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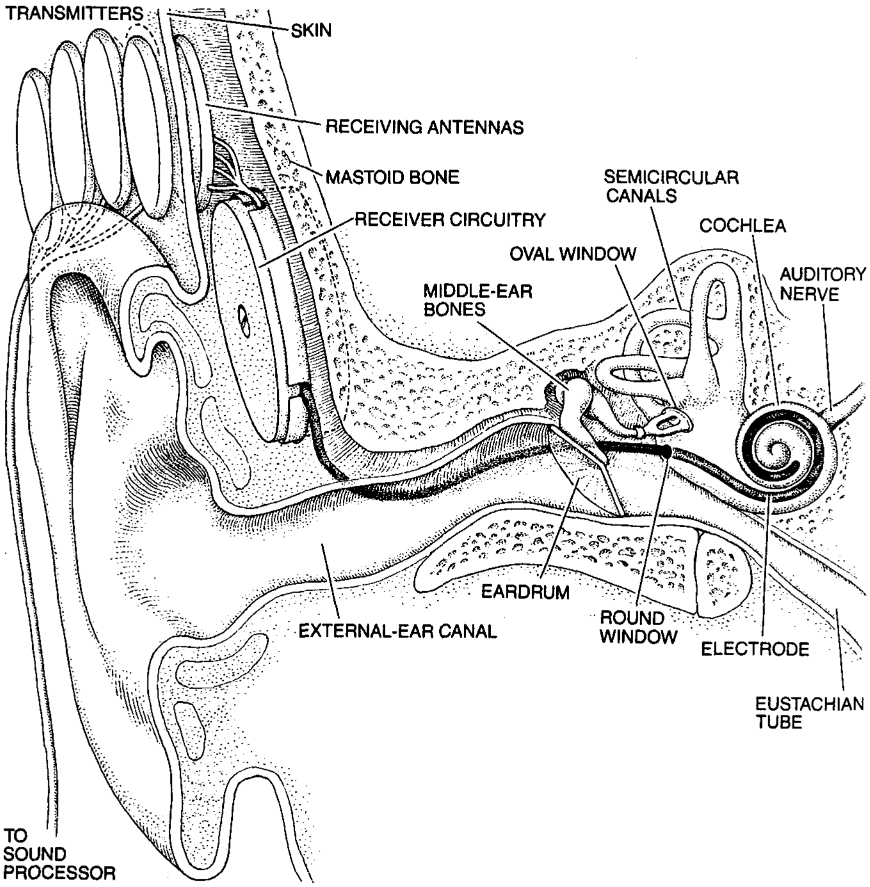
Recent advances in the fields of electronics and neurophysiology have led to the emergence of the new field of neural control. This experimental discipline relies on the exchange of information between an electronic circuit and a nervous system for the purpose of studying or supplementing a biological function. One of the main objectives of such research is the development of prosthetic devices for replacing defective parts of the human nervous system. Much of the progress in this area has resulted from long-term collaboration between teams of investigators engaged in both basic and applied research under the aegis of the Neural Prosthesis Program of the National Institute of Neurological and Communicative Disorders and Stroke. My own work on the functional replacement of the human ear has been done as part of such a project with a team at the University of California at San Francisco.

The cochlear implant, the particular neural prosthesis that is the subject of this article, is intended for patients with sensorineural deafness. In such patients the functioning of the sensory hair cells of the cochlea, the snail-shaped structure at the core of the inner ear, is impaired. In normal hearing sound travels through the external ear canal to the tympanic membrane, or eardrum, which transmits the vibrations in the air to a system of small bones in the middle ear. The innermost of these bones, called the stirrup, contacts the oval window, a membrane-covered opening in the base of the cochlea, relaying the vibration to the fluid-filled interior of the cochlea, where it is sensed by the hair cells in a structure known as the organ of Corti. The hair cells are arranged in four long rows on the basilar membrane, a flexible partition at the bottom of the organ of Corti that separates two of the cochlea's three parallel, spiral canals. The hair cells convert the vibration of the basilar membrane into an electrical signal, which travels along the auditory nerve to the brain.

Several kinds of cochlear implant have been designed to circumvent this elaborate transmission process in patients with sensorineural deafness. All the devices have four features in common: a microphone for picking up the sound, a microelectronic processor for converting the sound into electrical



