Auditory Nerve: Electrical Stimulation in Man

Abstract. *Auditory perceptions produced in a person deaf to acoustic stimulation were studied by electrically exciting the auditory nerve through permanently implanted electrodes. Pulsed current as small as 1 microampere peak-to-peak could be perceived. Pitch, as reported by the subject, varied with electrode selection, current amplitude, and pulse repetition rate from about 70 to at least 300 pulses per second. Loudness increased with amplitude and duration of pulse stimuli, and to a lesser extent with repetition rate. The total range in amplitude of the stimulus, from threshold to an uncomfortable loudness, was 15 to 20 decibels. Simultaneous stimulation in separate electrodes produced a number of complex effects.*

In this report we describe the results of experiments in which direct electrical stimulation was applied to the auditory nerve of a conscious human subject (*1*). The feasibility of such experiments and of eliciting reports of specific auditory sensations has already been demonstrated (*2*), although in most instances the conditions under which such perceptions were obtained allowed neither precise quantification of the results nor long-term testing of the subjects.

Our subject was a 60-year-old male who has been totally deaf in his right ear for several years. Hearing in his left ear was adequate until February 1964, when it deteriorated rapidly. Thereafter, only very intense acoustic stimulation could elicit an auditory response. No ability to discriminate speech has remained. Though the cause of the deafness remains unknown, it is quite possibly related to the subject's typical retinitis pigmentosa, present in some degree since childhood and now causing severe tunnel vision. It is thus possible to communicate verbally to him only by written messages in large block letters. His speech has not deteriorated, and his alertness and motivation remained high throughout this work.

In May 1964, two of us (F.B.S. and J.M.E.) permanently implanted a cluster of six gross electrodes in the modiolus portion of the eighth nerve on the right side, probably among fibers from the basal cochlear coil (see Fig. 1). The implant was performed under local anesthesia, so that the subject's responses to electrical stimulation through the electrodes could be utilized to insure that final placement was in the acoustic portion of the nerve. The electrodes led to a connector threaded into the skull just behind the right ear, where external contact could be made (*3*). After surgery, the remaining authors were invited to collaborate in the psychophysical experiments.

In most experiments, the stimulus was a regular train of biphasic pulses or a sinusoid, although other waveforms were tried including ramps, random noise (wide pass-band), randomly occurring pulses, speech, and pulse-encoded speech. All stimuli were supplied from a high-impedance source and were transformer-coupled so as to have no d-c component. Both bipolar stimulation (exciting current applied between two of the electrodes) and monopolar stimulation (indifferent electrode on the forehead) were tried. In most tests only one electrode pair was stimulated at a time, but in some trials several signals stimulated different electrode pairs simultaneously. Resistance between two electrodes averaged about 50,000 ohms initially but several months later averaged 100,000 ohms.

Stimulation through the electrodes was begun about 2 weeks after implantation. After the first few trials it became clear that the subject experienced differentiated auditory sensations, but was unable to describe them satisfactorily because he did not understand terms such as pitch. Therefore, a certain amount of instruction was given in which we utilized the residual hearing in the left ear for high-intensity tones. Reference was made to sounds familiar to the subject, such as those of musical instruments. Since this training, he has been a consistent observer.

In most experiments, when electrical signals were applied to the electrodes the subject either attempted to describe what he heard in terms of common sounds that he remembered, or he compared two signals presented sequentially and judged a specified quality of the second relative to the first. We often had to rely upon the second method since the subject was frequently reluctant to provide anecdotal descriptions.

A study of the parameters governing threshold disclosed that whereas large changes in repetition rate (for example, from 1 to 100 pulses per second) at constant pulse duration altered threshold by only a factor of two or three, the effect of changes in pulse duration was considerably greater. At a fixed repetition rate in the range 1 to 100 pulse/sec, increasing the pulse duration from 1 to 10 msec reduced threshold by a factor of about 50. The minimum pulse amplitude that elicited a response with monopolar stimulation was of the order of 1 μa peak-to-peak, and varied very little with electrode selection. With bipolar stimulation, on the other hand, the thresholds associated with various electrode pairs varied more widely, and on the average were higher than monopolar thresholds. Threshold also depended upon the polarity of the biphasic pulse; when an electrode in the nerve was made initially negative (relative to an indifferent electrode on the forehead), the current required for audibility was about half that required when the opposite polarity was employed.

