Section 3 Auditory Physiology

Chapter 1 Signal Transmission in the Auditory System

Chapter 1. Signal Transmission in the Auditory System

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1.1 Introduction

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Research on the auditory system is carried out in cooperation with two laboratories at the Massachusetts Eye and Ear Infirmary (MEEI). With the Eaton-Peabody Laboratory for Auditory Physiology, we pursue basic investigations with the objectives of (1) understanding the anatomical structures and physiological mechanisms that underlie vertebrate hearing, and (2) applying that knowledge to clinical problems. Studies of cochlear implants in humans are carried out at the MEEI Cochlear Implant Research Laboratory. The goal of cochlear implant research is to provide speech communication for the deaf by electrically stimulating intracochlear electrodes to elicit patterns of auditory nerve fiber activity that the brain can learn to interpret.

1.2 Signal Transmission in the External and Middle Ear

1.2.1 Structure-Function Relations in Middle Ears

Project Staff

Dr. John J. Rosowski, Professor William T. Peake, David A. Steffens

The goal of our work is to understand the relationship between the structure of the external and middle ear and their functions. In this approach, we determine how inter-specific variations in ear structure lead to functional differences. In the past year, we have investigated these issues using three basic techniques: (1) correlation of basic structural features of the middle ears of different mammals with differences in hearing ability, (2) description of signal processing by the external and middle ear based on measurements of function combined with a simple model, and (3) new functional measurements in the gerbil, a species with several peculiar auditory adaptations.

Specifically, in a paper[1] on the middle-ear function of one of the earliest known mammals, the relationship between the size of middle-ear structures and limits of hearing in modern mammals

[1] J.J. Rosowski and A. Graybeal, "What Did Morganucodon Hear?" *Zoolog. J. Linnean Soc.* 101:131-168 (1991).

was used to predict the auditory capabilities of the early mammal. This work points out that the middle ears of early mammals are similar to those of shrews and other small mammals with good high-frequency and poor low-frequency hearing. A subsequent book chapter[2] tested and expanded these predictions. The two papers argue that early mammals were capable of hearing high-frequency sounds and shed light on how the mammalian ear differs from that of other vertebrates.

A framework for understanding the role of the external and middle-ear in determining the shape of the audiogram and variations in susceptibility to damage by different noises was developed.[3] This work explains why low-frequency noise is less damaging to human hearing than high-frequency noise.

Methods for assessing the efficacy of middle-ear acoustic-power transmission were reviewed[4] with the conclusion that consideration of the external and middle ear together leads to the best assessment of optimum middle-ear function.

The significance of non-ossicular sound transmission through the normal and abnormal middle ear of both men and cats was predicted based on a new model.[5] This analysis suggests that direct acoustic stimulation of the cochlear window plays a major role in determining residual hearing in certain middle-ear disorders. The paper makes recommendations for middle-ear reconstructive surgery including the size of the residual middle-ear air spaces and stiffness of any round-window shield.

The acoustic input impedance of the gerbil middle ear and middle-ear air spaces was measured.[6] The middle-ear air spaces of the gerbil were found to play a significant role in determining the exceptional sensitivity of the gerbil ear to low frequency sounds. However, a flaccid tympanic membrane and ossicular chain were found to be necessary codevelopments of a low-frequency ear.

1.3 Basic and Clinical Studies of the Auditory System

1.3.1 Subproject 1: Middle Ear and Measurement of Middle-Ear Transfer Function

Project Staff

Dr. John J. Rosowski, Professor William T. Peake, Dr. Sunil Puria

The animal work described above is complemented by direct measurements of middle-ear function in a human temporal-bone preparation.

Measurements of the motion of the human malleus in response to sound[7] demonstrate that mallear motion can be described as simple rotation only for frequencies below 500 Hz. At higher frequencies the motion can be better described as a combination of rotational and translational components. This result conflicts with the popular description of middle-ear mechanical action and has implications for the design of middle-ear prostheses.

Together with Dr. S.N. Merchant at the Massachusetts Eye and Ear Infirmary, we have made some preliminary measurements of the input impedance of the stapes and cochlea in human temporal bones. These measurements specify the load on the middle ear and are essential for understanding

2 J.J. Rosowski, "Hearing in Transitional Mammals: Predictions from the Middle-ear Anatomy and Hearing Capabilities of Extant Mammals," in *The Evolutionary Biology of Hearing,* eds. D.B.Webster, A.N. Popper, and R.R. Ray (New York: Springer-Verlag, 1991), pp. 625-631.