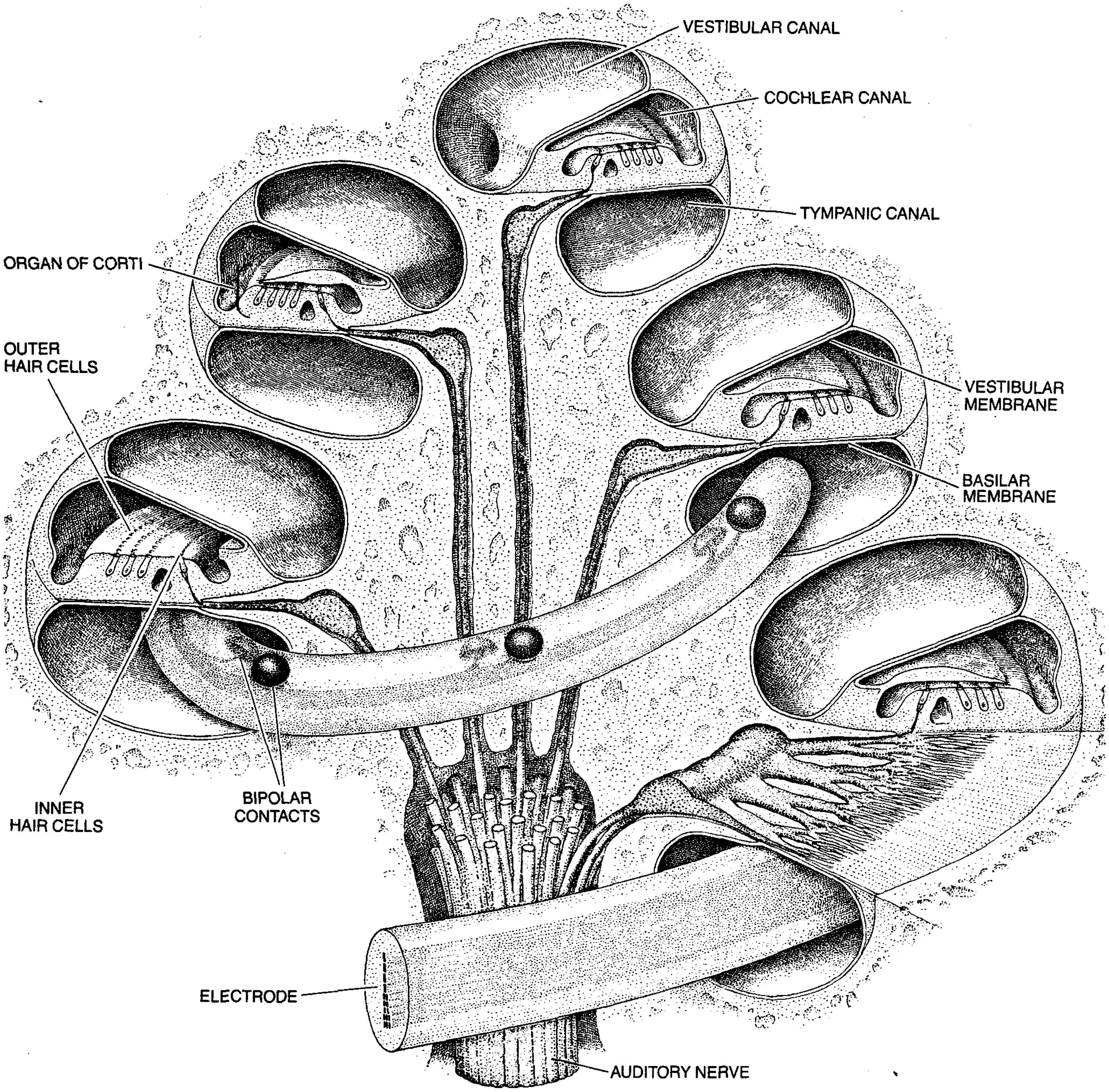
EXPERIMENTAL HEARING AID developed by workers at the University of California at San Francisco is shown implanted in a patient's ear in the cutaway drawing at the left. An enlarged interior view of the cochlea, the snail-shaped structure at the core of the inner ear, appears at the right. (The rows of sensory hair cells, included in this view, would be absent in a typical patient with sensorineural deafness.) The particular cochlear implant depicted is an eight-channel, bipolar device: it delivers stimuli at eight different frequencies

signals, a transmission system for relaying the signals to the implanted components, and a long, slender electrode that a surgeon snakes into the inner recesses of the cochlea so that the device delivers the electrical stimuli directly to the fibers of the auditory nerve in one or more places.

One such device, a comparatively primitive single-channel model, has recently been approved by the Food and Drug Administration for implantation in patients with sensorineural deafness. Developed by William House of the House Ear Institute of Los Angeles, it is manufactured by 3M [see "Tuning a Deaf Ear," "Science and the Citizen"; SCIENTIFIC AMERICAN, November, 1984].

More sophisticated single- and multichannel devices, currently in the research stage, promise to provide more realistic sound perception to such patients. The intensive study of the responses of these patients and of experimental animals to various patterns of electrical stimulation from such devices has the added benefit of providing fresh insights into the normal encoding and decoding of acoustic information by the nervous system.

In one sense the structure of acoustic information is very simple. The signal picked up by a microphone or an ear can be fully described by a single function of time, which characterizes the motion of a single point in space, such as the center of the microphone's diaphragm or the cochlea's oval window. In spite of its simplicity, such a signal typically contains complex



to separate groups of auditory-nerve fibers in the cochlea by means of eight closely spaced pairs of electrical contacts distributed along the length of the implanted electrode. Multichannel devices of this kind, currently in the clinical testing stage, are expected to provide more realistic sound perception to patients with sensorineural deafness than the single-channel devices now available. The operation of the main components of a four-channel "driver" for this device is shown in the illustration on page 108. Although the present driver has only four channels, the electrode (which may not be readily replaceable because of scar tissue) has been designed to accommodate eight channels; a surgically accessible connector in the base of the driver facilitates its replacement with improved versions.

information about the source of the sound; the nervous system is able to analyze the signal to extract the information. In the case of a human speaker the analysis is usually sufficient to identify the particular speaker and his words. The addition of a second information channel at a separate point in space—the other ear—makes it possible to distinguish multiple sound sources by their relative positions.

