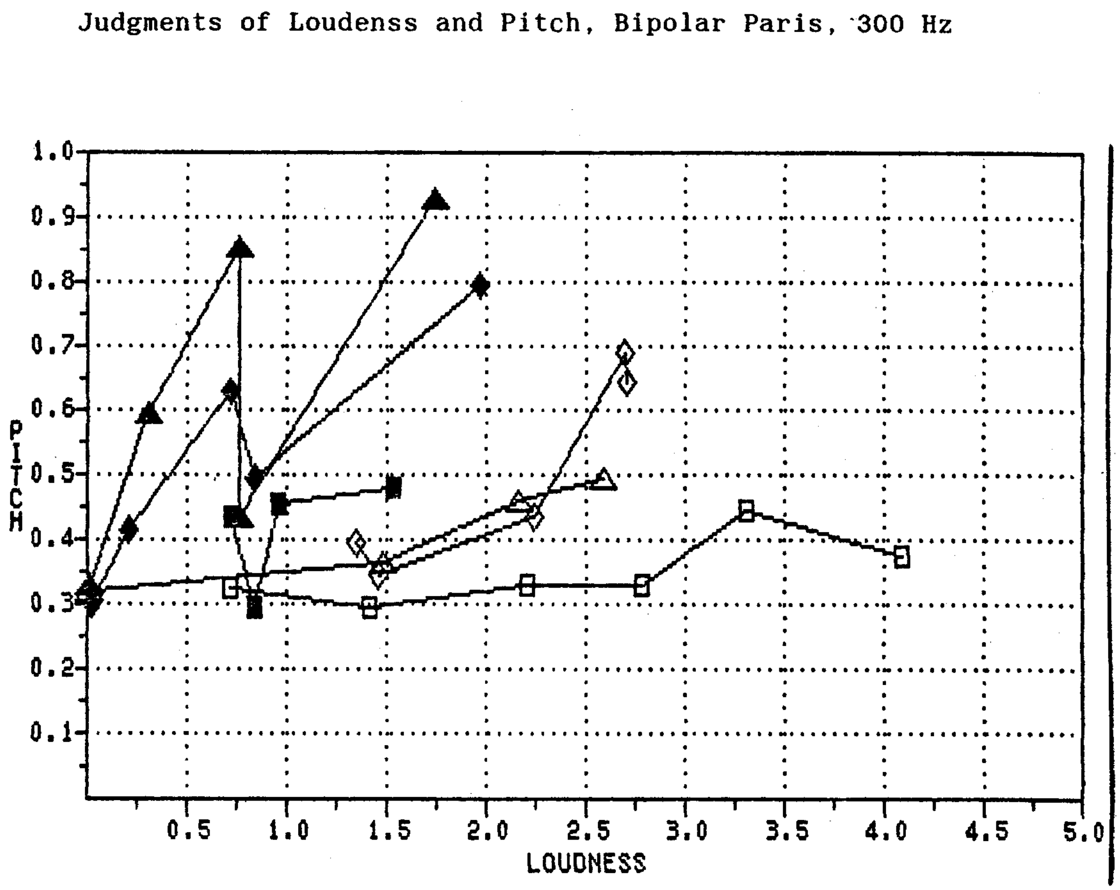

Judgments of Loudenss and Pitch, Bipolar Paris, 300 Hz

Fig. 4. Judgments of loudness and pitch for the pulse repetition frequency of 300 Hz. As in Fig. 2, the stimuli were delivered to bipolar pairs of the UCSF electrode array. The electrode assignments, symbol, minimum current and maximum current used for each of the six channels of stimulation are tabulated below:

Ch	pair	symbol	min uA	max uA
1	1-2	□	195	537
2	5-6	◇	244	977
3	7-8	△	244	977
4	11-12	■	293	977
5	13-14	◆	98	342
6	15-16	▲	98	342

Standard deviations for loudness and pitch, along with the number of responses for each condition, are presented in Table 3 of Appendix 2.

100 Hz case (Figs. 2 and 3), but in this instance channels 5 and 6 were reversed. The magnitudes and locations of reversals in the normal tonotopic map therefore appear to depend both on stimulus intensity and stimulus frequency.

Differences in pitch rankings for different stimulus frequencies are also evident in Figs. 3 and 5, where Fig. 3 shows averages and standard deviations of pitch judgments across channels for 100 Hz stimulation and Fig. 5 shows these data for 300 Hz stimulation. In Fig. 3 there is a significant reversal in tonotopic order between channels 5 and 6, and in Fig. 5 the reversal is between channels 2 and 3. In addition, there are differences in the patterns of channel discriminations for the two frequencies of stimulation. At low loudnesses between 0.5 and 1.5 three regions of cochlear excitation can be discriminated on the basis of pitch when the stimulus frequency is 300 Hz. Specifically, pitch judgments elicited by stimulation of channel 6 are significantly higher over this loudness range than pitch judgments elicited by stimulation of channel 5, and pitch judgments elicited by stimulation of channels 1, 2, 3 or 4 are all significantly lower than the judgments obtained with stimulation of channels 5 or 6. Inasmuch as none of the channels could be discriminated on the basis of pitch for 100 Hz stimulation for loudnesses between 0.5 and 1.5, place coding of pitch seems more salient at low loudnesses for 300 Hz stimulation. However, as loudnesses are increased the ranking of pitches across channels becomes less salient for 300 Hz stimulation. This last observation is made from the comparisons of adjacent pitch rankings in Table 2. In contrast to the three significant differences in adjacent rankings for the 100 Hz condition (Table 1), Table 2 indicates that only one pair of adjacent pitches can be discriminated when the judgments for all loudnesses are compared for the 300 Hz condition. Thus, substantial differences in the ability to rank adjacent pitches are found for 100 Hz and 300 Hz stimulation. At low loudnesses more separate areas of cochlear excitation can be discriminated when 300 Hz stimuli are used, and at moderate and higher loudnesses more areas can be discriminated when 100 Hz stimuli are used.

A final comparison of interest between Figs. 3 and 5, and between Tables 1 and 2, is in the ranges and absolute levels of pitch judgments across channels. Surprisingly, these values are similar for the 100 and 300 Hz stimulus conditions. That is, average pitch judgments range from 0.3 to

Judgments of Pitch Across Channels, Bipolar Pairs, 300 Hz

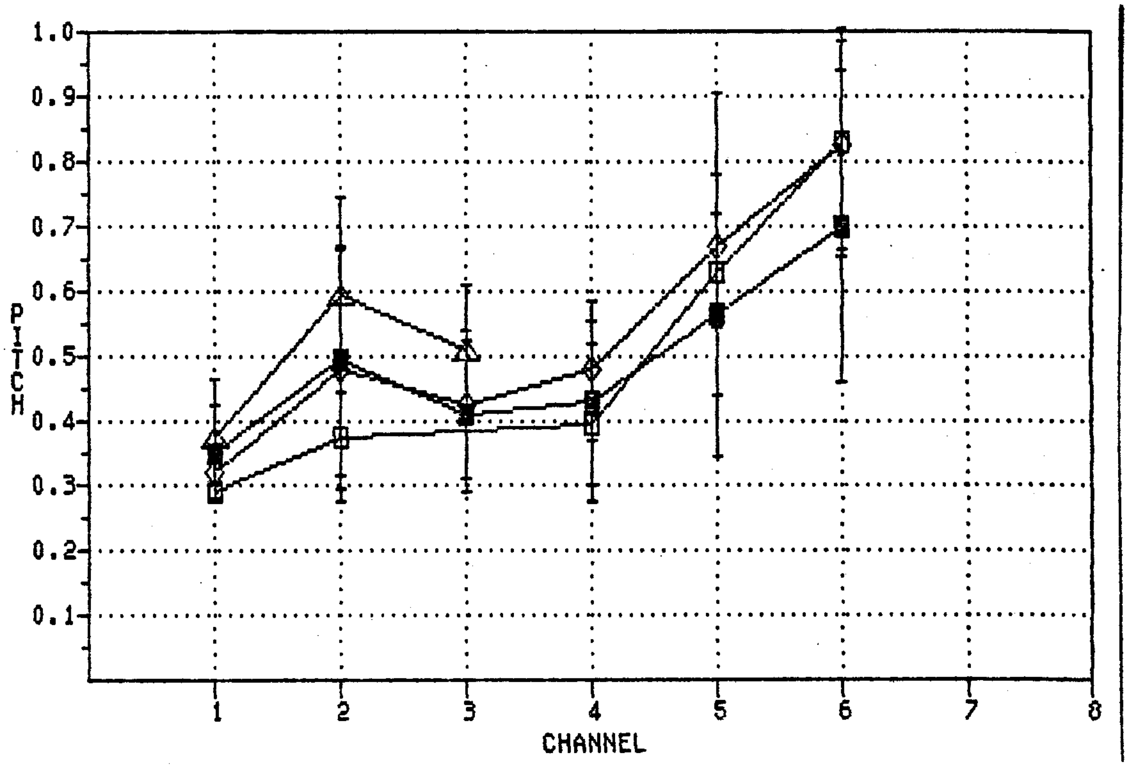


Fig. 5. Averages and standard deviations of pitch judgments across channels for the data shown in Fig. 4. The symbols for the different ranges of loudnesses are the same as those used in Fig. 3. Average pitch, standard deviation and number of responses for each condition are presented in Table 4 of Appendix 2.

Table 2. Analysis of pitch judgments across channels, bipolar pairs, 300 Hz, all loudnesses.*

Chan	Pitch	SD	N	T	dF	P
1	.349	.074	36			
3	.409	.118	24	2.42	58	<.02
3	.409	.118	24			
4	.429	.127	19	0.53	41	NS
4	.429	.127	19			
2	.493	.177	32	1.38	49	NS
2	.493	.177	32			
5	.563	.219	22	1.30	52	NS
5	.563	.219	22			
6	.699	.241	22	1.96	42	NS

---

*Notes: (1) Abbreviations are Chan for Channel, SD for standard deviation, N for number of trials, T for the value of the student's t statistic, dF for degrees of freedom, and P for the probability value; and (2) channels are ranked according to ascending judgments of pitch.

0.8 for both conditions, and the pitch judgments for 300 Hz are not significantly greater than the pitch judgements for 100 Hz on a channel-by-channel basis. In fact, the only significant difference is found for channel 5, which has a lower pitch for 300 Hz stimulation than for 100 Hz stimulation. As we will show later in Fig. 12, the curves for pitch versus frequency of stimulation are rather unusual for MH. Typically, for bipolar stimulation pitch rises with frequency up to about 160 Hz, then falls with further increases in frequency up to about 215 Hz, and finally increases again to a "second" pitch saturation limit. The differences in pitch judgments elicited by stimulation of individual channels with 100 Hz and 300 Hz pulse trains are not significant for any of the channels. In retrospect, then, a different choice of stimulus frequencies (e.g., 80 and 160 Hz) may have produced much larger absolute differences in pitches across channels for MH.

In all, the picture that emerges from the loudness and pitch judgments for bipolar stimulation (Figs. 2-5) is rather sobering. The patterns of these judgments are far from the ideal pattern of a family of horizontal lines on the loudness-pitch plane. Instead, pitch judgments depend primarily on intensity of stimulation and only secondarily on place of stimulation. Frequency of stimulation, at least for the selected frequencies of 100 and 300 Hz, seems to have little effect other than changing the locations of channel reversals in the normal tonotopic map and altering the ability to discriminate channels over different ranges of loudnesses. Together these findings indicate that independent coding of loudness and pitch is not easily achieved for an implant patient like MH. Application of multichannel processors that seek to represent the upper spectrum of speech (beyond the fundamental frequency) by place of intracochlear stimulation, for example, would certainly produce a highly distorted set of pitch percepts. In particular, most if not all frequency components in the speech signal would not be discriminated on the basis of pitch judgments at low loudnesses, and discrimination of these components at higher loudnesses would depend complexly on the spectral position of each component, the relative and absolute loudnesses of the components, and on the frequencies of electrical stimuli delivered to each channel.

Before presenting a way in which the loudness-pitch map might be made to approximate the ideal pattern, we will mention that many of MH's anecdotal reports are consistent with the findings presented in Figs. 2-5.

