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George Adelman

Foreword by Francis O. Schmitt

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A *Pro Scientia Viva* Title

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Auditory Prosthesis

Gerald E. Loeb

Functional auditory prostheses provide an information-carrying interface between electronic systems and neuronal systems. They provide coherent sensations of sound in patients suffering from profound (usually total) deafness as a result of various traumatic, infectious, and hereditary diseases that cause loss of the cochlear hair cells. These cells normally transduce the mechanical vibrations of sound waves (entering the fluid-filled cochlear chambers, via the middle ear ossicular chain) into bioelectric impulses to the brain. The axons of the spiral ganglion cells which make up the auditory nerve convey these impulses from the organ of Corti on the basilar membrane (where the hair cells are located) to the brain stem auditory nuclei. In the absence of the hair cells, the remaining spiral ganglion cells can be activated directly by electrical currents from stimulating electrodes either in or near the cochlear chambers (usually at the round window entrance or in the scala tympani) or in the auditory nerve proper as it courses through the bony modiolar canal. The auditory nerve activity so elicited is interpreted as sound by the central nervous system, with loudness, pitch, and timbre apparently dependent on the amplitude, location, and waveform of the stimulating current.

About a dozen different single-channel and multichannel devices are now in various stages of animal and clinical research and are beginning to be commercially available. All share the general components shown in Figure 1, including external parts similar to a hearing aid (battery-powered, wearable control box with a microphone) plus a radio telemetry link that conveys information and power to the implanted electronics for generating the stimulus waveform and conveying it to the desired location(s).

Single-channel devices provide only a single, temporally modulated waveform to a single stimulating electrode site.

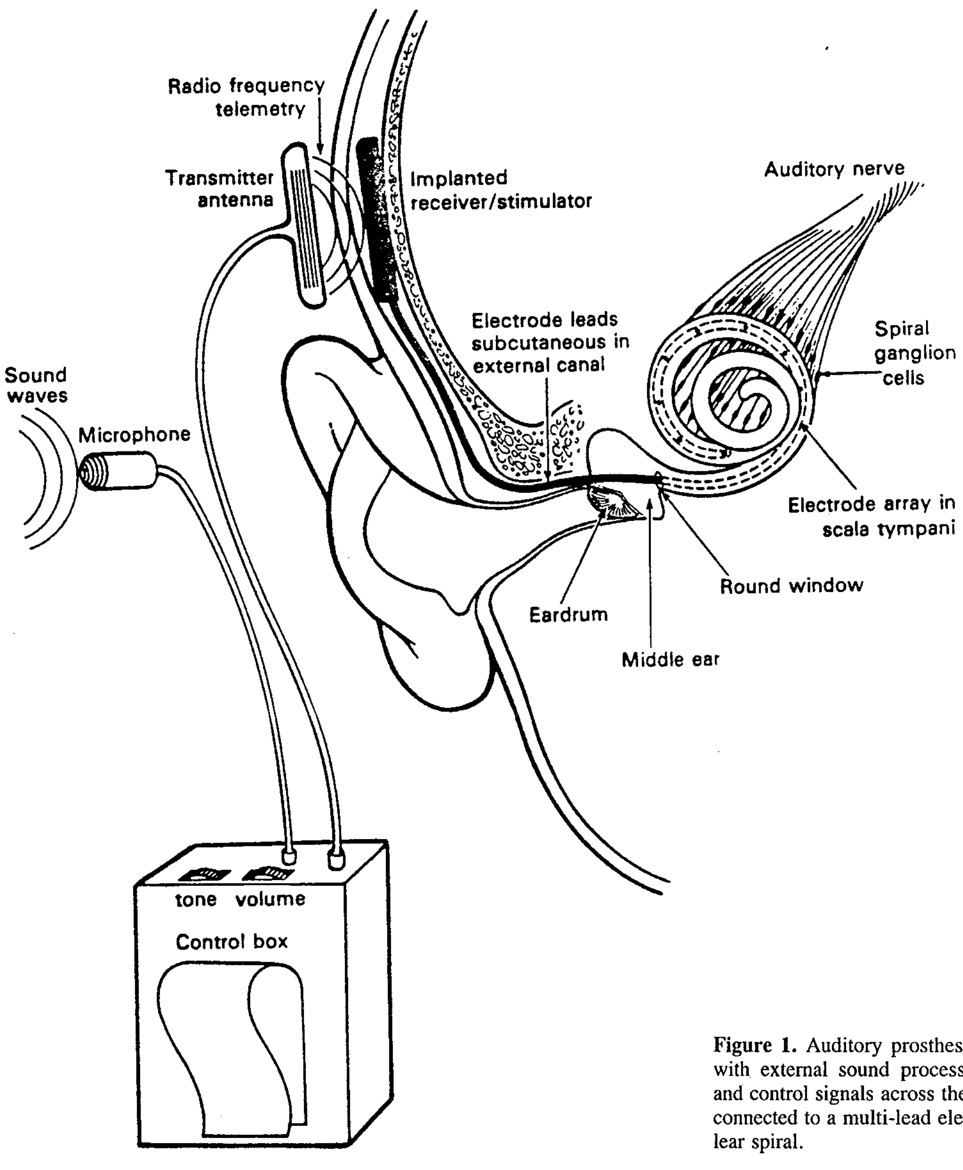

Figure 1. Auditory prosthesis. Typical multichannel cochlear prosthesis with external sound processor, radio frequency transmission of power and control signals across the skin, and implanted receiver and stimulator connected to a multi-lead electrode array inserted 1½ turns into the cochlear spiral.