In the course of this analysis the one-dimensional function must be broken down into its component frequencies. The separation of such a complex waveform into its spectral components by means of the time-honored mathematical method of Fourier analysis is now a common practice in electronics and is often available in modern test instruments at the push of a button. Since the late 19th century it has been assumed that the brain must be employing a comparable form of signal analysis in at least the first stages of hearing. It has also been recognized that the channels through which information flows in the nervous system, the individual neurons, are inherently very slow. Somehow an analytic system built up of a large number of information channels, each channel limited to about 300 pulses per second, must provide an accurate and almost instantaneous spectral analysis of signals covering a bandwidth of between 20 and 20,000 hertz (cycles per second). Furthermore, in spite of the presence of considerable noise in each channel, the overall performance of the system must not be seriously degraded over a dynamic range of a million to one (120 decibels) from the threshold of hearing to the beginning of pain.

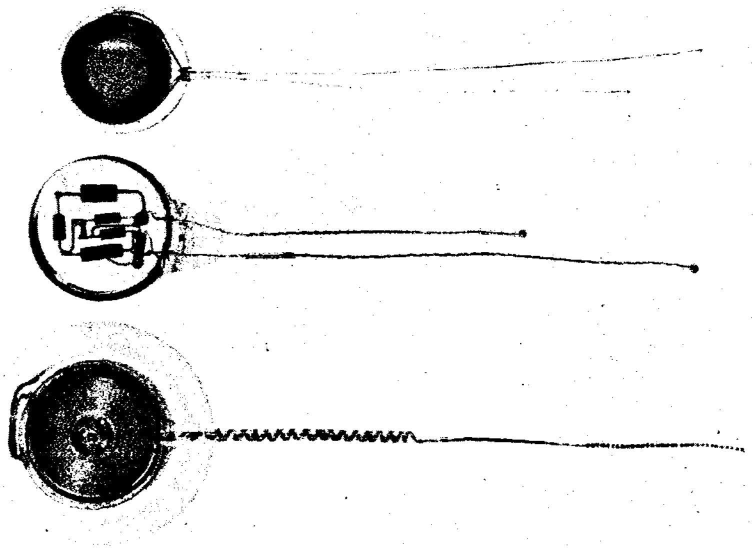
How does the ear accomplish this demanding task? Hermann von Helmholtz was one of several 19th-century physicists who recognized that the organ of Corti could be involved in some way in sampling sounds that were separated physically into their spectral components by the sympathetic vibration of the basilar membrane. Pioneering studies of the motion of the basilar membrane by Georg von Békésy in the 1950's established that when sound of a given frequency is applied to the base of the cochlea, it causes the basilar membrane to vibrate with the largest amplitude at a particular place, which is mechanically tuned to the frequency of the applied sound. A complex acoustic waveform, a composite of many individual sinusoidal frequencies, generates a spatial distribution of sympathetic vibration peaks along the basilar membrane; the higher frequencies are represented at the base of the cochlear spiral and the lower frequencies at the apex. The hair cells of the organ of Corti transduce the mechanical motion of the basilar membrane into electrical activity in the adjacent auditory-nerve fibers. As a result low-frequency impulses are generated in the parallel array of auditory-nerve fibers. Each fiber transmits information only about the amplitude of the vibration in a particular place.

This "place pitch" theory of sound perception underlies the design of most multichannel cochlear prostheses, although it will become apparent from what follows that the place-pitch mechanism is probably not sufficient to account for many important psychophysical phenomena of hearing, including some critical attributes of normal speech perception.

A cochlear implant relies on the fact that many of the auditory-nerve fibers often remain intact in patients with sensorineural deafness. As in the case of most electrically excitable cells, the surviving neurons can be stimulated to fire actively propagating nerve impulses by applying external electric currents of the proper strength, duration and orientation. Such "evoked potentials" arrive at the brain looking just like the impulses generated by acoustic signals that intact hair cells transduce; accordingly the brain interprets them as sound.

The loudness of the sound perceived depends roughly on the number of nerve fibers activated and their rates of firing. Both variables are functions of the amplitude of the stimulus current. The pitch is related to the place on the basilar membrane from which those nerve fibers once derived their acoustic input, in agreement with the place-pitch theory. In principle, with enough independent channels of stimulation, each controlling the activity of a small, local subset of the auditory-nerve fibers, one could re-create the normal neural response to acoustic stimuli of any spectral composition. The brain would then process that information in its usual manner and the subject would "hear" the "sounds."