All suprathreshold stimulation was perceived as auditory sensation. As might be expected, the loudness of these sensations always increased with the amplitude of the stimulation current. Loudness also grew with increases in pulse duration, and to a lesser extent with repetition rate. A fine control of loudness was possible, and the subject often selected his own "comfortable listening level" for suprathreshold experiments. The stimulus level usually selected was between 5 and 10 decibels above his threshold, and remained constant, without further adjustment of the stimulus, for several minutes at a time. More intense, "uncomfortably loud" sounds were produced by stimuli 15 to 20 decibels above threshold, the exact amount depending upon the stimulus parameters selected. Occasionally, intense stimulations may have caused poststimulatory tinnitus and threshold shifts, and on two occasions intense monopolar stimulation at low repetition rates produced slight synchronous facial twitching. Except for these two instances, there were no signs of electrical spread outside the acoustic eighth nerve. No vestibular sensations or pain have so far been described by the subject.

Many experiments were devoted to exploring the relation between "pitch" (*4*) and the stimulus parameters. One notable finding was that even a single stimulus pulse was reported to possess a "pitch." Such a "pitch" was associated with each electrode, and the subject could rank the electrodes according to their characteristic "pitch." In particular, when the stimulus consisted of one monopolar biphasic pulse per second and when the stimulus was adjusted in each electrode to produce equal loudness, one electrode had a considerably higher "pitch" than any of the others; two electrodes were equal in "pitch" and lower than the first; two others were slightly lower still and about equal to each other; one electrode consistently produced the lowest "pitch." Generally, this ranking was independent of stimulus waveform, repetition rate, and intensity. A ranking of electrode pairs according to "pitch" also appeared with bipolar stimulation, but possibly in a more complex manner since the relative rank of some combinations was affected by stimulus parameter changes. It was impossible to determine what these "pitches" were, but, judging from the subject's description of the sounds and from some crude attempts to scale them, we place these characteristic "pitches" high on the pitch scale. Such high-pitch sensations would be expected on the basis of a place theory of pitch perception if, as we suppose, the electrodes terminate among cochlear nerve fibers from the basal turn.

At near-threshold intensities, the subject attributed very little, if any, "pitch" to pulse trains or sine waves, regardless of repetition rate, while, for more intense stimuli of the same type, "pitch" rose with stimulus intensity. On the other hand, reports of a lower "pitch" with increased stimulus amplitude did occur but were largely confined to situations in which several electrode pairs were stimulated simultaneously.

Variation of stimulus frequency from 1 to about 300 pulse/sec and 20 to 300 cy/sec (sinusoids) produced consistent changes in the "pitch" of the resulting sound. However, we are uncertain about the nature of the perceptual continuum between the lowest and highest rates. At pulse repetition rates of about 1 pulse/sec the sound produced was usually described as either a "ping" or "ding." As the rate

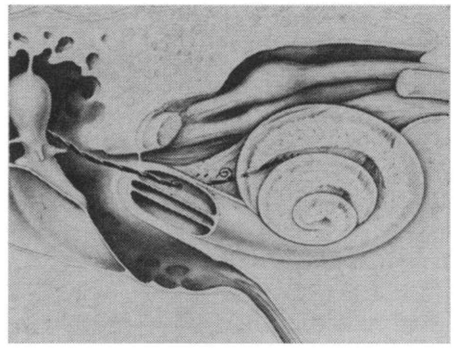

Fig. 1. Approximate configuration and location of electrode complex within the modiolus. Five, 0.003-inch (75-μ) stainless steel electrodes, insulated with Formvar, were spiraled around a 0.005-inch (125-μ) electrode, and exposed only at the tips. The drawing indicates that probably one, perhaps two electrodes, are bent away from the others. Otherwise, the tip separations were about 1 mm.