First, during the initial fitting of a new speech processor she often asks us to raise the loudness of her speech percepts beyond a critical minimum of 2.5 or so for "clarity." This request is consistent with the observation that the channels become more discriminable with increases in loudness (due to covariance between loudness and pitch on the basal channels). Next, when loudness is increased beyond 3.0 or 3.25, MH often reports a sudden loss of intelligibility or clarity in her speech percepts. Once this loss is evident, she will usually ask us to "jiggle" the level of stimulation for best clarity. Although sham adjustments in level indicate some lability in the clarity of percepts at a single level, both the lability and general loss of intelligibility at loudnesses above 3.0 are consistent the strong covariances between loudness and pitch on the basal channels. That is, at some point the advantages of channel separation due to these covariances will be overcome by the gross distortions in the pitch map produced at high loudnesses. Finally, MH often reports "squeaky" or "high pitch" percepts for processed speech tokens presented at high levels. These percepts are again consistent with the increasing upward range of pitch judgments with increases in stimulus intensity.

With these findings and anecdotal reports in mind, it seems obvious that a "straightening out" of the loudness-pitch map might be useful for patients like MH. Specifically, if some set of rules could be applied to produce a constant and unique pitch across loudnesses for each channel of stimulation, then perception of speech might be enormously improved. An initial attempt at separating pitch percepts across channels is illustrated in Figs. 6 and 7. The idea here is to exploit differences in pitch percepts produced by differences in frequencies of stimulation. In particular, 90, 100, 120 and 130 Hz stimuli are delivered to channels 1-4 respectively. Because increases in stimulus frequency produce increases in perceived pitch for frequencies up to 160 Hz (see Fig. 12), we expected that this manipulation would increase the distances between evoked pitches for the apical four channels. In fact, this objective was partially achieved. The pitch judgments shown in Figs. 6 and 7 are now ordered according to ascending judgments for ascending channel numbers. Before (see Figs. 2 and 3), there was a strong reversal in the normal tonotopic map for channels 2 and 3 with 100 Hz stimulation.

In addition to "unscrambling" the distorted tonotopic map, discrimination of channels on the basis of pitch judgments is improved

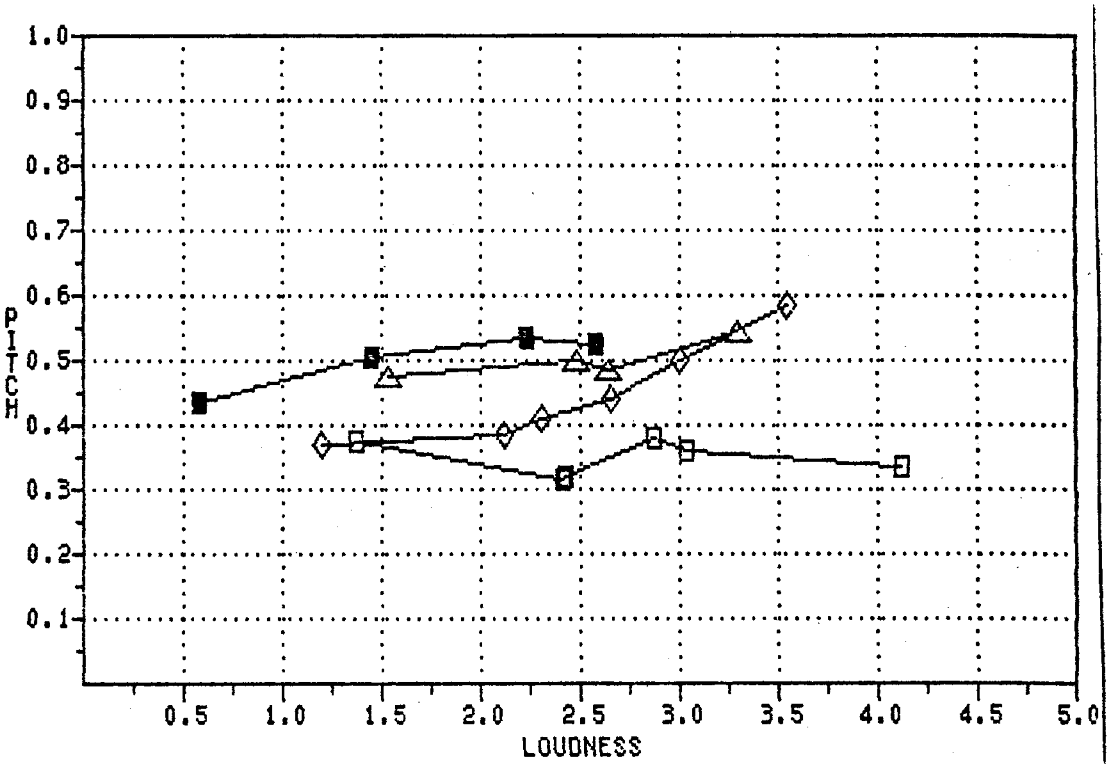

Judgments of Loudness and Pitch, Bipolar Pairs,
Manipulation of Pulse Repetition Frequency Across Channels

Fig. 6. Judgments of loudness and pitch for different frequencies of pulsatile stimulation for the different channels. The electrode assignments, symbol, pulse repetition frequency, minimum current and maximum current used for each of the four channels are tabulated below:

Ch	pair	symbol	frequency(Hz)	min uA	max uA
1	1-2	□	90	98	500
2	5-6	◇	100	125	1000
3	7-8	△	120	98	1000
4	11-12	■	130	195	1000

Standard deviations for loudness and pitch, along with the number of responses for each condition, are presented in Table 5 of Appendix 2.

Judgments of Pitch Across Channels, Bipolar Pairs,
Different Frequencies of Pulsatile Stimulation for Different Channels

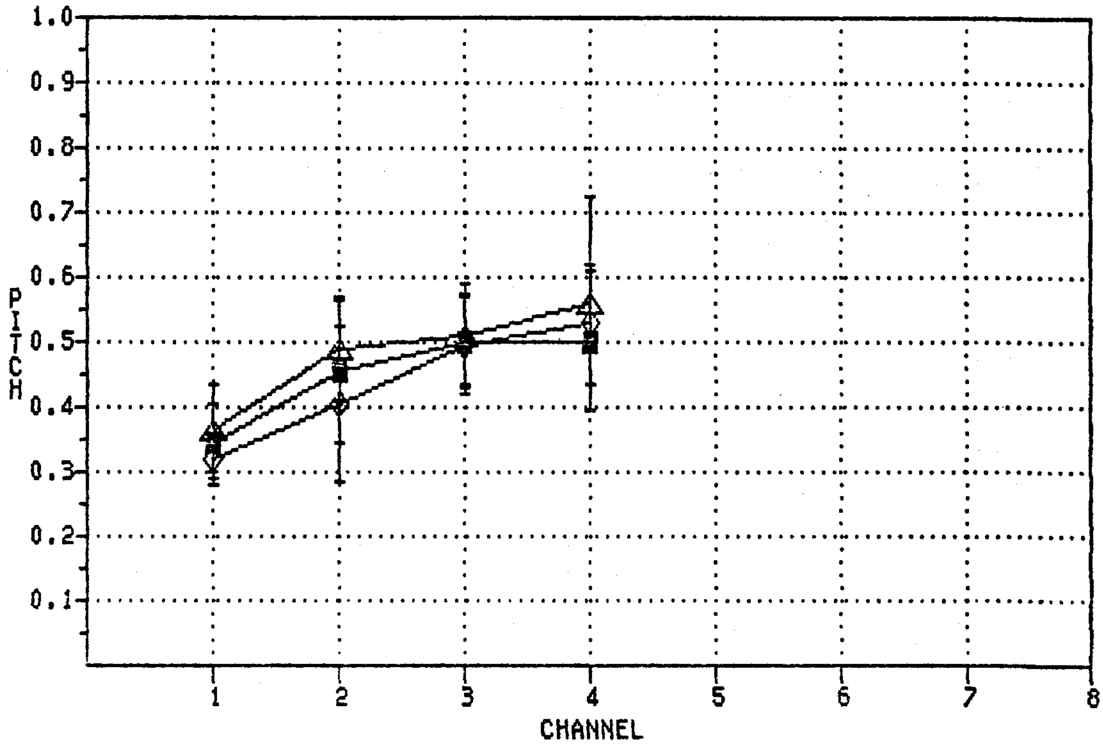


Fig. 7. Averages and standard deviations of pitch judgments across channels for the data shown in Fig. 6. The symbols for the different ranges of loudnesses are the same as those used in Fig. 3. Average pitch, standard deviation and number of responses for each condition are presented in Table 6 of Appendix 2.

somewhat by using different frequencies of stimulation for different channels. For the middle loudness range of 1.5 to 2.5, for example, channels 1 and 2 are discriminable from each other and from channels 3 and 4. Thus, three of four cochlear regions of excitation can be discriminated in this loudness range. For the judgments across all loudnesses, though, Table 3 indicates that only channel 1 can be discriminated from the rest and therefore only two regions can be identified on the basis of pitch. The decrease in discrimination ability with the increase in the range of loudnesses is mainly attributable to a moderate covariance between loudness and pitch on channel 2. A possible way in which this covariance could be lessened or eliminated would be to reduce the frequncy of stimulation with increases in the intensity of stimulation. Over the range where pitch percepts are reliably controlled by frequency of stimulation, a lowering of frequency could potentially offset the increases in pitch judgments otherwise produced by increases in stimulus intensity.

A final feature of note in Figs. 6 and 7 is the fact that the frequency manipulations changed judgments of pitch in the desired directions. This observation is most evident in Table 3A, where the pitch judgments obtained with stimulation of channels 1-4 are compared for the 100 Hz and multiple-frequency conditions. The judgments are significantly higher for the two channels that received higher frequencies of stimulation in the multiple-frequency condition (i.e., channels 3 and 4), and the judgments are not statistically different for the two channels that received identical (channel 2) or very close (channel 1) frequencies of stimulation for the two conditions. These findings suggest that a slightly different choice of stimulus frequencies could have produced clear discriminations across all channels. For example, reference to Fig. 12 indicates that a slight reduction in frequency for channel 2 (on the order of 10 to 20 Hz) and a slight increase in frequency for channel 4 (on the order of 20 Hz) would distribute pitch judgments in a discriminable way across channels.

In conclusion, one strategy for helping patients who cannot rank all of their channels on the basis of pitch is to assign different frequencies of stimulation for different channels. In this way the upper spectrum of speech might be conveyed by modulating the intensity of stimulation for each channel with an appropriate transform of the RMS energy in that channel's bandpass. Further, the deleterious effects of covariances between loudness and pitch might be reduced or eliminated by lowering the frequencies of

Table 3. Analysis of pitch judgments across channels, bipolar pairs, different frequencies of pulsatile stimulation for different channels, all loudnesses.*

Chan	Pitch	SD	N	T	dF	P
1	.347	.057	36			
2	.455	.111	33	5.15	67	<.001
2	.455	.111	33			
3	.500	.071	23	1.71	54	NS
3	.500	.071	23			
4	.502	.110	21	0.07	42	NS

---

*Notes: (1) Abbreviations are Chan for Channel, SD for standard deviation, N for number of trials, T for the value of the student's t statistic, dF for degrees of freedom, and P for the probability value; (2) channels are ranked according to ascending judgments of pitch; and (3) the frequencies of stimulation for channels 1, 2, 3 and 4 were 90, 100, 120 and 130 Hz, respectively.

Table 3A. Comparison of pitch judgments for single-frequency and multiple-frequency conditions. Pitch data are from Tables 1 (condition 1) and 3 (condition 2).

Chan	Cond	Freq	Pitch	SD	N	T	dF	P
1	1	100	.328	.050	36			
	2	90	.347	.057	33	1.50	70	NS
2	1	100	.457	.166	35			
	2	100	.455	.111	33	0.06	66	NS
3	1	100	.408	.155	32			
	2	120	.500	.071	23	2.65	53	<.02
4	1	100	.420	.086	34			
	2	130	.502	.110	21	3.09	53	<.01

---

[*] Abbreviations are Chan for channel, Cond for condition, Freq for frequency in Hz, SD for standard deviation, N for number of trials, T for the value of the student's t statistic, dF for degrees of freedom, and P for the probability value.

stimulation on the offending channels as the levels of stimulation are increased. We plan to evaluate these ideas in future studies with MH.