The problem faced by the designer of a neural prosthesis is that all the auditory-nerve fibers are swimming in the same pool of electrically conducting tissues and fluids. An electric current injected into this medium tends to spread out symmetrically from the source; as a result the current density



IMPLANTED COMPONENTS of three auditory prostheses are compared. At the top is a single-channel cochlear implant developed by William House of the House Ear Institute in Los Angeles. Manufactured by 3M, it is the first such device to receive the approval of the Food and Drug Administration. The implanted components consist of a simple wire coil leading directly to a pair of ball-shaped electrodes, one of which is inserted in the tympanic canal at the base of the cochlea. (The other electrode is grounded to a nearby part of the middle ear.) In the middle is a more advanced single-channel device developed by Inge J. Hochmair-Desoyer and Erwin S. Hochmair of the Technical University of Vienna and currently being tested by 3M. The receiver circuitry can be seen inside the clear plastic enclosure; in this case both ball electrodes are designed to be placed outside the cochlea in the middle ear. At the bottom is a multichannel device developed by Graeme M. Clark and his colleagues at the University of Melbourne and manufactured by Nucleus Limited. The hermetically sealed titanium enclosure of this device contains the complex circuitry needed to decode a transmitted signal that selects and actuates one of 22 contacts along the electrode.

decreases as the square of the distance from a monopolar source. For such a stimulus to selectively activate a particular subset of the auditory-nerve fibers the electrode must be much closer to those fibers than to other fibers.

This constraint is a difficult one. The auditory-nerve fibers spread out to their greatest extent as they enter the organ of Corti on the basilar membrane. A longitudinal array of electrodes can be inserted in the tympanic canal and passed along the basilar membrane for a distance of about 25 millimeters from a second opening in the base of the cochlea, called the round window. Distributed along the path are the fibers that normally transmit information about sound frequencies above 500 hertz. The shortest distance from the auditory-nerve fibers to the best location in the tympanic canal (along the medial wall) is on the order of one millimeter. A pulse of stimulation current four times the threshold for fibers at one location (characterized as having a moderate loudness) will start to influence fibers two millimeters away in both directions.

When natural variations in the size of the fibers and their susceptibility to stimulation are factored in, the stimulus spread is probably even greater. Obviously only a small number of independent stimulation sites with any appreciable dynamic range could be accommodated along the available length. For speech perception the critical bandwidth is between 500 and 3,000 hertz, representing a distance along the basilar membrane of less than 14 millimeters; this distance is capable in turn of accommodating perhaps two or three independent stimulation sites that can contain a reasonable dynamic range. Experiments in which speech is simulated by means of a small number of amplitude-modulated single-tone generators, on the other hand, suggest that at least six channels must be available for intelligibility.

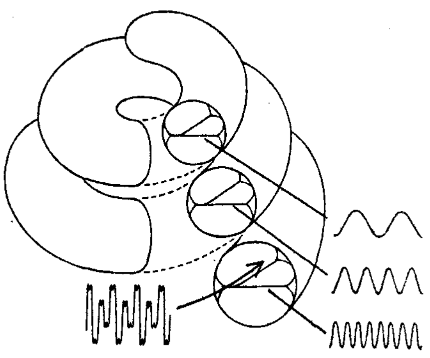
One way to effectively divide the fibers into an adequate number of discrete channels is to apply bipolar stimulation. In this approach the source and the sink of the current pulse are placed close to each other. (In monopolar stimulation the current sink needed to complete the circuit is a large, remote contact that acts as a ground for all sources.) The current-density lines around a pair of bipolar electrodes look like the magnetic-flux lines around a bar magnet: they have an elliptical shape whose major axis is oriented parallel to the line between the poles [*see illustration on page 109*].

Since the activation of neurons requires the induction of longitudinal currents along their processes, bipolar electrodes oriented at right angles to the long axis of the tympanic canal (radially to the spiral) can selectively activate the local nerve fibers passing immediately over them. Furthermore, the gradient of current density in the tissues that extends outward from a pair of bipolar electrodes is much steeper than it is for a monopolar electrode, reducing the stimulus spread even at high intensities. Tests in both animals and patients with a cochlear prosthesis have shown that such radial bipolar electrodes produce a more localized activation over wider dynamic ranges than monopolar or longitudinal bipolar configurations do.

The actual number of independent channels that can be established and their dynamic ranges depend on the condition of the remaining auditory-nerve fibers. These sometimes die back some distance from the organ of Corti, reducing their proximity to an electrode array in the tympanic canal. In some patients, however, it appears that radial bipolar pairs can be positioned about two millimeters apart without significant interaction. This spacing makes it possible for eight independent channels to span the speech-frequency sites lying between 10 and 24 millimeters from the round window.

There are several technical problems involved in actually delivering these eight bipolar stimulation channels to the human auditory nerve. The first 24 millimeters of the basilar membrane are coiled into one and a half of the two and a half turns of the cochlear spiral. The round window into the tympanic canal lies at the back of the middle-ear cavity, forcing the surgeon to work through the long, narrow external-ear canal. This means the electrode must be held in a straightened configuration as it is fed into the cochlea. It cannot, however, simply be pushed into the cochlear spiral as if it were a plumber's snake passing through a curved drainpipe. The half-cylindrical cross section of the tympanic canal causes a flexible object pressing against the side wall to be deflected upward against the extremely fragile basilar membrane. The fluid in the cochlear canal just above the membrane has a high potassium content, making it toxic to the auditory-nerve fibers in the event that it leaks into the tympanic canal.