was increased to 3 to 4 pulse/sec, pulses were described as individually heard "clicks" which seemed to merge into a "buzz" at rates above about 10 per second. At times, 10-pulse/sec rates were described as "telephone ringing," but this description was usually volunteered only as the stimulus rate increased beyond about 20 per second, depending upon stimulus intensity and electrode selection. As stimulus rates were increased beyond 30 pulse/sec, the predominant descriptive term changed to "car horn," "telephone ring muffled by pillow," or "bee buzz." A transition in the "nature of the sound" (but not necessarily its "pitch") from "a buzzing sound" to a "steady sound" took place between 50 and 80 pulse/sec. Rates between 100 and 300 pulse/sec were typically described as "steady high-pitched ringings," "whistles," or "buzzes."

Stimuli in the range of 50 to 300 pulse/sec which the subject judged to be of equal loudness had to differ in frequency by at least 30 pulse/sec in order to be distinguished, although only slightly greater differences in frequency were judged to be considerably different in "pitch." The values given for the range over which repetition rates could be distinguished and for the frequency difference limen apply to both pulse and sinusoidal stimulation, and the same range and difference limen were found in all electrodes. Again, judging from the subject's description of the sounds and from crude scaling, we place the "pitches" associated with the repetition rate at the lower end of the pitch scale. The comparison with a bee buzz offered by the subject seemed particularly informative because it corresponds to low-frequency modulation of a signal of higher frequency.

We must be cautious in interpreting these observations on pitch since it appears that we are dealing with auditory perceptions containing multiple pitch components. It does seem clear enough that one pitch quality is characteristic of each electrode—thereby corresponding to a place-pitch representation—and that another quality is independent of electrode selection but is associated with stimulus repetition rate—corresponding to a volley-pitch representation (*5*). The upper limit of discrimination of the repetition rate (300 pulse/sec) may only represent the highest rate detectable by the psychophysical method employed (*6*). It is consistent with one psychoacoustic study (*7*), but falls short of the 750- to 1000-per-second limit found by Harris (*8*). Synchronous neural firing in response to repetitive acoustic stimuli has been detected at repetition rates of up to 200 per second at the auditory cortex (*9*), 2000 per second in the brainstem (*10*), and 4000 per second in the eighth nerve (*11*).

We also studied the ability of the subject to resolve auditory events closely spaced in time. Two short pulses in the same electrode presented at moderate amplitude with a small enough time interval between them were perceived as a single "tick" or "ding," but if the time interval was about 5 msec or greater the subject was able to resolve the two pulses perceptually, reporting a "doubleness" or "echo." When the pulses were presented at higher amplitude, so that the sensation was quite loud, the minimum resolvable interval increased from 5 msec to 10 msec.

It appeared to be possible for at least two stimuli to retain their perceptual identities when presented simultaneously through different electrode sets. With bipolar pairs of electrodes, one stimulus can also be made to "mask" another, or the two may interact to produce a third sound in addition to the two primary stimuli or in lieu of them. Several experiments on the perceptual effects of introducing trains of stimuli that alternated between two sets of electrodes were run to explore a facet of the volley theory of pitch perception. Two electrodes (monopolar stimulation) or two pairs of electrodes (bipolar stimulation) were selected which had approximately equal "pitch." The subject was asked to compare two pulse trains, one at 50 pulse/sec and the other at 100 pulse/sec, applied to the same electrode; he judged the 100-pulse/sec presentation to have a much higher "pitch." He was then asked to compare 50 pulse/sec applied to one electrode with an equally loud signal consisting of 100 pulse/sec applied to the two electrodes alternately (odd-numbered pulses to one electrode and even-numbered pulses to the other so that each was pulsed at a rate of 50 per second). When presented in this way, the 100-pulse/sec stimulus was judged to have the same "pitch" as, or even a lower "pitch" than the 50-pulse/sec stimulus. In general, rectangular stimuli (duration, 1 to 2 msec) presented alternately in this way to two electrodes at rates between 20 and 200 per second did not combine to produce a pitch sensation any higher than that obtainable by presenting alternate pulses to one electrode alone (*12*).