Monopolar Stimulation

Presentation of pulsatile stimuli to monopolar electrodes in the UCSF array produced patterns of loudness and pitch judgments quite unlike the patterns observed for bipolar stimulation. Fig. 8, for example, shows loudness and pitch judgments for 100 Hz stimuli delivered to the "lateral" monopolar electrodes. The remarkable feature of these judgments is that they are very tightly clustered for loudnesses below 2.5 and at least somewhat clustered for higher loudnesses. The divergence of pitch judgments at the higher loudnesses is due to slight covariances between loudness and pitch on the basal three channels (solid symbols). While the bipolar judgments of pitch showed at least some dependence on place of stimulation (Figs. 2 and 3), the monopolar judgments demonstrate negligible dependence on place. Also, the monopolar judgments generally range between pitches of 0.3 to 0.5 (with most judgments between 0.3 and 0.4) compared with the bipolar range of 0.3 to 0.8. The clustering of pitch judgments for monopolar stimulation is consistent with the observation that the spread of electrical excitation is far broader with monopolar coupling than with bipolar coupling. That is, the overlap in neural excitation fields is likely to be much greater with monopolar stimulation, and therefore percepts arising from monopolar stimulation are more likely to have a high degree of commonality compared with the percepts from bipolar stimulation. A homogeneity of percepts is certainly demonstrated in Fig. 8 for monopolar stimulation.

The clustering of pitch judgments for monopolar stimulation is also clearly shown in Fig. 9, which presents the averages and standard deviations of these judgments across channels. When the judgments of pitch across all loudnesses and channels are compared (solid squares), not one of the adjacent rankings is significantly different from its neighbors. Moreover, the entire range of average pitch judgments is only one fourth of the range for the bipolar configuration (0.3 to 0.4 for monopolar versus 0.3 to 0.7 for bipolar). Thus, for 100 Hz stimulation the monopolar results demonstrate a much reduced discrimination of channels on the basis of pitch

Judgments of Loudness and Pitch, Monopolar Electrodes, 100 Hz

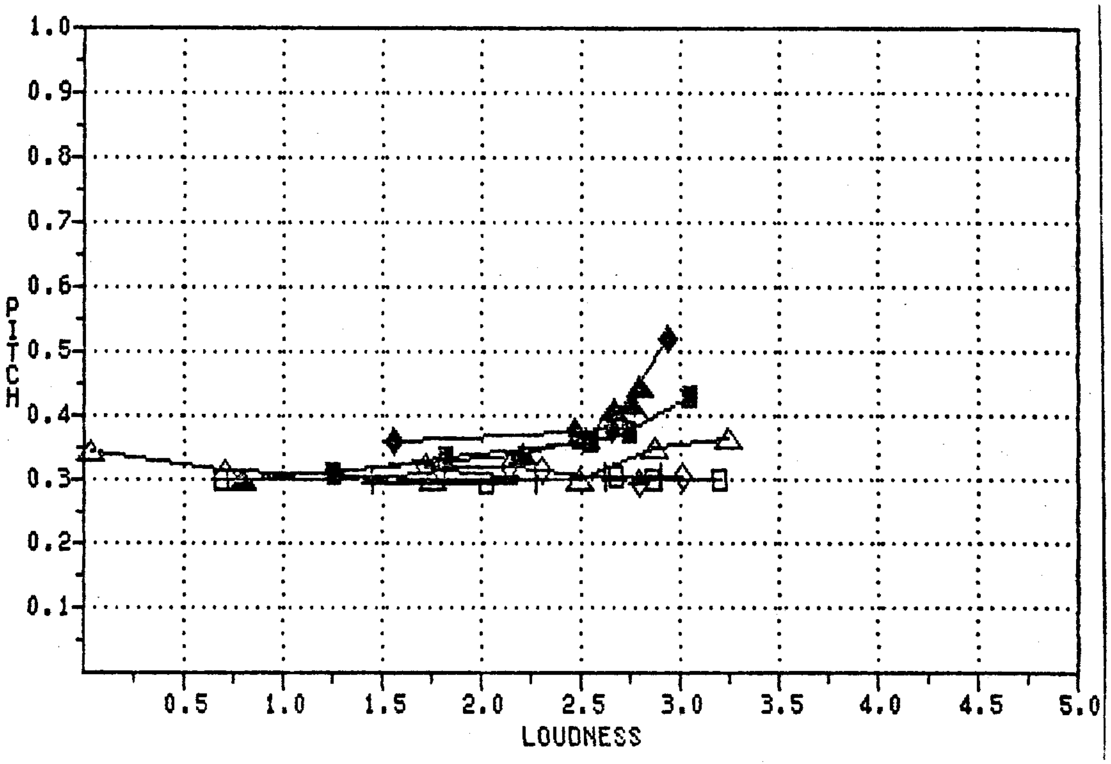


Fig. 8. Judgments of loudness and pitch for 300 msec bursts of "monophasic-like" pulses presented to different monopolar electrodes in the UCSF electrode array. As in Fig. 2 for bipolar stimulation, the pulse repetition frequency was 100 Hz. The electrode assignments, symbol, minimum current and maximum current used for each of the 7 channels of stimulation are tabulated below:

Ch	pair	symbol	min uA	max uA
1	1/Ref	□	9.8	48.8
2	3/Ref	+	9.8	39.0
3	5/Ref	◇	9.8	53.7
4	7/Ref	△	4.9	48.8
5	9/Ref	■	4.9	43.9
6	11/Ref	◆	4.9	43.9
7	13/Ref	▲	19.5	58.6

Standard deviations for loudness and pitch, along with the number of responses for each condition, are presented in Table 7 of Appendix 2.

Judgments of Pitch Across Channels, Monopolar Electrodes, 100 Hz

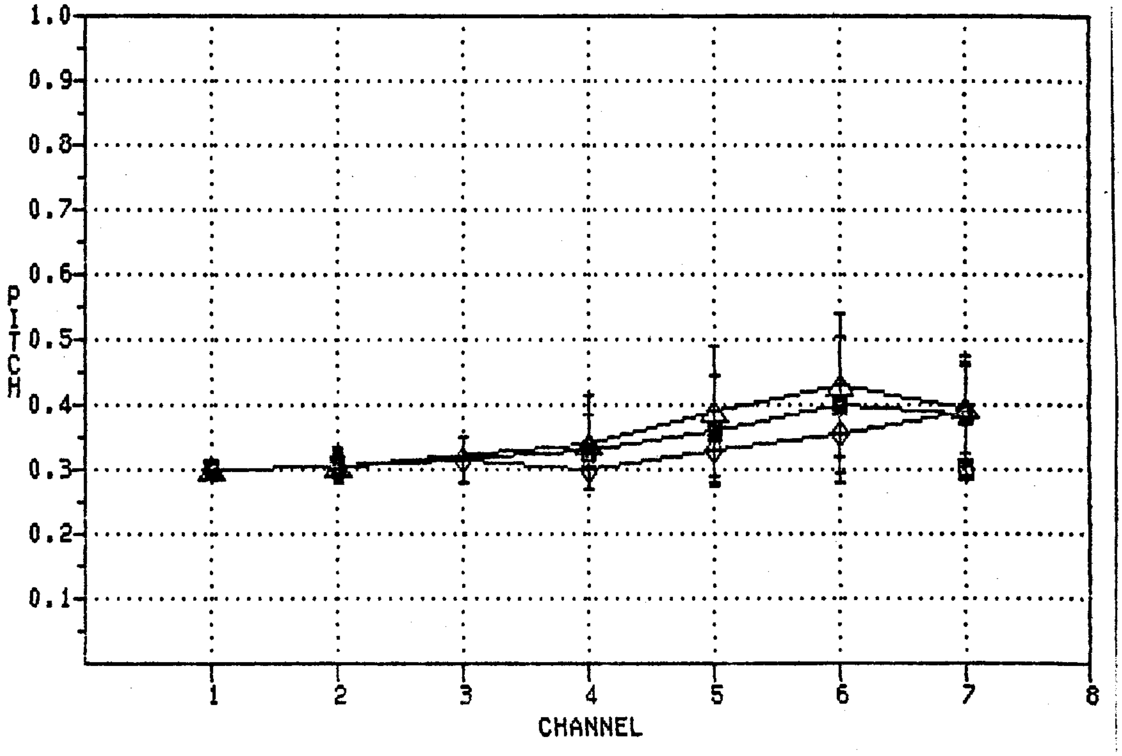


Fig. 9. Averages and standard deviations of pitch judgments across channels for the data shown in Fig. 8. The symbols for the different ranges of loudnesses are the same as those used in Fig. 3. Average pitch, standard deviation and number of responses for each condition are presented in Table 8 of Appendix 2.

judgments and a smaller overall range of these judgments compared with the bipolar results.

Another large difference between coupling configurations is in the changes of loudness and pitch judgments produced by increasing the stimulation frequency from 100 Hz to 300 Hz. The judgments obtained with delivery of 300 Hz stimuli to the monopolar electrodes are shown in Fig. 10. In this figure a striking covariance between loudness and pitch is evident for the basal five channels. Indeed, the growth of pitch judgments between loudnesses of 2.0 and 3.0 typically covers more than half of the entire pitch scale for these channels (e.g., for channel 11/Ref judgments of average pitch increase from 0.36 to 1.00 over this loudness range). This degree of covariance is much greater than the rather modest covariances found for the basal three channels with 100 Hz stimulation (Fig. 8). Thus, covariance between loudness and pitch depends strongly on both <u>intensity</u> of stimulation and <u>frequency</u> of stimulation for the monopolar coupling configuration. Recall that for bipolar coupling the only effect on covariance produced by the change in frequency of stimulation was to introduce nonmonotonicities in the loudness-pitch curves for the basal three channels.

Effects of covariances between loudness and pitch for monopolar stimulation at 300 Hz are also manifested in the pattern of pitch judgments across channels shown in Fig. 11. As in Fig. 9 for 100 Hz stimulation none of the adjacent rankings is significantly different from its neighbors; however, the variability of pitch judgments (i.e., length of the standard deviation bars) is far greater for the 300 Hz condition. This increase in variability is produced by the steep growth of pitch for the basal five channels when loudness rises above 2.0. Finally, comparisons of pitch judgments across all loudnesses for the 100 Hz and 300 Hz conditions indicate that the judgments are significantly higher for 300 Hz stimulation on channels 2-7. These increases in pitch across channels are again attributable to the strong covariances between loudness and pitch observed for 300 Hz stimulation on channels 3-7, and the small but present covariance observed on channel 2. The only channel that does not have a significant increase in pitch when the stimulus frequency is increased from 100 Hz to 300 Hz is channel 1; this channel is also the only one without covariances between loudness and pitch at either frequency.