One solution has been to use a very slender, flaccid electrode, which ideally can be coaxed into position with a minimum of trauma. Nevertheless, it is difficult, if not impossible, to control the exact orientation of the stimulation contacts of such an electrode; it tends to lie against the outer wall, far from the nerve fibers that need to be activated. The selectivity and dynamic range of the radial bipolar-electrode array depend on accurately positioning each pair on the medial wall.



PLACE-PITCH THEORY explains how the cochlear sound-detection system separates a complex acoustic waveform into its spectral components. In this representation of the theory a composite sound wave propagating in the cochlear fluid causes a sympathetic vibration of the basilar membrane, the thin, flexible partition separating two of the cochlea's three spiral canals. The vibration peaks are distributed spatially along the membrane; as shown here, the higher frequencies are detected at the base of the cochlea and the lower frequencies at the apex.

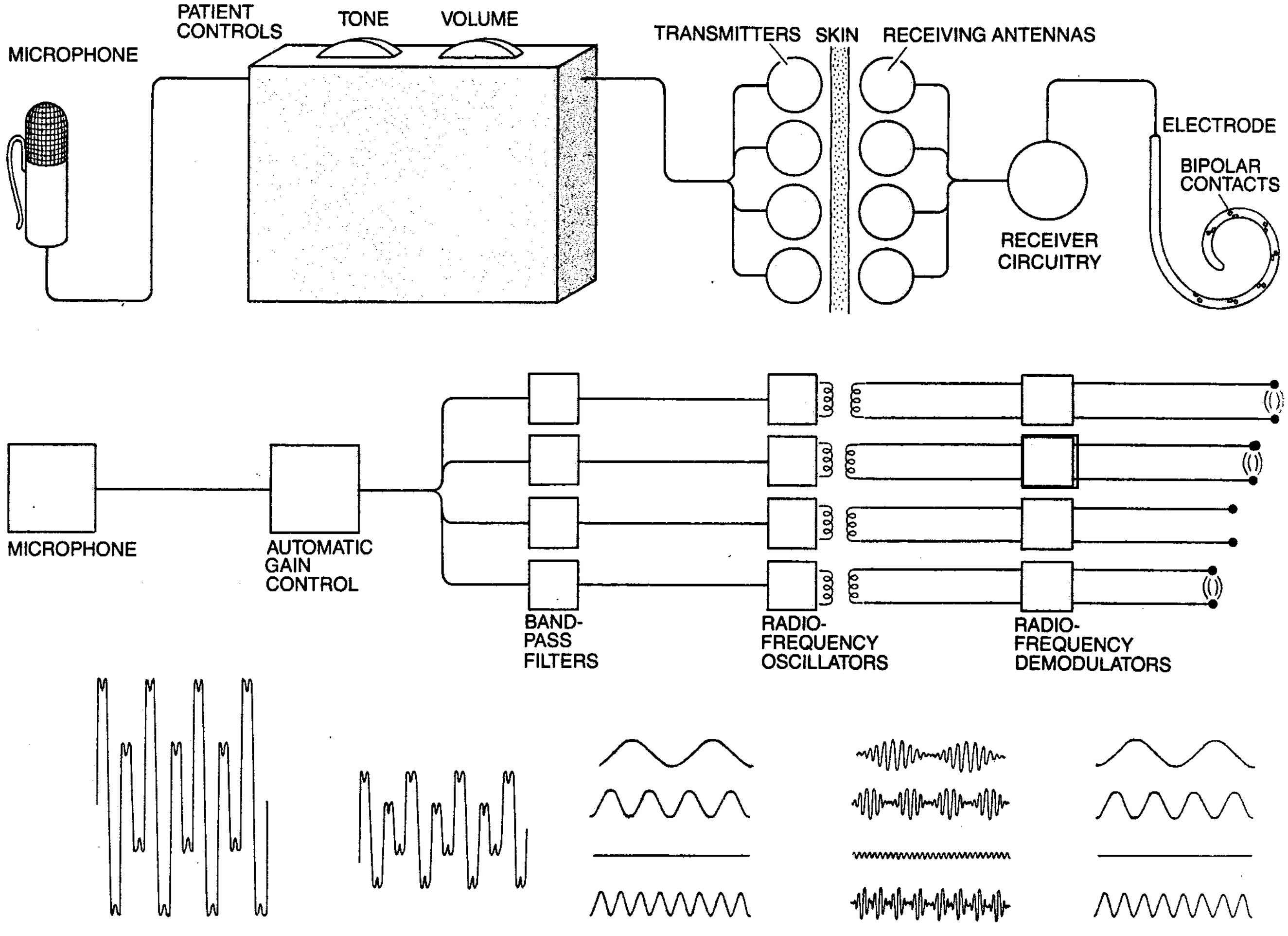
This task can be achieved only by using a comparatively thick electrode with a "memory" of a spiral shape that causes the electrode to hug the medial wall around the turns. Such handling properties have been achieved in an eight-bipolar-pair array designed by the research team at the University of California at San Francisco. It combines the mechanical properties of a silicone-rubber carrier and specially flattened and stacked platinum-iridium lead-out wires from the 16 electrode contacts distributed along the spiral form [*see illustration on pages 104 and 105*].