If two sinusoids of equal frequency were used to stimulate two pairs of electrodes (bipolar stimulation), one phase condition regularly was described as "louder but lower pitch," while a phase reversal in one pair of electrodes evoked the response "very much higher pitch" than either stimulus alone, and no change in loudness. This higher "pitch" was not clearly related to a simple multiple of the basic stimulus rate and was, on occasion, judged to be higher than any single-channel stimulus that we could provide for comparison. It is obviously of considerable importance to resolve this unexpected perceptual dissimilarity between sets of alternating rectangular and sinusoidal waveforms.

The subject's inability to discriminate frequencies above 250 to 300 pulse/sec suggested that stimulation with an unmodified speech signal would not be understood, and this expectation was confirmed. However, such signals were recognized as speech by the subject, probably as a result of their rhythms. An attempt to separate the speech spectrum into frequency bands and to process each band so as to produce pulse stimuli which would make more efficient use of the characteristic "pitches" of the various electrodes also failed to produce any discrimination among speech-derived signals.

Attempts to record neural responses from one electrode while stimulating through another were terminated without success because of the difficulty in identifying a response amid the very large electrical artifacts associated with the stimulus.

Although much remains uncertain in our study, the results show that electrical excitation of the eighth nerve with currents of a few microamperes leads to an auditory sensation that increases in loudness with increasing current amplitude. "Pitch" is affected by both electrode selection and stimulus repetition rate, suggesting that two modes of "pitch" encoding are operative within one group of auditory fibers. It is unlikely that stimulation with any speech-derived signal would permit this subject to discriminate an appreciable number of words, unless considerable learning were possible.

F. BLAIR SIMMONS
JOHN M. EPLEY
Division of Otolaryngology, Stanford University School of Medicine, Stanford, California
ROBERT C. LUMMIS
NEWMAN GUTTMAN
LAWRENCE S. FRISHKOPF
LEON D. HARMON
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
EBERHARD ZWICKER
Institut für Nachrichtentechnik, Stuttgart, Germany

References and Notes

1. The observations reported here are the mutually agreed upon and confirmed results of two series of experiments conducted independently. The first series was conducted by the first two authors at Stanford University, and the second by the remaining authors at the Veterans Administration Hospital in Lyons, New Jersey. We are aware that a degree of interpretive error may exist, and therefore caution the reader that the conclusions and interpretations of the data advanced at this time are tentative and are offered only in an attempt to clarify the relationships among the data.
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3. Complete technical details will be reported in subsequent publication.
4. The word pitch is enclosed in quotation marks whenever it is used to report a description or judgment made by the subject, because "pitch" was the only word used to denote a measure of the tonal quality in communication with the subject. Timbre might be more appropriate in some places, but to distinguish between pitch and timbre would require a more intimate appreciation of the subject's auditory sensations than is possible.
5. The two kinds of "pitch" were probably elicited simultaneously by many stimuli, and under some conditions were confused by the subject. For example, when the frequency of sinusoidal or pulse stimuli was varied in the range of about 20 to 70 per second, the resulting sensations were readily identified as different, but "pitch" judgments were difficult. On those occasions when he was willing to make "pitch" comparisons for pulse stimuli of these frequencies, lower rates were judged higher in "pitch." We think these judgments indicate that at low stimulation frequencies (that is, below 30 pulse/sec) the high characteristic "pitch" of the electrode dominates the sensation, while at higher stimulation frequencies (between 70 and about 300 pulse/sec) the "pitch" associated with the low repetition rate dominates the sensation.
6. There is some suggestion that a different testing procedure would result in substantially higher repetition rates being discriminated from one another, but this problem was not studied by both laboratories and is therefore not discussed in this report.

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12. It should be pointed out that this observation can be made with some degree of certainty only for stimuli equally loud separately. Manipulation of stimulus intensity in one electrode during simultaneous stimulation did upon occasion produce pitch percepts described as different from those obtained by stimulating either electrode alone.
13. Although this research itself was not supported by outside funds, we acknowledge the National Institutes of Health, NINDB grant B-2167, which supported the animal experiments preceding this work.

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