Cochlear implants*

By R. P. MICHELSON (San Francisco)

SPEECH discrimination by means of electrical stimulation of the auditory nerve alone has not so far been possible. The single channel devices which we have thus far used, synchronously stimulate a large segment of auditory nerve. The resulting sensation of hearing is produced by the mechanism of 'periodicity pitch'. No 'place pitch' encoding of sound is possible with these devices. In total deafness lip reading skills are enhanced and awareness of environmental sounds have resulted. Thus the distressing isolation of this disability has been partially overcome.

Pitch discrimination performed by the patients is near-normal, up to 600–700 Hz. Tonal sensation is present, however, even at frequencies as high as 10 kHz. Paradoxically sine and square wave stimuli, even at high frequencies, produce different auditory percepts.

Thus far it has not been possible to produce neural activity patterns with sufficient information content for the unaided recognition of speech or other complex sounds.

Histopathological studies by Robert Schindler (Schindler and Merzenich, 1974) and physiological studies by M. Merzenich (Merzenich *et al.*, 1973) indicate that functioning auditory nerve survives cochlear implantation even though massive hair cell destruction occurs. Injury to basal membrane does however produce severe localized neural degeneration.

Implantation of small electrode arrays into spiral ganglion also results in some localized neural degeneration (Simmons, 1969).

These animal findings correlate well with patient observations. No deterioration in patient threshold has been observed after periods extending to five years.

Threshold responses of our patients and those obtained from animal inferior colliculus neurons were nearly identical (Fig. 1).

The sensation of loudness varied in ordered relation to electrical stimulus strength.

Merzenich has shown in animals that phase-locked activity breaks up when stimulus frequencies are greater than 700 Hz. This observation correlated very well with pitch scaling experiments performed with our implanted patients.

As previously indicated our early single channel prosthetic devices were capable only of synchronously stimulating a broad segment of

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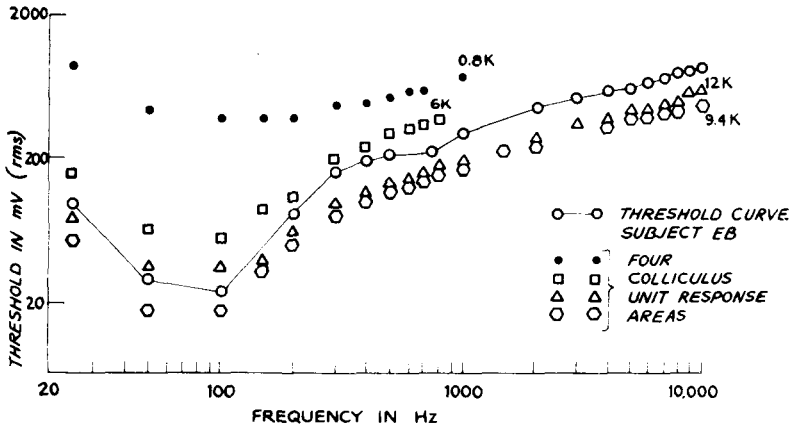


FIG. 1.

Threshold to electrical stimulation of the auditory nerve in man and laboratory animal. Reproduced from *The Annals of Otology, Rhinology and Laryngology* with the kind permission of the editor.

auditory nerve. The stimulus form was the electrical analog of the acoustic input modified in two ways. First the frequency response of the external driving system was modified so that the patient's threshold response was flat. Second, an automatic gain control was incorporated, which effectively increased the patient's dynamic range from approximately 15db to 50db. In addition, efforts were made to reduce system harmonic distortion to a minimum. With these modifications, implanted subjects reported that voices sounded 'natural' and in some instances they were able to distinguish voices of the same sex. There was no difficulty in distinguishing male from female voices. Unaided speech discrimination was still not possible.

An A.M. radio frequency system was first used to transmit information across the intact skin to the internal receiver. Electromagnetic interference did not present a problem. Component failure, however, did present a problem. The broad frequency response (100 hz to 20 kHz) was advantageous. Later simple electromagnetic coupling across the skin proved to be the most reliable, although frequency response was limited to 300 Hz to 4 kHz.