This signal may be simply a filtered and dynamically compressed version of the acoustic signal picked up by the microphone or it may be synthesized by complex algorithms for preprocessing the acoustic signal to enhance the intelligibility of human speech. Regardless of the form of processing or the site of the stimulating electrode, most patients appear to obtain similar benefits from single-channel prostheses, including significantly enhanced lip-reading, improved modulation of their own voices, and useful awareness and identification of ambient sounds. Both theoretical considerations and empirical results suggest that unaided speech perception probably is not possible with single-channel prostheses.

The approaches and results of multichannel prostheses, most of which are still in early stages of clinical research, are much less easily summarized. All the multichannel systems attempt to make use of the tonotopic organization of the normal cochlea, in which high-frequency sounds are normally transduced at the basal end of the mechanically tuned basilar membrane, and lower frequencies are represented progressively more apically in the spiral. Multicontact electrode arrays have been implanted in the cochlea so as to permit local stimulation of subsets of the spiral ganglion cells. As might be expected, the stimulation of several such adjacent sites individually gives rise to sensations of sound with a distinct spatial ordering of pitch, at least as long as the stimulus intensity is low enough to activate only those ganglion cells in the immediate vicinity of each stimulating electrode. Unfortunately, the quality of the sound is not at all tonelike, even for presumably well-localized stimulation, regardless of the frequency or waveform of the electrical stimulus.

Despite this limitation, most multichannel prostheses have proceeded with stimulation schemes based on the principle of a frequency-channel vocoder synthesizer. Intelligible speech can be synthetically reproduced by six to eight single-frequency sound sources, each temporally modulated in proportion to the instantaneous power present in the band of frequencies immediately surrounding the center frequency of the source oscillator. Multichannel prostheses usually filter the incoming acoustic information into bands corresponding to the place-pitch sensations evoked by each available stimulating electrode site, and they use multichannel telemetry to modulate appropriately the electrical activation of each site. Systems with just four such independent channels have resulted in significant levels of word recognition in some but not all deaf subjects. As many as eight independent channels are probably feasible based on biophysical and technological considerations.

The ultimate capabilities of multichannel auditory prostheses will depend on progress in three key areas: 1. Biomaterials engineering. With the technology and materials currently available, we have probably gone as far as we can in the fabrication of complex devices and their safe surgical insertion and long-term operation in the delicate and confined space of the cochlea. 2. Electrophysiological factors. The selective activation and external control of one group of neurons, located in electrically conductive fluids and adjacent to other neurons, is a complex biophysical problem. Critical factors include the exact location, size, and orientation of the electrode contacts as well as the numbers and conditions of the remaining spiral ganglion cells; the latter appear to be highly variable among deaf subjects. 3. Speech processing. It is not clear why or how the various electrical stimulation parameters give rise to the particular sound sensations that have been reported, nor is there any theory to suggest how to transform optimally the acoustic speech signal into electrical stimuli that will provide the critical cues for word recognition despite the complex distortions.

See also Auditory System; Deafness; Prostheses, Neural

Further reading

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Schindler RA, Merzenich MM, eds. (1985): *Cochlear Implants.* New York: Raven Press

Auditory System

John F. Brugge

The auditory system is remarkable in the range of sound frequencies and intensities it can detect and in the small differences in these parameters it can discriminate. A young listener can hear sounds ranging in frequency from 20 Hz (cycles per second) to 20,000 Hz (20kHz). Within this range, as little as a 0.1% change in frequency is detectable. In the intensity domain, the same listener detects displacements of the ear drum two orders of magnitude smaller than the diameter of a hydrogen atom. At the same time, hearing is quite clear when the amplitude of the sound is raised by a factor of 10^6, which gives good listeners a dynamic range of more than 100 decibels (dB) on the scale of acoustic energy. Within this dynamic range, a change of 1 or 2 dB is easily detected. Our listener may detect with uncanny accuracy the location of a sound in space and will discriminate between two speakers located within a few degrees of each other on the horizontal plane. This ability to both detect and discriminate sounds is achieved by mechanisms operating at the levels of the external ear, middle ear, and inner ear (Fig. 1) and in the central auditory pathways of the brain (Fig. 2).

External ear

The external ear consists of the pinna (auricle) and external ear canal which is closed at its central end by the ear drum or tympanic membrane. The shapes of the pinna and ear canal help to amplify sound by as much as 20 dB over a broad range of frequencies centered around 4 kHz. Pinnae vary considerably in size and shape from one mammalian species to the next and, especially in those mammals with mobile pinnae, this structure may act as a directional amplifier to aid in localizing the source of a sound in space.