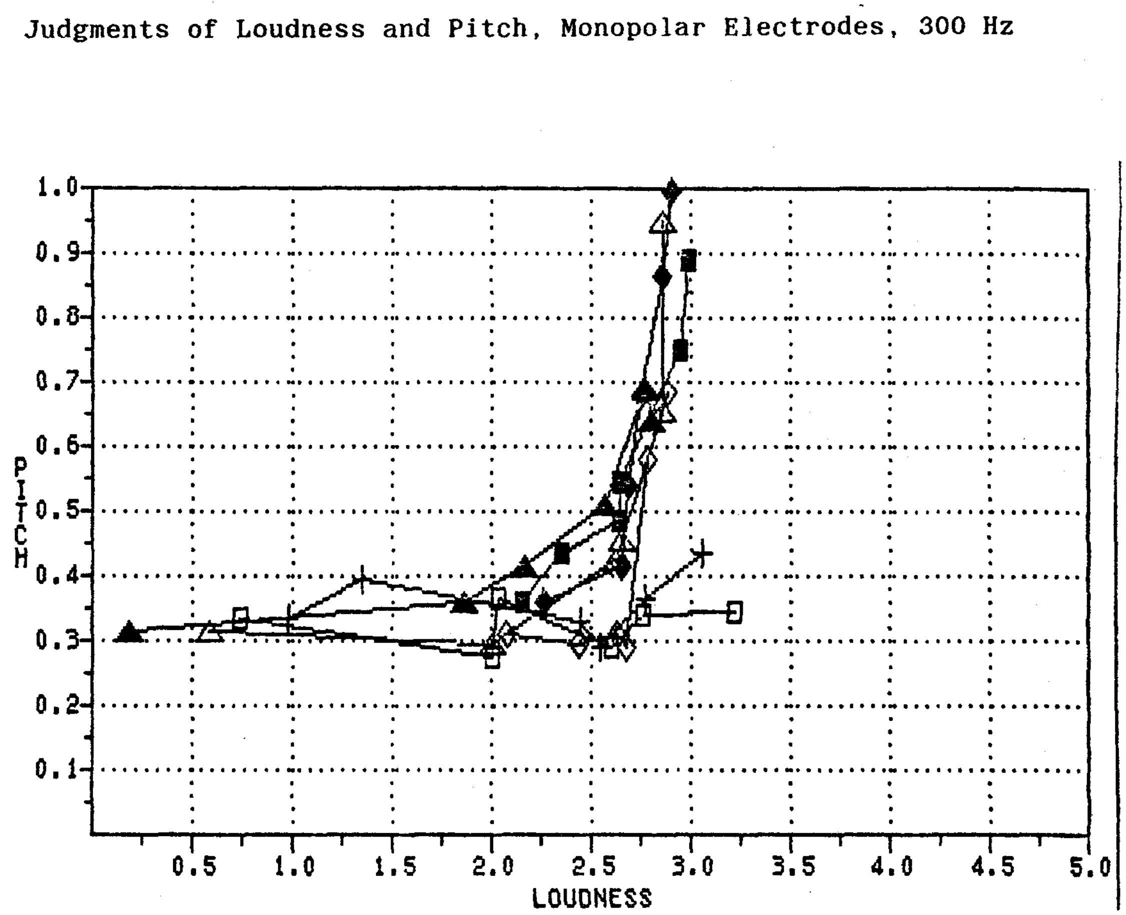


Fig. 10. Judgments of loudness and pitch for the pulse repetition frequency of 300 Hz. As in Fig. 9, the stimuli were delivered to monopolar electrodes of the UCSF electrode array. The electrode assignments, symbol, minimum current and maximum current used for each of the 7 channels of stimulation are tabulated below:

Ch	pair	symbol	min uA	max uA
1	1/Ref	□	19.5	117.2
2	3/Ref	+	19.5	117.2
3	5/Ref	◇	19.5	117.2
4	7/Ref	△	19.5	117.2
5	9/Ref	■	19.5	117.2
6	11/Ref	◆	29.3	136.7
7	13/Ref	▲	29.3	136.7

Standard deviations for loudness and pitch, along with the number of responses for each condition, are presented in Table 9 of Appendix 2.

Judgments of Pitch Across Channels, Monopolar Electrodes, 300 Hz

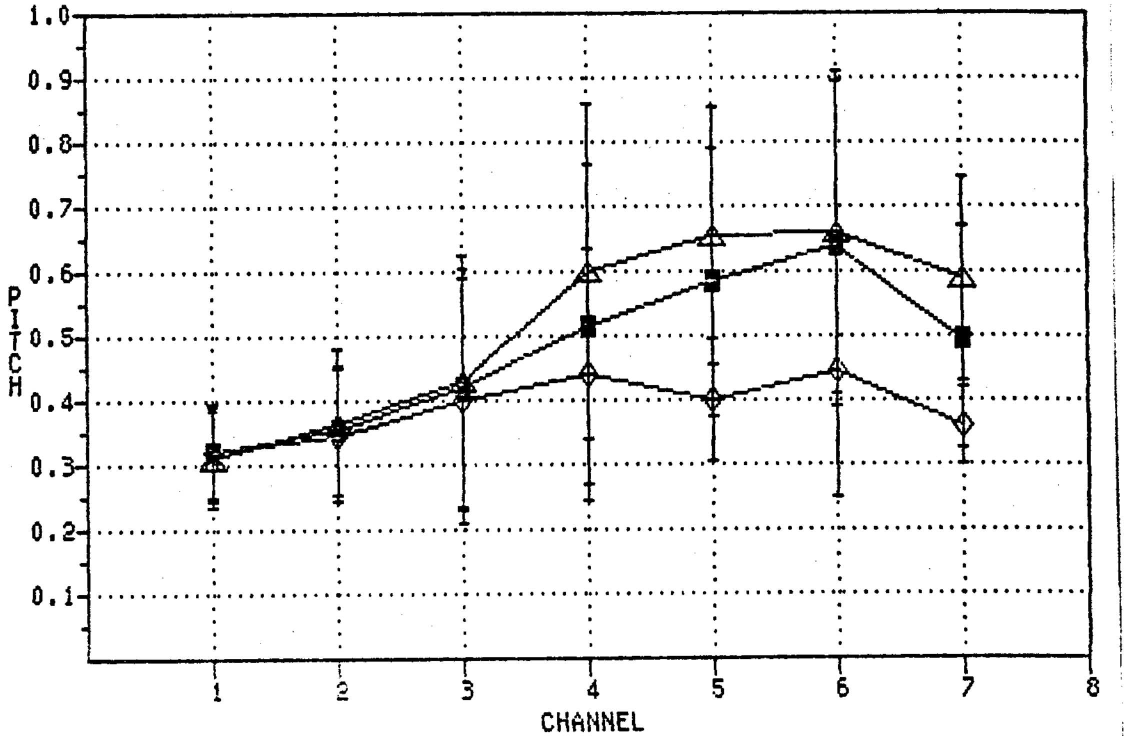


Fig. 11. Averages and standard deviations of pitch judgments across channels for the data shown in Fig. 10. The symbols for the different ranges of loudnesses are the same as those used in Fig. 3. Average pitch, standard deviation and number of responses for each condition are presented in Table 10 of Appendix 2.

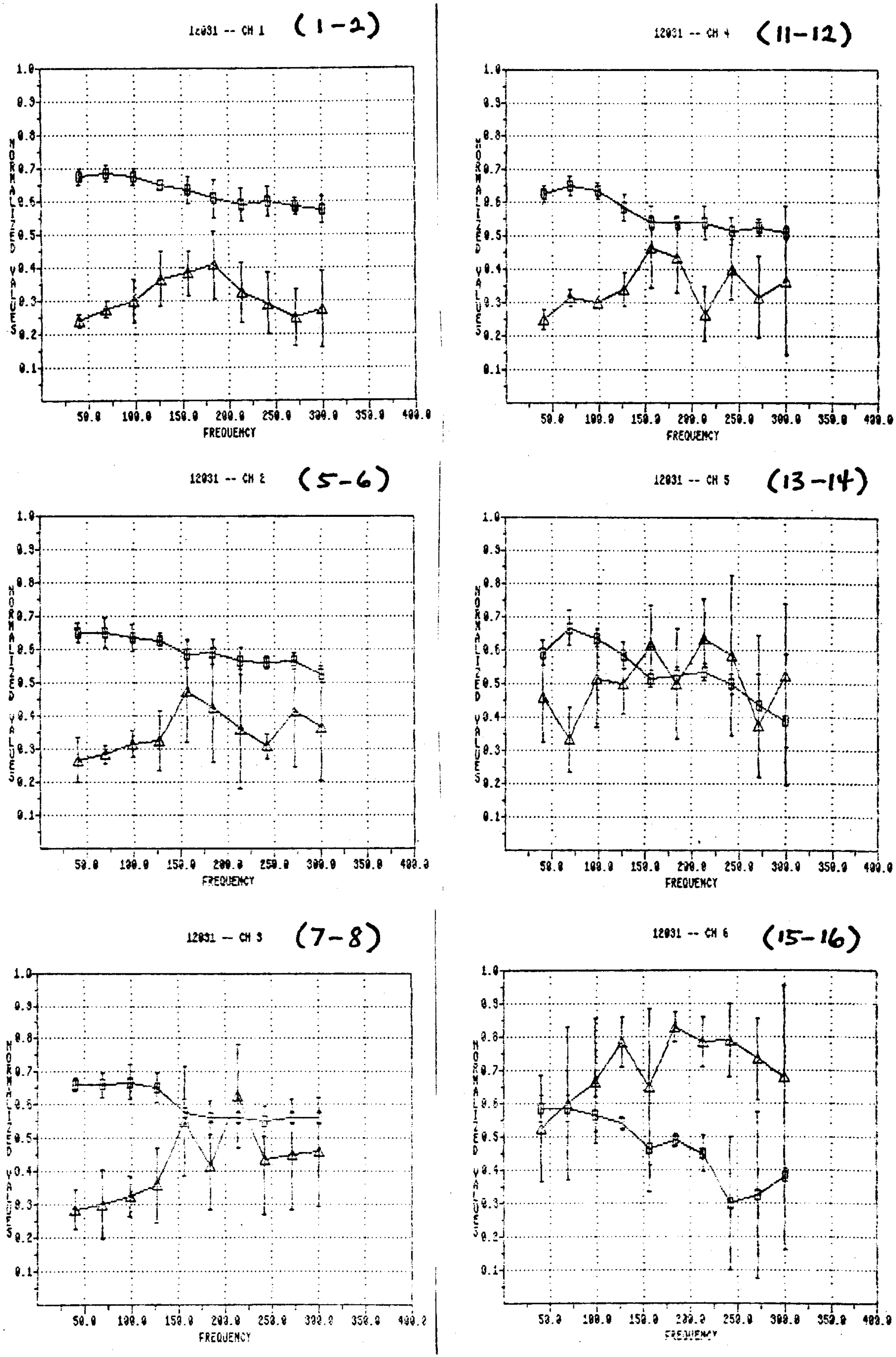
Frequency Manipulations within Channels of Bipolar and Monopolar Stimulation

The final series of experiments to be described in this report involved manipulations of pulse repetition frequency within channels of bipolar and monopolar stimulation. In these experiments the intensity of stimulation was held constant for each channel while frequency was varied in 10 linear steps between 40 and 300 Hz. The intensity for each channel was set so that comfortable loudnesses (i.e., loudnesses in the immediate neighborhood of 3.0) would be elicited with 40 Hz stimuli. Pilot studies demonstrated a slight decrease in loudness with increases in stimulus frequency, so we were confident that this procedure for setting intensities would prevent the occurrence of uncomfortably-loud percepts.

Results for the bipolar coupling configuration are presented in Fig. 12 and in Tables 4 and 5. In Fig. 12 the loudness judgments for each stimulation frequency are indicated by the open squares and the pitch judgments by the open triangles. As expected, loudness declined somewhat with increases in stimulus frequency. The loudness at 300 Hz is significantly lower than the loudness at 40 Hz for all channels, and the decreases in loudness with increases in frequency are generally monotonic. In contrast, the relationship between loudness and pitch appears to be nonmonotonic on every channel. Pitch always increases with frequency up to a local maximum at about 160 Hz and then either "oscillates" within the error of the measurement around the peak pitch value (e.g., channel 3, pair 7-8) or starts to decline at higher frequencies. For some channels in this latter category the judgments fall to a local minimum (e.g., at about 215 Hz for channel 4, pair 11-12) and then rise to a "second" pitch saturation limit thereafter, and for other channels the judgments appear to fall to an asymptotic value (e.g., channel 1, pair 1-2).

These findings, of reliable increases in pitch judgments up to the stimulation frequency of 160 Hz and of significant decreases in pitch judgments on some channels at higher frequencies, are further demonstrated in Tables 4 and 5. Table 4 shows the minimum increments in frequency required at each reference frequency to produce a statistically-significant (P <.05, single tailed) increase in judged pitch. The average minimum increment is around 60 Hz for these absolute, stepwise judgments, and the limiting reference frequency beyond which increases in frequency will not

Fig. 12. Bipolar loudness (□) and pitch (△) (see caption on next page)



Stimuli: 300 ms trains of 0.5 ms pulses at the indicated frequencies

Fig. 12. Judgments of loudness and pitch for pulse trains of 10 different pulse repetition frequencies between 40 and 300 Hz. The stimuli were delivered in random order across channels and frequencies. Each panel shows pitch (triangles) and normalized loudness (squares; the loudnesses were normalized by dividing the measured values by 5) judgments for the indicated pair of bipolar electrodes. The intensity of stimulation was set for each channel so that moderate loudnesses would be maintained across pulse repetition frequencies. The settings for the channels are tabulated below:

Ch	pair	intensity (uA)
1	1-2	210
2	5-6	459
3	7-8	674
4	11-12	732
5	13-14	293
6	15-16	225

Finally, there were six trials per condition; the vertical bars represent the standard deviations of the judgments for each condition.

Table 4. Frequency increments required for significant increases in pitch judgments, bipolar stimulation.