Patient acceptance in our small carefully selected series was surprisingly good in spite of repeated failures requiring replacement of the implant.

Our experience to date has been limited to genetic and ototoxic deafness; the results in the two types of deafness have been very similar. Enhancement of lip-reading skills and recognition of environmental sounds resulted in each case. Our one prelingually deaf patient did not improve her communication skills although she expressed pleasure with simple environmental sounds which she quickly learned to recognize.

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It now appears that multichannel differential stimulation of the auditory nerve will be necessary, if recognizable speech patterns are to be generated by this means. Means of 'place' as well as 'periodicity' encoding of speech signals must be provided. Work in our laboratory principally by Merzenich (Merzenich *et al.*, 1974) has demonstrated the feasibility of exciting small segments of auditory nerve through the scala tympani. The observations in animals were made with a platinum electrode permanently implanted in a laboratory animal. The electrode was 0·003 inches in diameter, and was held in place against the under surface of the basal membrane by means of a molded silastic insert. Isolation between stimulating electrodes at best was on the order of 25 db per octave. It is possible that even better performance can be obtained with different electrode configurations. Using simple bipolar electrodes, preliminary observations indicate that electrode spacings of less than 200 microns degrade performance. Placement against the bony modiolus is ineffective. With properly placed electrodes, performance improves up to about six weeks, evidenced by a decrease in threshold stimulus amplitude. Histologic studies indicate that the formation of a connective tissue envelope around the implant effectively isolated the electrical contacts from the conductive cochlear fluids.

The total number of channels (electrodes) that are feasible will probably be determined by the electrical field size producing the maximum sensation level.

The length of basal membrane that need be differentially excited for speech discrimination is probably 20 mm. at the basal end or approximately 1½ turns of the basal coil.

Our group at the University of California, San Francisco, have developed an eight channel electrode array that can be inserted into the human cochlea through the round window for a distance of 23 mm. In addition, new molding techniques have provided a more accurate fit to the contours of the scala tympani. This will allow even more accurate electrode alignment.

An important objective is to determine the most effective mode of electrical stimulation. More exact information on tissue-electrode interface reactions as well as more exact details of neurons excitation under these conditions are sorely needed.

Two methods of encoding information for the meaningful excitation of the auditory nerve array seem to warrant investigation at this time. First the analog electrical stimulus and second the pulse stimulus. Each of these modes of stimulation can be programmed in many ways in a systematic manner and the percepts determined.

Our group have presently under design consideration an implantable device consisting of eight channels. Eight active analog filters are provided with their centre frequencies at 1/2 octave intervals from 700 Hz to 8 kHz.

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The frequency elements of speech would be delivered to the appropriate 'frequency place' of the neural array in the basal membrane.

This device and our previous single channel device has serious limitations of flexibility for research purposes. With this idea in mind, preliminary engineering studies indicate that a device might be constructed within the desired size constraints and have the following characteristics:

1. Independent control of each channel.
2. Sufficient channel band-width to allow delivery of a wide variety of stimulus wave forms including specified pulses.
3. Backward telemetry to provide monitoring the actual stimulus parameters *in situ*.

With such a device, the perceptual consequences of various stimulus parameters could be compared in a single individual.

Summary and conclusions

All presently devised single channel devices generate a primitive sensation of hearing by the mechanism of 'periodicity pitch'. No 'place pitch' encoding is possible. Although some enhancement of communicative skills with lip reading results, unaided speech discrimination is not possible. Definite psychological advantages for the totally deaf have been observed with these simple devices.

Multiple segments of auditory nerve must be stimulated in a manner which will simulate the complex patterns of neural activity necessary for speech discrimination.

Electrode optimization and the pathophysiological consequences of electrical stimulation of the auditory nerve can best be determined in animals. The perceptual consequences of electrical stimulation of the auditory nerve, however, can best be determined in man.

How much we will have to innovate the methods of aural rehabilitation will depend upon how well we can generate perceptual speech patterns by electrical excitation of the auditory nerve.

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Department of Otolaryngology,
University of California at San Francisco,
Coleman Memorial Laboratory,
San Francisco,
California 94143.

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