The delivery of stimulation current from electronic circuits to biological tissues is also a delicate matter. Electric currents in metal conductors are carried by electrons, whereas in the aqueous body fluids they are carried by ions. The electrochemical reactions at the interface of even the most biocompatible metals and the complex soup of the body's fluids is fraught with danger for both the electrodes and the tissues. Electrolytic corrosion of many supposedly inert metals is rapidly enhanced by the chelating action of chloride ions, the major negatively charged ions in extracellular fluids. This process changes the electrical properties of the interface and releases highly toxic heavy-metal ions into the immediate vicinity of the neurons, which are among the most sensitive cells of the body. The electrolysis of water alone can produce mechanically disruptive bubbles of hydrogen and oxygen, leaving behind local concentrations of hydroxyl and hydronium ions that can reach toxic levels of alkalinity and acidity respectively.

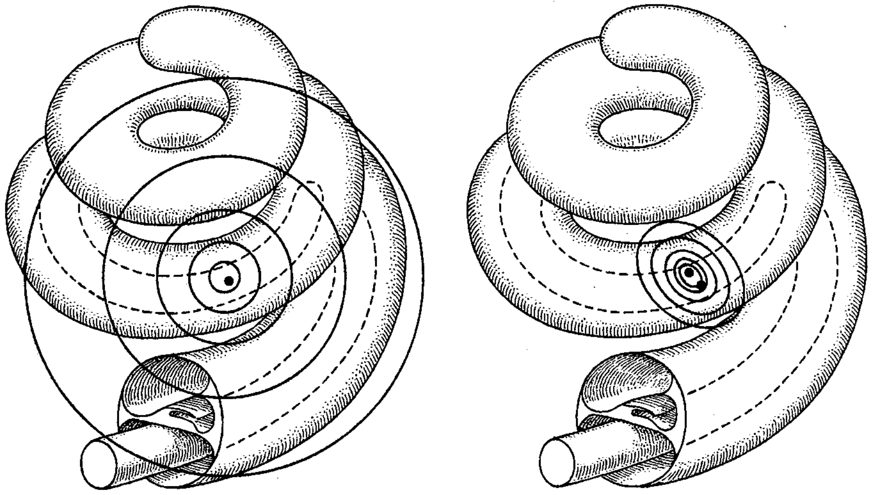
It is only in the past few years that these reactions and their consequences have been studied on a quantitative level, largely by S. Barry Brummer and his colleagues at the EIC Laboratories, Inc., in Norwood, Mass. These studies have established certain rather strict conditions for which electric currents passing through certain metals such as platinum and iridium can safely induce ionic currents in body fluids by reversible, nontoxic electrochemical reactions.

Once the electrodes are in place and the stimulation current is safely delivered, what does the patient hear? The results to date have been a generally encouraging but somewhat confusing mixture of the expected and the unexpected.

By far the largest sample of patients have been tested with single-channel stimulators. Moderately filtered waveforms taken directly from a microphone are transmitted to an implanted stimulator, which activates some auditory-nerve fibers near the base of the cochlea. Predictably, the sensations are those of a complex, amplitude-modulated noise. There is only the broadest sense of pitch and only at stimulation frequencies below a few hundred hertz. Nevertheless, a sense of the rhythm and the loudness of the sounds heard is strong. In patients who are profoundly deaf, for whom even the most powerful conventional hearing aid is no help, such sound information can provide quite helpful cues for everyday living. The lowest frequencies of the acoustic spectrum include important information about the presence and nature of ambient noises such as the sounds of telephones and automobiles, and about the loudness and cadence of speech, both for the subject's own vocalizations and for those of a person he or she may be trying to



OPERATION OF A FOUR-CHANNEL IMPLANT is outlined. Sound is picked up by a lapel microphone and sent for processing to a box worn by the patient and equipped with standard hearing-aid controls for tone and loudness. An automatic-gain-control circuit on a microelectronic chip in the box first reduces the wide fluctuations in loudness that characterize normal ambient sound to the much more limited range suitable for electrical stimulation of the inner ear. A set of band-pass filters then divides the complex alternating-current waveform into four frequency channels corresponding to the major formants produced by the human vocal system in making vowel sounds. The resulting narrow-band signals (one of which is zero in this example) modulate the amplitude of four independent radio-frequency oscillators mounted in the antenna-coil assembly. The transmitting antennas are held in place on the scalp over the implanted receiver coils by mating pairs of ceramic magnets. Each receiver circuit acts as an independent AM-radio set to demodulate the carrier frequency and recover the original narrow-band signal for direct transmission to a pair of stimulation contacts on the electrode, which is inserted in the tympanic canal. Such a scheme is limited to a fairly small number of channels. A group at Stanford University has recently developed an improved eight-channel system in which the detailed characteristics of each channel's output signal are digitally encoded for transmission on a single carrier frequency and decoded in the implanted receiver circuitry.