	Required increments at the indicated frequencies									
Ch	40	69	98	127	156	184	213	$\overline{X}$	SD	N
1	29	58	58					48.3	16.7	3
2	116	87	58	29				72.5	37.4	4
3	116	87	58	29				72.5	37.4	4
4	29	87	29	29				43.5	29.0	4
5	116	29						72.5	61.5	2
6	87	58	86					77.0	16.4	3
$\overline{X}$ =	82.2	67.7	57.8	29.0						
SD =	42.7	23.7	20.2	0.0						
N =	6	6	5	3						

produce significant increases in pitch is 127 Hz for channels 2-4, 98 Hz for channels 1 and 6, and 69 Hz for channel 5. Thus, the effective limit of pitch saturation on all channels is no more than 190 Hz (i.e., 127 Hz plus the "absolute difference limen" of 60 Hz) and is typically 160 Hz or lower.

As indicated above, the behavior of pitch judgments beyond the first local maximum is generally complex. One aspect of this behavior on some channels is a <u>decrease</u> in pitch judgments with increases in stimulus frequency. In Table 5 we have described this phenomenon in greater detail by comparing the pitch judgments at the first local maximum with the judgments at the first local minimum beyond the peak. Two features of particular interest in Table 5 are the observations that (1) the frequency corresponding to the first local maximum is within 30 Hz of 156 Hz for all channels and (2) a significant decrease in pitch is found at higher frequencies for 3 of the 6 channels. For bipolar stimulation with MH, then, the effective limit of pitch saturation is around 160 Hz across channels, and further increases in stimulus frequency actually produce significant decreases in pitch on half of the channels.

The findings just reviewed for bipolar stimulation are at odds with the generally-accepted picture of monotonic increases in pitch with increases in stimulus frequency up to a limit of pitch saturation, usually in the neighborhood of 300 Hz. Because pitch covaries with loudness on some channels, it is tempting to suggest that the differences in loudness across stimulus frequencies could produce the complex behavior seen in Fig. 12. For example, the relatively-large reduction in loudness on channel 6 could produce lowered pitch judgments at high stimulus frequencies compared with the judgments that would be obtained for the condition of a uniform loudness across frequencies. However, Figs. 2 and 4 show covariances between loudness and pitch only on channels 2, 5 and 6, and the covariance on channel 2 occurs at loudnesses beyond those used in the studies of Fig. 12. The complex behavior of the pitch versus frequency curves (Fig. 12) is certainly not restricted to these channels. The pitch judgments from stimulation of channel 1, for instance, exhibit a significant decline for frequencies beyond the frequency of the first local maximum. The observations of a relatively-low limit of pitch saturation at 160 Hz and of complex behavior beyond this limit therefore do not appear to be an artifact of loudness differences across frequencies.*

Table 5. Comparison of pitch judgments for the first peak beyond 98 Hz and the first valley beyond this peak, bipolar stimulation.*

Ch	Peak Hz	Pitch	SD	Valley Hz	Pitch	SD	T	P
1	184	4.083	1.021	271	2.500	0.837	2.94	<.02
2	156	4.750	1.541	242	3.083	0.376	2.57	<.05
3	156	5.500	1.643	184	4.167	1.329	1.55	NS
4	156	4.667	1.211	213	2.667	0.816	3.35	<.01
5	156	6.167	1.169	184	5.000	1.673	1.40	NS
6	127	7.833	0.753	184	6.500	2.345	1.33	NS
$\bar{X}$ =	155.8			213.0				
SD =	18.0			36.7				

---

*Note: The number of judgments for each condition was six, and the degrees of freedom for the two-tailed statistical comparisons was ten.

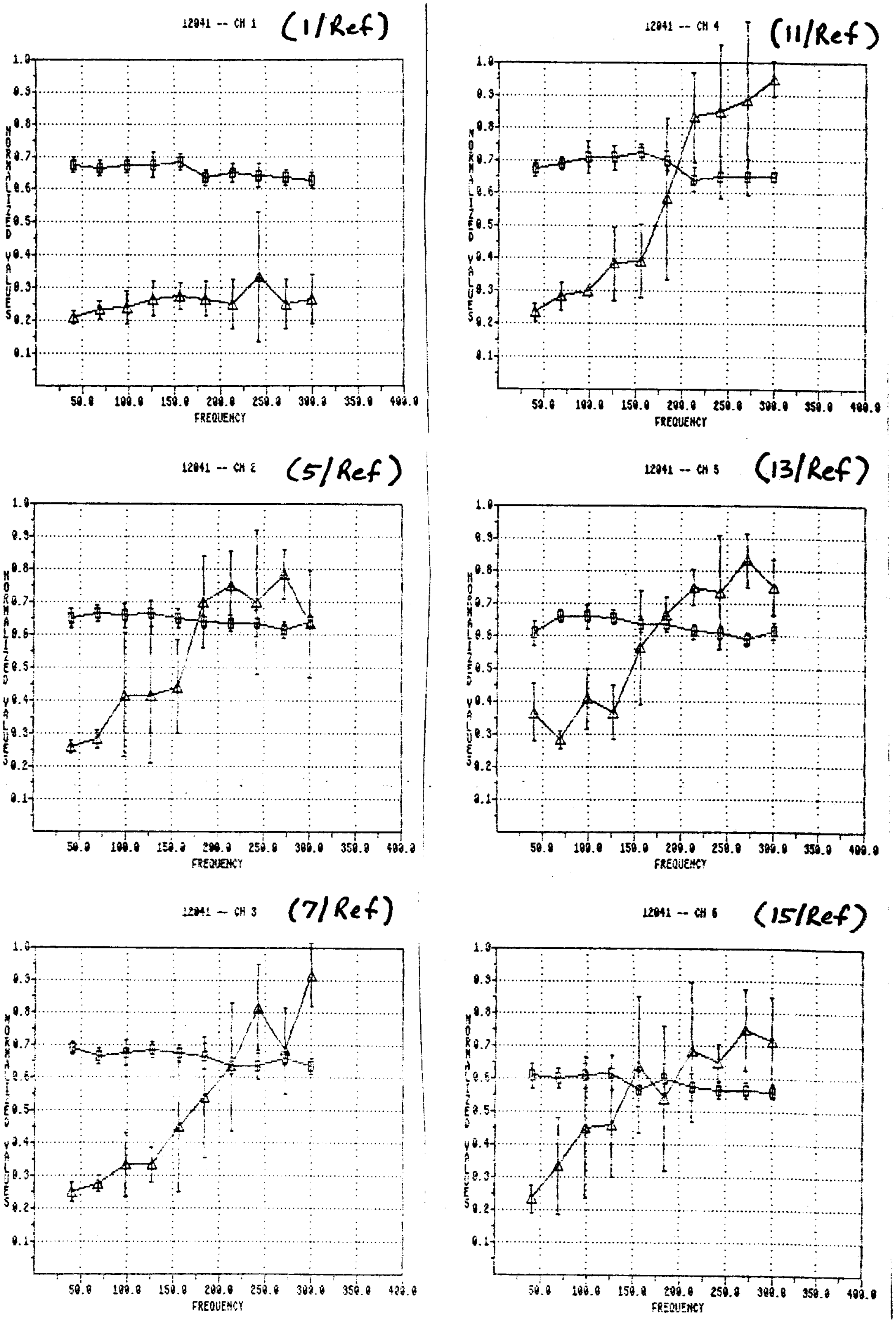
Somewhat surprisingly, the results for monopolar stimulation were quite different from the results just described for bipolar stimulation. The monopolar results are presented in Fig. 13 and Table 6. In contrast to the picture for bipolar stimulation shown in Fig. 12, Fig. 13 demonstrates that the relationship between pitch and frequency is monotonic for 5 of the 6 channels of monopolar stimulation. The exception is the relationship found for chanenl 1, which shows relatively-uniform judgments of pitch across frequencies.

In addition to the monotonic relationships between pitch and frequency on most channels of monopolar stimulation, it is noteworthy that the limits of pitch saturation are generally much higher than the bipolar limits of about 160 Hz. This observation is most evident in Table 6, which shows the minimum increments in frequency required at each reference frequency to produce a statistically-significant increase in judged pitch for monopolar stimulation. The limiting reference frequency beyond which increases in frequency will not produce significant increases in pitch is 213 Hz for channels 3-5, 156 Hz for channel 2, 127 Hz for channel 6, and 69 Hz for channel 1. Examination of the pitch curves in Fig. 13 suggests that the limits of pitch saturation are around 156 Hz for channel 1, 184 Hz for channel 2, 242 Hz for channel 3, 213 Hz for channel 5, and 156 Hz for channel 6. The pitch saturation limit for channel 4 may be higher than 300 Hz inasmuch as the pitch judgments are still increasing at this highest tested frequency. In all, then, the limits of pitch saturation are substantially higher with monopolar stimulation than with bipolar stimulation on the basal five channels (compare the numbers just listed with those tabulated in the second column of Table 5). This difference between coupling configurations indicates that frequency may be a more salient cue for pitch with monopolar stimulation. Recall, however, that _place_ of

---

[*] Indeed, in studies with subsequent patients we have observed the same phenomena using a procedure in which loudnesses were balanced across frequencies. In one patient with various manifestations of poor nerve survival, for example, we observed pitch saturation limits at about 170 Hz and significant decreases in pitch judgments at higher frequencies (around 300 Hz in this case).

Fig. 13. Monopolar loudness (□) and pitch (△)
(see caption on next page)



Stimuli: 300 ms trains of 0.5 ms pulses at the indicated frequencies

Fig. 13. Judgments of loudness and pitch for pulse trains of 10 different pulse repetition frequencies between 40 and 300 Hz. Each panel shows pitch (triangles) and normalized loudness (squares) judgments for the indicated <u>monopolar</u> electrodes. The intensity of stimulation was set for each channel so that moderate loudnesses would be maintained across pulse repetition frequencies. The settings for the channels are tabulated below:

Ch	pair	intensity (uA)
1	1/Ref	78.1
2	5/Ref	87.9
3	7/Ref	78.1
4	11/Ref	78.1
5	13/Ref	107.4
6	15/Ref	156.3

Finally, there were six trials per condition; the vertical bars represent the standard deviations of the judgments for each condition.

Table 6. Frequency increments required for significant increases in pitch judgments, monopolar stimulation.

	Required increments at the indicated frequencies									
Ch	40	69	98	127	156	184	213	$\bar{X}$	SD	N
1	29	87						58.0	41.0	2
2	29	87	86	57	28			57.4	29.0	5
3	58	58	86	57	86	58	29	61.7	19.6	7
4	29	58	29	86	57	29	87	53.6	25.9	7
5	116	29	58	29	57	29	58	53.7	31.0	7
6	58	87	115	86				86.5	23.3	4
$\bar{X}$ =	53.2	67.7	74.8	63.0	57.0	38.7	58.0			
SD =	33.9	23.7	32.5	23.9	23.7	16.7	29.0			
N =	6	6	5	5	4	3	3			

stimulation is the more salient cue when the bipolar coupling configuration is used (e.g., compare Figs. 3 and 9). Therefore, a tradeoff appears to exist between frequency of stimulation and place of stimulation for the bipolar and monopolar conditions.

The differences between the patterns of pitch judgments for the bipolar and monopolar conditions are further illustrated in Figs. 14 and 15. In Fig. 14 the pitch data from the individual panels of Fig. 12 are all plotted in the same graph, and in Fig. 15 the pitch data from the individual panels of Fig. 13 are all plotted in the same graph. Thus, Fig. 14 provides a direct comparison of pitch judgments across channels and frequencies for bipolar stimulation and Fig. 15 provides this comparison for monopolar stimulation.

As might be expected, Fig. 14 demonstrates clear differences in pitch for different channels of bipolar stimulation. For the great majority of frequencies the judgments of pitch are highest for channel 6, next highest for channel 5, and lowest for channels 1-4. Further, pitch judgments generally increase with frequency up to 127 or 156 Hz. The judgments for the apical four channels are tightly clustered over this frequency range and therefore appear to arise primarily from frequency cues. At higher frequencies the pitch curves for all channels exhibit the complex behavior described before in the discussion of Fig. 12. Finally, we note that the pitch judgments for channel 3 seem to be somewhat higher than the judgments for channels 1, 2 and 4 for frequencies greater than 150 Hz.