SPREAD OF EXCITATION from a given stimulation site within the cochlea to distant parts of the auditory nerve is the most critical factor limiting the number of channels in a multichannel cochlear prosthesis. The problem is particularly troublesome in the case of monopolar contacts (*left*). Increasing the intensity of the stimulation current delivered by such a contact causes the current to spread in a radially symmetric pattern within the fluid-filled chambers of the inner ear, allowing the excitation to reach parts of the auditory nerve that normally serve different places on the cochlea and thereby giving rise to different pitch sensations; stimulation currents from other contacts in these regions would in turn interfere with the pattern shown, making the separate stimulation channels noisy and difficult to resolve. One way to confine the spread of stimulation current is to employ radial bipolar contacts, which tend to produce a much more localized pattern of excitation (*right*).

lip-read. Most patients with either congenital or adult-onset deafness have been enthusiastic users of even the simplest single-channel prostheses.

Efforts are now under way to improve the quality of the sound by more sophisticated preprocessing and better fidelity in the transmission system that serves to convey the signals from the patient's control unit to the implanted electrodes. One important development has been the realization that most, if not all, of the single-channel capabilities can be realized with extracochlear stimulation in the middle ear. This finding bodes well for the conservative but important clinical application of the technology to many patients (particularly children) during a period of uncertainty over evolving and conflicting multichannel designs. It is generally acknowledged, however, that single-channel stimulators cannot deliver enough information to the nervous sytem to enable a patient to converse without visual aids.

The effectiveness of the various multichannel prostheses now available is less clear. The devices are inherently complex, and only a few patients who use them have been thoroughly studied. Moreover, the ranks of these patients include individuals in whom the cause of deafness varies widely, as does the condition of the remaining auditory nerve.

When a small, local subset of the auditory-nerve endings along the cochlea is activated with a multichannel device (by either low-intensity monopolar stimulation or bipolar stimulation), the noisy sensation takes on a definite pitch. When several physically separated subsets are activated sequentially, the subject has little difficulty ordering them into a musical scale. It is important to realize that the psychophysical term "pitch" refers to a subjective judgment by the observer, usually of a highly complex acoustic waveform that may carry little or no spectral energy at the actual frequency corresponding to the stated pitch. Patients with a multichannel prosthesis have likened what they hear to the quacking of ducks or the banging of garbage cans. Such sounds can be ranked by pitch, but they are not at all like the pure tones that are perceived in the case of a sinusoidal acoustic waveform.

It is not clear whether these complex auditory sensations are combinable in the same way as pure sine waves are combined in the speech-simulation experiments. The normal auditory nervous system has an extraordinary capacity for extracting underlying information from noisy signals and generalizing across only distantly related spectral patterns. That is why one can understand human speech by a bass and by a soprano, at a whisper and at a shout, and from speakers with wide variations of accent, nasality and inflection. In fact the spectrographic presentation of a given word is so complex and variable that even an experienced analyst cannot identify most words from such visual records.

Two approaches to utilizing the place-pitch dimension of acoustic information are now being investigated clinically. One is related to the frequency-channel, or vocoder, simulation of speech sounds, in that it filters the acoustic signal into a set of bands, each corresponding approximately to the pitch perception generated by one of the available bipolar electrode pairs. For eight such electrodes there would be eight independent time-varying activations of the auditory-nerve subsets, each activation conveying information about the instantaneous, relative intensity of sound energy in its own band. In principle the particular amplitude-modulated waveform used to activate each channel should not matter. For several reasons, however, the actual waveforms transmitted by each band-pass filter in the sound processor are usually applied directly to the electrodes. Special preprocessing steps are added to compensate for the narrow dynamic range and the frequency-dependent sensitivity of the neurons to electric currents.

The number of independent, parallel stimulation channels is expected to have a significant effect on the intelligibility of speech. This effect, however, will be apparent only if each such channel actually does activate a spatially well-localized subset of the auditory-nerve fibers over the dynamic ranges and temporal patterns typically encountered in normal hearing.

At least five separate teams of investigators have studied patients equipped with between three and 12 stimulation channels each. In general, differences in surgical approach, electrode configuration and waveform selection, together with individual patient variability, overwhelm any meaningful comparison. In a few cases a single patient has been tested with systematic variation of the division of the speech spectrum into different numbers of bands and channels. Additional channels lead to dramatic and immediate improvements in word recognition for subjects whose electrodes allow such localized activation. The identification of words from a random sampling has been reported as high as 80 percent with just four-channel stimulation, a level that approaches functional rehabilitation, given the redundancy and contextual cues available in ordinary conversation.

An alternative approach to the

place-pitch encoding employed in most multichannel devices relies on a multichannel electrode array that continuously varies the point of application of a single channel of stimulation. Both the electrodes and the transmission system are considerably simpler in this scheme, but the processing of the speech signal is much more complex. Even closely spaced monopolar electrodes tend to have an orderly sequence of place-pitch sensations when they are activated singly, apparently because the central nervous system has little difficulty identifying the midpoint of a comparatively broad gradient of activated neurons.