The picture for monopolar stimulation, presented in Fig. 15, is fundamentally different from the picture just described for bipolar stimulation (Fig. 14). The remarkable feature of Fig. 15 is that the pitch judgments for 5 of the 6 channels overlie each other across the entire range of frequencies. Moreover, frequency seems to be a salient and powerful cue for pitch for these channels for frequencies of up to 200 Hz or greater. On the other hand, the only evidence for a place cue for pitch is in the significantly lower judgments for channel 1. This channel has relatively-uniform pitches across frequencies and therefore the difference in pitch judgments between channel 1 and the remaining channels grows with stimulus frequency.

Although we have presented the monopolar pitch data with the obvious interpretation that frequency is the primary cue for pitch, a re-examination of Figs. 8 and 10 suggests an alternative explanation for the results. In

Pitch Judgments Across Channels and Frequencies for Bipolar Stimulation

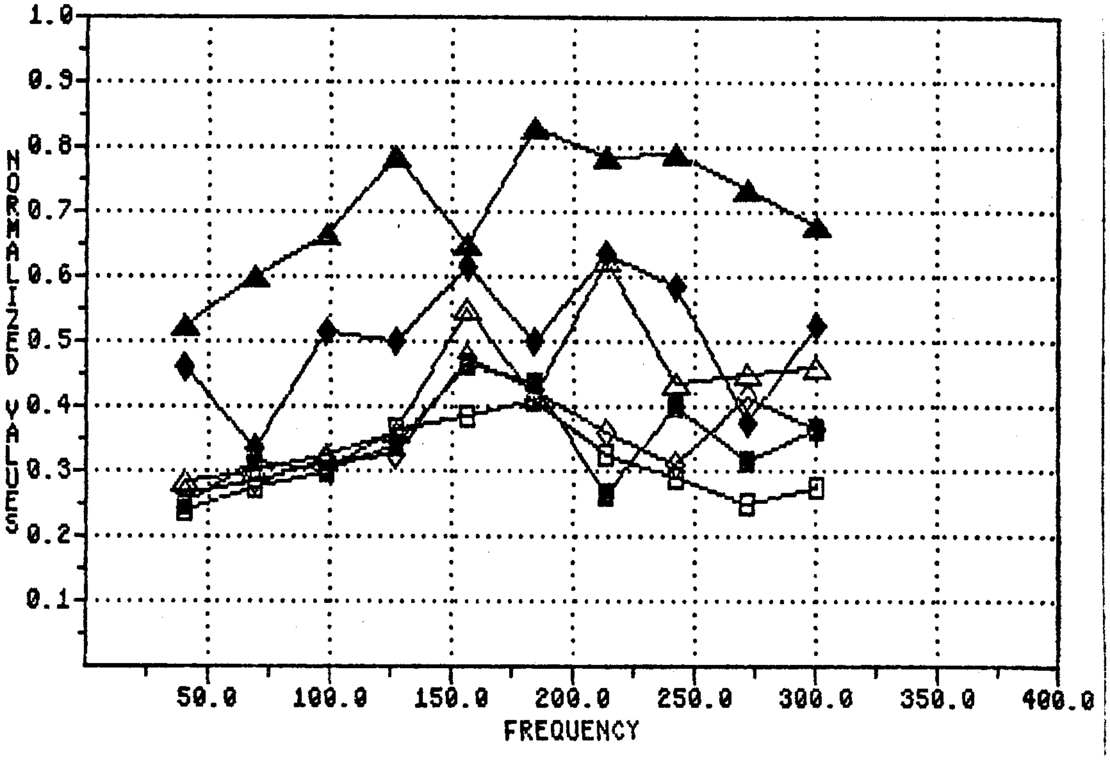


Fig. 14. Pitch judgments across channels and pulse repetition frequencies for bipolar stimulation. The data for this figure are those plotted in a different way in Fig. 12. The channel assignments and symbols are tabulated below:

Ch	pair	symbol
1	1-2	□
2	5-6	◇
3	7-8	△
4	11-12	■
5	13-14	◆
6	15-16	▲

Pitch Judgments Across Channels and Frequencies for Monopolar Stimulation

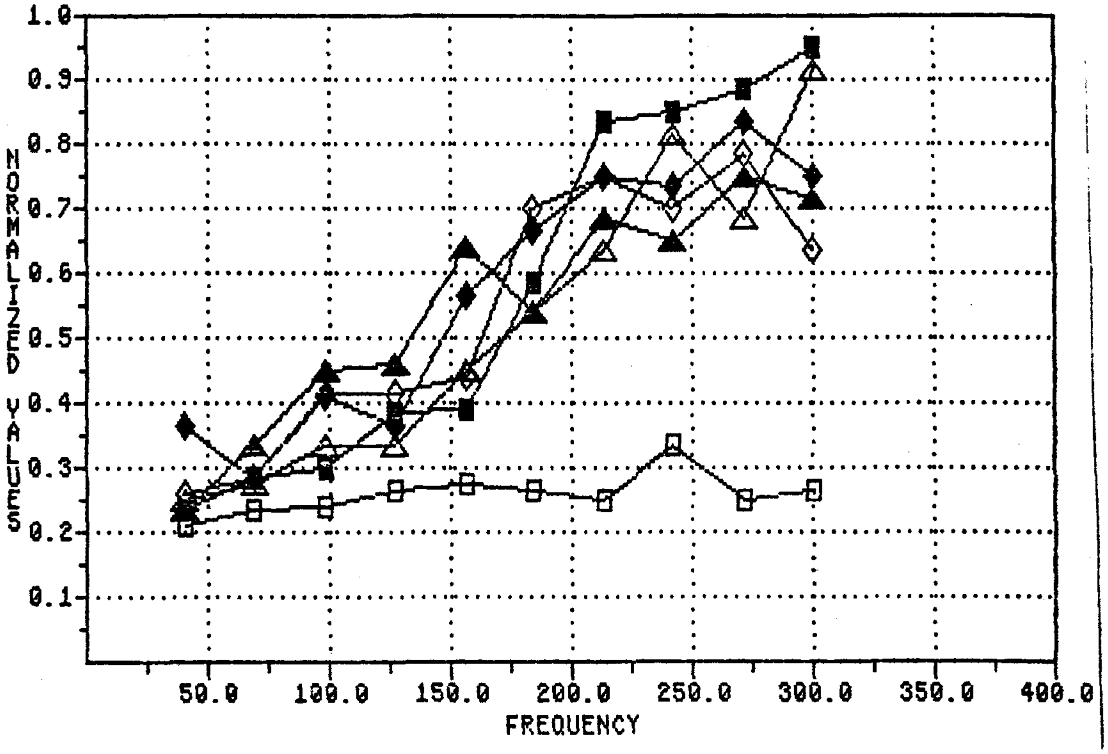


Fig. 15. Pitch judgments across channels and pulse repetition frequencies for monopolar stimulation. The data for this figure are those plotted in a different way in Fig. 13. The channel assignments and symbols are tabulated below:

Ch	pair	symbol
1	1/Ref	□
2	5/Ref	◇
3	7/Ref	△
4	11/Ref	■
5	13/Ref	◆
6	15/Ref	▲

these figures very small covariances between loudness and pitch are seen for 100 Hz stimuli delivered to the basal three monopolar channels (Fig. 8), while huge covariances are seen for 300 Hz stimuli delivered to the basal five monopolar channels (Fig. 10). Therefore, differences in the covariances between loudness and pitch at different frequencies could produce distinct pitch percepts. One might imagine a graded covariance across frequencies (greatest at 300 Hz and least at 40 Hz) that could account for the behavior seen in Fig. 15 for the basal five channels. For such a mechanism changes in frequency would only indirectly cue changes in pitch via a change in the degree of covariances at the different frequencies. If this mechanism is in fact responsible for the monopolar pitch results, then one would further expect that the pitch map would "collapse" at lower loudness levels. That is, Figs. 8 and 10 show negligible covariances for loudnesses below 2.5 and therefore only frequency would remain as a cue for pitch if the experiment of Figs. 13 and 15 were repeated at a lower loudness (e.g., at a loudness of 2.25 instead of the original loudness of 3.0). Finally, we will mention that the apparently anomalous behavior of pitch judgments for channel 1 is entirely consistent with the idea that the coding of pitch is particularly sensitive to intensity (or loudness) for monopolar stimulation. Specifically, channel 1 is the only channel without significant covariances between loudness and pitch over the range of conditions used in the experiments of Figs. 13 and 15. In view of the possibility that differences in covariances can cue differences in pitch, it is therefore not surprising to see little or no increase in pitch for stimulus frequencies above 150 Hz. We plan to repeat the "pitch-mapping" experiment for monopolar stimulation using a loudness level of 2.25 to test the above hypothesis.

Discussion

The results presented in this report have important implications for speech coding and for the design of studies on pitch perception for cochlear implant patients. First, the large differences in the patterns of pitch judgments for monopolar and bipolar stimulation indicate that the representation of speech information might also be quite different with these two coupling configurations. In broad overview, the results indicate that pitch is coded by the intensity, frequency and place of stimulation for both configurations, but the relative salience of these stimulus attributes is different for bipolar and monopolar coupling. For bipolar coupling intensity and place of stimulation are most salient, and for monopolar coupling some combination of cues from intensity and frequency of stimulation codes pitch. Because pitch is mapped over a very wide and discriminable space with both bipolar and monopolar coupling, it is not altogether surprising that "star patients" can be found for either type of electrode coupling. Indeed, many results reported by others are consistent with this general expectation and with some of the particular findings presented in this report. Certain patients using the Symbion prosthesis with an array of four monopolar electrodes, for example, have outstanding results in speech perception studies (Eddington, 1983). With a multidimensional scaling analysis of vowel confusions made by these patients, Eddington demonstrated that their recognition results can be largely explained by perception of the first formant frequency of speech (F1) and further that perception of the place of stimulation, if present, contributes little to recognition. These findings are consistent with the present findings of relatively-high limits of pitch saturation (so that under the right conditions of intensity of stimulation and good nerve survival F1 might be perceived) and the general absence of place cues for pitch with the monopolar coupling configuration.

On the other hand, excellent results have also been obtained with the bipolar coupling configuration (see, e.g., Schindler *et al.*, in press). In these instances performance seems to be related to perception of the second formant of speech, which is primarily coded in the bipolar UCSF/Storz prosthesis by place of stimulation. The lesson to us from these findings and observations is that pitch and loudness are coded in different ways with the bipolar and monopolar coupling configurations. Therefore, frequency components in speech can be represented with either configuration, but over different ranges and by different mechanisms. An understanding of these mechanisms may lead to ways in which the perceptual capabilities of implant patients can be better exploited to improve the transmission of speech information.

III. Plans for the Next Quarter

The main activity planned for the next quarter is completion of our series of studies with six patients implanted with the 4-channel UCSF/Storz auditory prosthesis. For each of these patients we will compare the performance of their own compressed-analog-outputs processor (the UCSF/Storz processor) with the performance of the interleaved-pulses processors developed in this project (see QPRs 2 and 4, NIH project N01-NS-5-2396). The comparisons will be made with a wide variety of tests, including (1) all tests of the Minimal Auditory Capabilities Battery; (2) speech tracking with and without the use of the prosthesis; (3) tests of vowel and consonant perception using confusion matrices; (4) the Diagnostic Discrimination Test for consonant perception; and (5) the Iowa medial consonant test for perception of these phonemes with the aid of lipreading. We expect to study each of these patients for a one-week period, and to present the results of all studies in our next quarterly progress report.

In addition to the studies just outlined, we will continue ongoing efforts, including (1) psychophysical and speech perception studies with our cable patient MH; (2) development of new computer programs to support and extend all of the above studies; (3) further development of hardware and software for implementing various multichannel and single-channel coding strategies in portable, real-time processors; and (4) collaboration with the team at UCSF on the development of a new, 8-channel transcutaneous transmission system. Finally, we will begin our preparations for major presentations of project results at the upcoming national meeting of the Triological Society this April and the Gordon Conference on Implantable Auditory Prostheses this June.

IV. References

Eddington, D.K., Speech recognition in deaf subjects with multichannel intracochlear electrodes, Ann. N.Y. Acad. Sci., 405 (1983) 241-258.

Eddington, D.K., Dobelle, W.H., Brackman, D.E., Mladejovsky, M.G. and Parkin, J.L., Auditory prosthesis research with multiple channel intracochlear stimulation in man, Ann. Otol., 87, Suppl. 53 (1978a) 1-39.