The amplitude modulation and frequency modulation of certain parts of the speech spectrum, such as the formants produced by the shape of the mouth cavity, convey particularly useful information for discriminating many acoustic elements of speech. A speech processor based on a microcomputer chip can identify and track one such spectral feature, known as the second formant, and select the best stimulation site and intensity, based on a stored map of the sensations produced by each electrode in a particular subject. The frequency of the stimulation applied at the currently activated site can be used to encode the fundamental frequency of vocal-cord vibration, which corresponds to the low-frequency range for which subjects report a vibrationlike sensation of pitch. A system of this type with 22 individual electrodes, developed by Graeme M. Clark and his colleagues at the University of Melbourne, has been implanted in about 20 patients. Again, the variability among patients overwhelms any attempt to compare results with single-channel electrodes or with multichannel designs, but at least some subjects have achieved significant scores on word-recognition tests.

To improve performance, information channels corresponding to the first and third vowel formants, together with high-frequency consonants, will be needed. Perhaps two or even three simultaneous stimuli might be delivered without significant channel interaction, if they could be kept far enough apart. It remains to be seen whether this general approach to the basic trade-off between the number of channels and their independence will provide the necessary information in a form that is compatible with the information-processing capabilities of the auditory nervous system.

The complexity of the sensations evoked by even the most localized stimulation of the cochlea has surprised and intrigued many investigators. The place-pitch theory in its simplest form predicts that local activation will elicit a fairly pure tonal sensation, corresponding to the local resonant frequency of the basilar membrane. Changes in the frequency and waveform of the electrical stimulus should result only in simple changes in loudness and only to the extent that such changes affect the average rate of firing among the active neurons. How then do spectrally complex sensations such as buzzes and clangs arise? Can they be systematically controlled to provide another form of prosthetic information transfer?

It has long been known that the auditory-nerve activity transmitted to the brain contains rather detailed temporal information about the exact phase of the motion of the basilar membrane. For sound frequencies below 5,000 hertz the exact timing of each neural impulse in an auditory-nerve fiber is locked to the phase of the mechanical motion sensed by the particular hair cell providing its sole input. Even though the fiber must pause for two or three milliseconds between impulses, a spectral analysis of the activity in any single fiber will reveal the frequency of the stimulation that activated it, whether or not the frequency corresponds to the characteristic resonant frequency of that place on the basilar membrane. Some of the central neurons receiving an input from the auditory nerve have a specialized synaptic structure that can transmit and preserve such high-resolution temporal information in spite of the limitation on the overall firing rate of about 300 impulses per second. Furthermore, subjects in psychophysical studies appear to be able to extract precise spectral information even when the loudness of the acoustic stimulus causes the firing rate to be saturated over extended regions of the cochlea. In recent years Murray B. Sachs and Eric D. Young of the Johns Hopkins University School of Medicine have emphasized the potential importance of this temporal information for the discrimination of vowel sounds. Their findings suggest that the nervous system might well be capable of extracting this phase-locked spectral information, and that the failure to correctly reproduce such temporal patterns may give rise to complex, noisy sensations.

What are the critical temporal cues? If many phase-locked neural signals, each with a low overall firing rate, are combined, the frequency of the acoustic source signal can be reconstructed. This approach, however, begs the question of how any particular central neuron receiving such high-frequency driving senses what the frequency is. One way to think of a receiver neuron that is selectively tuned to a particular repetition frequency of its input pattern is to imagine that it is designed to operate by a technique known as temporal autocorrelation. In this approach the input signal is delayed by a time equal to one cycle of the frequency to be detected, and the delayed and undelayed signals are multiplied together. Models of auditory perception often postulate an array of such periodicity detectors in the first few synaptic relays of the brain stem.

Biophysical theory predicts and animal experiments have demonstrated that electrical stimulation with either sinusoidal or pulsed alternating-current waveforms causes significant phase-locking of auditory-nerve fibers for frequencies ranging up to at least 3,000 hertz. Yet prosthesis users consistently report very little change in pitch and only subtle changes in the quality of the sound as the frequency of the stimulus is increased above 300 hertz. Even when the natural resonant frequency of the stimulus site and the repetition frequency of the stimulus waveform coincide, there is no sudden improvement in the weak tonality of the sensation.

Such observations are forcing a reexamination of the class of mechanisms whereby networks of neurons might extract temporal information on a time scale that is much finer than their usual synaptic and conduction processes. One possible model, proposed by Mark W. White, Michael M. Merzenich and me, calls for spatial cross correlation to detect particular configurations of basilar-membrane motion caused by the progress of traveling waves of a given frequency. The process is analogous to the localization of sounds in space based on different signal delays between the two ears; indeed, the two processes might share some of the same neural circuitry. The temporal resolution of both sound localization and phase-locked frequency discrimination is on the order of 10 microseconds.

Obviously whether or not one can prosthetically control these processes and the sensations to which they give rise will depend on the critical input cues for each process. Such control may require finer spatial and temporal control of the electrical stimulation than one can ever hope to achieve. Alternatively, some simple trick of electrode configuration or stimulus timing that has not yet been tried may turn out to do the job.