Eddington, D.K., Dobelle, W.H., Brackman, D.E., Mladejovsky, M.G. and Parkin, J.L., Place and periodicity pitch by stimulation of multiple scala tympani electrodes in deaf volunteers, Trans. Am. Soc. Artif. Organs, 24 (1978b) 1-5.

Godfrey, D.A., Kiang, N.Y.S. and Norris, B.E., Single unit activity in the posteroventral cochlear nucleus of the cat. J. Comp. Neurol., 162 (1975) 247-268.

Loeb, G.E., Byers, C.L., Rebscher, S.J., Casey, D.E., Fong, M.M., Schindler, R.A., Gray, R.F. and Merzenich, M.M., Design and fabrication of a experimental cochlear prosthesis, Med. & Biol. Eng. & Comput., 21 (1983) 241-254.

Merzenich, M.M. and White, M., Cochlear implants: The interface problem. In F.T. Hambrecht and J.B. Reswick (Eds.), Functional Electrical Stimulation: Applications in Neural Prostheses, Marcel Dekker, New York, 1977, pp. 321-340.

Pfingst, B.E. and Rush, N.L., Discrimination of simultaneous frequency and level changes in electrical stimuli, Ann. Otol., 96, Suppl. 128 (1987) 34-37.

Shannon, R.V., Multichannel electrical stimulation of the auditory nerve in man. I. Basic psychophysics, Hearing Res., 11 (1983) 157-189.

Simmons, F.B., Walker, M.G., Mathews, R.G. and White, R.L., Percepts and discrimination by auditory nerve stimulation: A summary of results and some proposals for nerve viability evaluation. In D.L. McPherson and M.S. Davis (Eds.), Advances in Prosthetic Devices for the Deaf: A Technical Workshop, National Technical Insititute for the Deaf, Rochester Institute of Technology, Rochester, NY, 1979, pp. 271-274.

van den Honert, C. and Stypulkowski, P.H., Physiological properties of the electrically stimulated auditory nerve. II. Single fiber recordings, Hearing Res., 14 (1984) 225-243.

van den Honert, C. and Stypulkowski, P.H., Spatial mapping of electrical excitation patterns within the cochlea derived from single fiber responses. In ARO Abstracts, 8th Midwinter Research Conference, p. 106, 1985.

White, M.W., Formant frequency discrimination and recognition in subjects implanted with intracochlear stimulating electrodes, Ann. N.Y. Acad. Sci., 405 (1983) 348-359.

Appendix 1

Summary of Reporting Activity for the Period of September 26 through December 26, 1986, NIH Contract N01-NS-5-2396

The following presentations were made in the present reporting period:

Lawson, DT: Cochlear implants. Invited luncheon address at the Annual Meeting of the NC Regional Chapter of the Acoustical Society of America, Tanglewood Park, NC, Oct. 9-10, 1986.

Wilson, BS: Speech processors for auditory prostheses, 17th Annual Neural Prosthesis Workshop, Bethesda, MD, Oct. 15-17, 1986.

Wilson, BS: Cochlear implants. Invited lecture presented in the session on auditory signal processing, First North Carolina Workshop on Bioelectronics, Quail Roost, NC, Oct. 24-26, 1986.

In addition to the above presentations, the RTI/Duke cochlear implant team hosted a site visit for NIH representatives on December 8, 1986.

Appendix 2

Supplementary Tables of Loudness and Pitch Data

Table 1. Judgments of Loudness and Pitch, Bipolar Pairs, 100 Hz.

The results of the loudness and pitch measures were the following:*

Chan	Duration	Intensity	Charge	Loudness	SD	Pitch	SD	N
1	.50	200	48.83	2.140	.375	.318	.046	6/ 6
1	.50	365	89.11	2.648	.202	.360	.064	6/ 6
1	.50	530	129.39	3.033	.183	.307	.042	6/ 6
1	.50	694	169.43	3.358	.263	.347	.055	6/ 6
1	.50	859	209.72	3.841	.323	.297	.005	6/ 6
1	.50	1024	250.00	4.237	.230	.338	.053	6/ 6
2	.50	256	62.50	.129	.245	.368	.091	5/ 5
2	.50	614	149.90	2.481	.495	.310	.020	6/ 6
2	.50	972	237.30	2.841	.316	.367	.123	6/ 6
2	.50	1331	324.95	2.716	.611	.522	.131	6/ 6
2	.50	1689	412.35	3.006	.522	.545	.178	6/ 6
2	.50	2047	499.76	3.252	.373	.617	.162	6/ 6
3	.50	200	48.83	.096	.121	.405	.134	2/ 2
3	.50	569	138.92	1.841	.656	.379	.069	6/ 6
3	.50	939	229.25	2.515	.262	.382	.098	6/ 6
3	.50	1308	319.34	2.960	.226	.370	.057	6/ 6
3	.50	1678	409.67	2.703	.606	.427	.149	6/ 6
3	.50	2047	499.76	3.233	.159	.483	.164	6/ 6
4	.50	400	97.66	.084	.109	.380	.075	5/ 5
4	.50	729	177.98	.845	.841	.360	.037	5/ 5
4	.50	1059	258.54	1.750	.961	.453	.048	6/ 6
4	.50	1388	338.87	1.737	.677	.467	.082	6/ 6
4	.50	1718	419.43	2.708	.112	.432	.080	6/ 6
4	.50	2047	499.76	2.481	.466	.413	.114	6/ 6
5	.50	128	31.25	1.159	1.543	.400	.127	2/ 2
5	.50	205	50.05	.754	.622	.564	.089	5/ 5
5	.50	282	68.85	1.036	1.220	.653	.113	5/ 6
5	.50	358	87.40	2.051	.410	.765	.127	6/ 6
5	.50	435	106.20	2.316	.430	.757	.106	6/ 6
5	.50	512	125.00	2.224	.377	.967	.058	6/ 6
6	.50	200	48.83	.150	.241	.385	.126	4/ 4
6	.50	240	58.59	1.118	.536	.426	.128	5/ 5
6	.50	280	68.36	1.468	.675	.453	.137	6/ 6
6	.50	320	78.12	1.699	.444	.530	.094	6/ 6
6	.50	360	87.89	1.915	.594	.763	.122	6/ 6
6	.50	400	97.65	1.981	.357	.913	.075	6/ 6

---

*Notes: (1) Duration is measured in msec, intensity in digital-to-analog-converter units, and charge in nano coulombs; (2) N is the number of audible trials for each condition of stimulation; and (3) pulse-train stimuli were presented in 300 msec bursts with a rise/fall time of 5.0 msec.

Table 2. Judgments of Pitch Across Channels, Bipolar Pairs, 100 Hz.

Pitch reports for all audible stimuli:

Chan	Pitch	SD	N
1	.328	.050	36
2	.457	.166	35
3	.408	.115	32
4	.420	.086	34
5	.705	.159	31
6	.595	.222	33

Pitch reports for the loudness range of 0.5 to 1.5:

Chan	Pitch	SD	N
1	.000	.000	0
2	.320	.000	1
3	.350	.057	2
4	.452	.083	6
5	.552	.298	4
6	.485	.171	10

Pitch reports for the loudness range of 1.5 to 2.5:

Chan	Pitch	SD	N
1	.335	.055	6
2	.452	.176	4
3	.463	.081	6
4	.403	.084	7
5	.739	.190	13
6	.560	.225	18

Pitch reports for the loudness range of 2.5 to 3.5:

Chan	Pitch	SD	N
1	.321	.049	18
2	.477	.181	24
3	.402	.127	21
4	.431	.095	15
5	.774	.296	9
6	.712	.142	4

Table 3. Judgments of Loudness and Pitch, Bipolar Pairs, 300 Hz.

The results of the loudness and pitch measures were the following:*

Chan	Duration	Intensity	Charge	Loudness	SD	Pitch	SD	N
1	.50	400	97.66	.714	.860	.327	.054	6/ 6
1	.50	490	119.63	1.411	.708	.295	.005	6/ 6
1	.50	600	146.48	2.210	.229	.328	.045	6/ 6
1	.50	734	179.20	2.784	.092	.328	.053	6/ 6
1	.50	899	219.48	3.301	.482	.445	.085	6/ 6
1	.50	1100	268.55	4.091	.214	.373	.081	6/ 6
2	.50	500	122.07	.256	.330	.355	.092	2/ 2
2	.50	660	161.13	1.452	.593	.345	.087	6/ 6
2	.50	871	212.65	1.345	.988	.397	.113	6/ 6
2	.50	1149	280.52	2.239	.323	.433	.132	6/ 6
2	.50	1516	370.12	2.706	.182	.643	.086	6/ 6
2	.50	2000	488.28	2.693	.432	.692	.155	6/ 6
3	.50	500	122.07	----->	No trials	for this	condition	
3	.50	660	161.13	.011	--------	.300	--------	1
3	.50	871	212.65	.011	.016	.319	.041	5/ 5
3	.50	1149	280.52	1.477	.876	.363	.125	6/ 6
3	.50	1516	370.12	2.165	.398	.462	.115	6/ 6
3	.50	2000	488.28	2.589	.213	.495	.094	6/ 6
4	.50	600	146.48	.023	--------	.400	--------	1
4	.50	763	186.28	.833	.135	.293	.026	3/ 3
4	.50	971	237.06	.000	--------	.390	--------	1
4	.50	1236	301.76	.719	.856	.437	.228	3/ 3
4	.50	1572	383.79	.952	.769	.456	.157	5/ 5
4	.50	2000	488.28	1.538	.516	.482	.040	6/ 6
5	.50	200	48.83	----->	No trials	for this	condition	
5	.50	257	62.74	.023	.012	.300	.010	3/ 3
5	.50	330	80.57	.833	.767	.493	.177	3/ 3
5	.50	424	103.52	.207	.438	.416	.133	5/ 5
5	.50	545	133.06	.723	1.011	.630	.196	5/ 5
5	.50	700	170.90	1.966	.610	.795	.092	6/ 6
6	.50	200	48.83	----->	No trials	for this	condition	
6	.50	257	62.74	.011	.012	.330	.053	3/ 3
6	.50	330	80.57	.765	1.286	.437	.110	3/ 3
6	.50	424	103.52	.307	.470	.595	.116	4/ 4
6	.50	545	133.06	.756	.735	.853	.051	6/ 6
6	.50	700	170.90	1.735	.599	.930	.046	6/ 6

---

*Notes: (1) Duration is measured in msec, intensity in digital-to-analog-converter units, and charge in nano coulombs; (2) N is the number of audible trials for each condition of stimulation; and (3) pulse-train stimuli were presented in 300 msec bursts with a rise/fall time of 5.0 msec.

Table 4. Judgments of Pitch Across Channels, Bipolar Pairs, 300 Hz.

Pitch reports for all audible stimuli:

Chan	Pitch	SD	N
1	.349	.074	26
2	.493	.177	32
3	.409	.118	24
4	.429	.127	19
5	.563	.219	22
6	.699	.241	22

Pitch reports for the loudness range of 0.5 to 1.5:

Chan	Pitch	SD	N
1	.290	.010	3
2	.377	.100	4
3	.300	.000	1
4	.396	.123	8
5	.632	.089	5
6	.832	.175	6

Pitch reports for the loudness range of 1.5 to 2.5:

Chan	Pitch	SD	N
1	.321	.043	11
2	.480	.184	14
3	.427	.115	10
4	.478	.109	5
5	.672	.232	5
6	.823	.160	6

Pitch reports for the loudness range of 2.5 to 3.5:

Chan	Pitch	SD	N
1	.373	.091	10
2	.595	.148	13
3	.509	.100	8
4	.000	.000	0
5	.845	.064	2
6	.000	.000	0

Table 5. Judgments of Loudness and Pitch, Bipolar Pairs, Manipulation of Pulse Repetition Frequency Across Channels.

The results of the loudness and pitch measures were the following:*

Chan	Duration	Intensity	Charge	Loudness	SD	Pitch	SD	N	
1	.50	200	48.83	1.365	.955	.375	.040	6/ 6	
1	.50	277	67.63	2.424	.171	.318	.040	6/ 6	90 Hz
1	.50	384	93.75	2.411	.292	.315	.042	6/ 6	
1	.50	533	130.13	2.868	.141	.378	.069	6/ 6	
1	.50	739	180.42	3.032	.220	.362	.080	6/ 6	
1	.50	1024	250.00	4.121	.165	.333	.045	6/ 6	
2	.50	256	62.50	1.201	1.020	.370	.147	3/ 3	
2	.50	388	94.73	2.119	.386	.383	.121	6/ 6	
2	.50	588	143.55	2.305	.469	.410	.095	6/ 6	100 Hz
2	.50	891	217.53	2.657	.466	.440	.096	6/ 6	
2	.50	1351	329.83	2.996	.250	.500	.009	6/ 6	
2	.50	2047	499.76	3.540	.197	.533	.037	6/ 6	
3	.50	200	48.83	---->	No trials	for this	condition		
	.50	318	77.64	.966	--------	.410	--------	1	
3	.50	507	123.78	1.534	.744	.477	.097	4/ 4	120 Hz
3	.50	807	197.02	2.477	.694	.500	.057	6/ 6	
3	.50	1286	313.96	2.644	.395	.483	.076	6/ 6	
3	.50	2047	499.76	3.290	.401	.545	.049	6/ 6	
4	.50	400	97.66	---->	No trials	for this	condition		
4	.50	554	135.25	.966	--------	.390	--------	1	
4	.50	769	187.74	.572	.991	.437	.055	3/ 3	
4	.50	1065	260.01	1.447	.831	.505	.109	6/ 6	130 Hz
4	.50	1477	360.60	2.225	.348	.533	.105	6/ 6	
4	.50	2047	499.76	2.577	.144	.524	.146	5/ 5	

---

*Notes: (1) Duration is measured in msec, intensity in digital-to-analog-converter units, and charge in nano coulombs; (2) N is the number of audible trials for each condition of stimulation; (3) pulse-train stimuli were presented in 300 msec bursts with a rise/fall time of 5.0 msec; and (4) the pulse repetition frequencies for each channel of stimulation are indicated in the rightmost column of the table.

Table 6. Judgments of Pitch Across Channels, Bipolar Pairs, Different Frequencies of Pulsatile Stimulation for Different Channels.

Pitch reports for all audible stimuli:

Chan	Pitch	SD	N
1	.347	.057	36
2	.455	.111	33
3	.500	.071	23
4	.502	.110	21

Pitch reports for the loudness range of 0.5 to 1.5:

Chan	Pitch	SD	N
1	.395	.007	2
2	.000	.000	0
3	.410	.000	1
4	.535	.205	2

Pitch reports for the loudness range of 1.5 to 2.5:

Chan	Pitch	SD	N
1	.320	.039	13
2	.405	.121	15
3	.497	.076	11
4	.528	.093	13

Pitch reports for the loudness range of 2.5 to 3.5:

Chan	Pitch	SD	N
1	.357	.069	14
2	.489	.081	15
3	.511	.077	8
4	.560	.166	5

---

*Note: The frequency of stimulation for channel 1 was 90 Hz; for channel 2, 100 Hz; for channel 3, 120 Hz; and for channel 4, 130 Hz.

Table 7. Judgments of Loudness and Pitch, Monopolar Electrodes, 100 Hz.

The results of the loudness and pitch measures were the following*:

Chan	Duration	Intensity	Charge	Loudness	SD	Pitch	SD	N
1	.50	20	4.89	.682	1.151	.300	.000	3/ 3
1	.50	28	6.84	.753	.962	.300	.008	4/ 4
1	.50	38	9.28	2.025	.789	.297	.005	6/ 6
1	.50	53	12.94	2.676	.262	.303	.005	6/ 6
1	.50	72	17.58	2.880	.091	.302	.004	6/ 6
1	.50	100	24.41	3.193	.163	.302	.004	6/ 6
2	.50	20	4.88	1.034	--------	.310	--------	1
2	.50	26	6.35	1.441	.939	.300	.000	5/ 5
2	.50	35	8.54	1.816	.907	.315	.043	6/ 6
2	.50	46	11.23	2.273	.290	.300	.006	6/ 6
2	.50	61	14.89	2.617	.187	.307	.027	6/ 6
2	.50	80	19.53	2.907	.046	.305	.008	6/ 6
3	.50	20	4.88	1.720	.949	.320	.045	5/ 5
3	.50	28	6.84	2.140	.598	.318	.040	6/ 6
3	.50	40	9.77	2.305	.167	.317	.036	6/ 6
3	.50	56	13.67	2.797	.176	.297	.020	6/ 6
3	.50	78	19.04	3.013	.280	.307	.014	6/ 6
3	.50	110	26.86	3.291	.265	.102	.541	6/ 6
4	.50	10	2.44	.038	.035	.347	.057	3/ 3
4	.50	16	3.91	.708	.878	.315	.242	6/ 6
4	.50	25	6.10	1.750	.897	.302	.004	6/ 6
4	.50	40	9.77	2.489	.256	.307	.000	6/ 6
4	.50	63	15.38	2.871	.127	.350	.086	6/ 6
4	.50	100	24.41	3.235	.231	.365	.076	6/ 6
5	.50	10	2.44	2.534	.692	.305	.007	2/ 2
5	.50	16	3.91	1.250	1.202	.308	.010	6/ 6
5	.50	24	5.86	1.814	.910	.337	.054	6/ 6
5	.50	37	9.03	2.546	.226	.362	.049	6/ 6
5	.50	58	14.16	2.735	.131	.377	.075	6/ 6
5	.50	90	21.97	3.045	.189	.432	.148	6/ 6
6	.50	10	2.44	2.256	.330	.300	.000	2/ 2
6	.50	16	3.91	.000	--------	.310	--------	1
6	.50	24	5.86	1.559	.870	.360	.295	5/ 5
6	.50	37	9.03	2.468	.273	.377	.106	6/ 6
6	.50	58	14.16	2.652	.182	.382	.079	6/ 6
6	.50	90	21.97	2.934	.102	.522	.069	6/ 6
7	.50	40	9.77	.788	.790	.302	.004	5/ 5
7	.50	50	12.21	2.203	.585	.336	.053	6/ 6
7	.50	62	15.14	2.527	.172	.365	.051	6/ 6
7	.50	77	18.80	2.661	.223	.410	.075	6/ 6
7	.50	96	23.44	2.754	.235	.432	.068	6/ 6
7	.50	120	29.30	2.797	.109	.445	.073	6/ 6

---

*Notes: (1) Duration is measured in msec, intensity in digital-to-analog-converter units, and charge in nano coulombs; (2) N is the number of audible trials for each condition of stimulation; and (3) pulse-train stimuli were presented in 300 msec bursts with a rise/fall time of 5.0 msec.

Table 8. Judgments of Pitch Across Channels,
Monopolar Electrodes, 100 Hz.

Pitch reports for all audible stimuli:

Chan	Pitch	SD	N
1	.301	.005	31
2	.306	.022	32
3	.275	.224	35
4	.329	.057	33
5	.359	.085	32
6	.400	.105	25
7	.383	.077	35

Pitch reports for the loudness range of 0.5 to 1.5:

Chan	Pitch	SD	N
1	.300	.000	1
2	.305	.007	2
3	.400	.000	1
4	.300	.000	2
5	.000	.000	0
6	.000	.000	0
7	.300	.010	3

Pitch reports for the loudness range of 1.5 to 2.5:

Chan	Pitch	SD	N
1	.302	.007	8
2	.306	.028	14
3	.315	.274	14
4	.301	.003	9
5	.328	.049	11
6	.355	.077	10
7	.388	.084	12

Pitch reports for the loudness range of 2.5 to 3.5:

Chan	Pitch	SD	N
1	.301	.005	18
2	.307	.218	12
3	.221	.318	17
4	.341	.274	14
5	.390	.101	17
6	.429	.111	15
7	.396	.071	19

Chan	Duration	Intensity	Charge	Loudness	SD	Pitch	SD	N
1	.50	40	9.77	2.034	.041	.363	.060	3/ 3
1	.50	57	13.92	.742	1.256	.337	.064	3/ 3
1	.50	82	20.02	2.004	.639	.277	.035	6/ 6
1	.50	117	28.56	2.601	.163	.288	.015	6/ 6
1	.50	168	41.02	2.761	.131	.342	.117	6/ 6
1	.50	240	58.59	3.214	.508	.345	.094	6/ 6
2	.50	40	9.77	1.349	.787	.397	.159	3/ 3
2	.50	57	13.92	.975	1.331	.336	.060	5/ 5
2	.50	82	20.02	2.441	.250	.330	.079	6/ 6
2	.50	117	28.56	2.547	.199	.290	.014	6/ 6
2	.50	168	41.02	2.771	.103	.367	.097	6/ 6
2	.50	240	58.59	3.051	.340	.437	.135	6/ 6
3	.50	40	9.77	2.074	.693	.310	.008	4/ 4
3	.50	57	13.92	2.434	.171	.295	.010	6/ 6
3	.50	82	20.02	2.634	.153	.308	.041	6/ 6
3	.50	117	28.56	2.669	.249	.292	.010	6/ 6
3	.50	168	41.02	2.782	.184	.580	.128	6/ 6
3	.50	240	58.59	2.880	.389	.687	.189	6/ 6
4	.50	40	9.77	.589	1.009	.313	.045	6/ 6
4	.50	57	13.92	2.002	1.061	.295	.008	6/ 6
4	.50	82	20.02	2.625	.137	.423	.137	6/ 6
4	.50	117	28.56	2.653	.176	.453	.128	6/ 6
4	.50	168	41.02	2.860	.407	.655	.124	6/ 6
4	.50	240	58.59	2.862	.227	.952	.044	6/ 6
5	.50	40	9.77	2.152	.115	.362	.057	5/ 5
5	.50	57	13.92	2.345	.189	.433	.111	6/ 6
5	.50	82	20.02	2.640	.093	.545	.065	6/ 6
5	.50	117	28.56	2.636	.111	.485	.144	6/ 6
5	.50	168	41.02	2.943	.151	.748	.088	6/ 6
5	.50	240	58.59	2.987	.326	.892	.095	6/ 6
6	.50	60	14.65	2.263	.628	.358	.073	6/ 6
6	.50	82	20.02	2.648	.129	.417	.137	6/ 6
6	.50	111	27.10	2.682	.111	.542	.171	6/ 6
6	.50	151	36.87	2.750	.168	.680	.070	6/ 6
6	.50	206	50.29	2.860	.203	.863	.079	6/ 6
6	.50	290	68.36	2.899	.228	.995	.005	6/ 6
7	.50	60	14.65	.189	.334	.316	.053	5/ 5
7	.50	82	20.02	1.555	1.044	.359	.020	5/ 5
7	.50	111	27.10	2.159	.320	.413	.062	6/ 6
7	.50	151	36.87	2.560	.068	.510	.132	6/ 6
7	.50	206	50.29	2.805	.169	.642	.051	6/ 6
7	.50	280	68.36	2.774	.131	.692	.197	6/ 6

---

*Notes: (1) Duration is measured in msec, intensity in digital-to-analog-converter units, and charge in nano coulombs; (2) N is the number of audible trials for each condition of stimulation; and (3) pulse-train stimuli were presented in 300 msec bursts with a rise/fall time of 5.0

Table 10. Judgments of Pitch Across Channels, Monopolar Electrodes, 300 Hz.

Pitch reports for all audible stimuli:

Chan	Pitch	SD	N
1	.320	.075	30
2	.357	.100	32
3	.419	.188	34
4	.515	.247	36
5	.584	.208	35
6	.642	.252	36
7	.497	.175	34

Pitch reports for the loudness range of 0.5 to 1.5:

Chan	Pitch	SD	N
1	.280	.000	1
2	.000	.000	0
3	.310	.000	1
4	.290	.000	1
5	.000	.000	0
6	.300	.000	1
7	.290	.000	1

Pitch reports for the loudness range of 1.5 to 2.5:

Chan	Pitch	SD	N
1	.321	.070	11
2	.347	.102	8
3	.400	.150	9
4	.440	.194	8
5	.401	.094	11
6	.447	.199	3
7	.359	.060	9

Pitch reports for the loudness range of 2.5 to 3.5:

Chan	Pitch	SD	N
1	.309	.076	15
2	.366	.112	19
3	.429	.194	24
4	.598	.260	22
5	.654	.198	24
6	.660	.252	33
7	.580	.157	21