3 J.J. Rosowski, "The Effects of External- and Middle-ear Filtering on Auditory Threshold and Noise-induced Hearing Loss," *J. Acoust. Soc. Am.* 90: 124-135 (1991).

4 W.T. Peake and J.J. Rosowski, "Impedance Matching, Optimum Velocity and Ideal Middle Ears," *Hear. Res.* 53: 1-6 (1991).

5 W.T. Peake, J.J. Rosowski, and T.J. Lynch III, "Middle-ear Transmission: Acoustic Versus Ossicular Coupling in Cat and Human," *Hear. Res.* 57: 245-268 (1992).

6 M.E. Ravicz, J.J. Rosowski, and H.F. Voigt, "Sound-power Collection by the Auditory Periphery of the Mongolian Gerbil Meriones Unguiculatus: I. Middle-ear Input Impedance," submitted to *J. Acoust. Soc. Am.*

7 K.M. Donahue, J.J. Rosowski, and W.T. Peake, "Can the Motion of the Human Malleus be Described as Pure Rotation?" Abstracts of the 14th Midwinter Research Meeting of the Association for Research in Otolaryngology 53 (1991).

middle-ear function. The preparation we are developing will also enable us to test fundamental assumptions of cochlear function including whether the volume velocity of the oval and round window are equal.[8]

Publications

Donahue, K.M., J.J. Rosowski, and W.T. Peake. "Can the Motion of the Human Malleus be Described as Pure Rotation?" Abstracts of the 14th Midwinter Research Meeting of the Association for Research in Otolaryngology 53 (1991).

Merchant, S.N., M.E. Ravicz, and J.J. Rosowski. "The Acoustic Input Impedance of the Stapes and Cochlea in Human Temporal Bones." Abstracts of the 15th Midwinter Research Meeting of the Association for Research in Otolaryngology. Forthcoming.

Peake, W.T., and J.J. Rosowski. "Impedance Matching, Optimum Velocity and Ideal Middle Ears." *Hear. Res.* 53: 1-6 (1991).

Peake, W.T., J.J. Rosowski, and T.J. Lynch III. "Acoustic Coupling to Cochlear Windows." Abstracts of the Fourteenth Midwinter Meeting of the Association for Research in Otolaryngology, p. 121 (1991).

Peake, W.T, J.J. Rosowski, and T.J. Lynch III. "Middle-ear Transmission: Acoustic vs. Ossicular Coupling in Cat and Human." *Hear. Res.* 57: 245-268 (1992).

Ravicz, M.E., J.J. Rosowski, and H.F. Voigt. "Sound-power Collection by the Auditory Periphery of the Mongolian Gerbil Meriones Unguiculatus: I. Middle-ear Input Impedance." Submitted to *J. Acoust. Soc. Am.*

Rosowski, J.J. "The Effects of External- and Middle-ear Filtering on Auditory Threshold and Noise-induced Hearing Loss." *J. Acoust. Soc. Am.* 90: 124-135 (1991).

Rosowski, J.J. "Hearing in Transitional Mammals: Predictions from the Middle-ear Anatomy and Hearing Capabilities of Extant Mammals." In *The Evolutionary Biology of Hearing.* Eds. D.B. Webster, A.N. Popper, and R.R. Ray. New York: Springer-Verlag, 1991, pp. 625-631.

Rosowski, J.J., and A. Graybeal. "What Did Morganucodon Hear?" *Zoolog. J. Linnean Soc.* 101:131-168 (1991).

1.4 Cochlear Mechanisms

Project Staff

Professor Thomas F. Weiss, Professor Lawrence S. Frishkopf, Dr. Dennis M. Freeman, Kristin J. Dana, Farzad Ehsani, Charles Q. Davis

Our goal is to study the mechanisms by which the motion of macroscopic structures in the inner ear produce motions of the mechanically sensitive hair bundles of sensory receptor (hair) cells. Except for certain populations of hair cells found in lizards, auditory hair cells are surmounted by a gelatinous tectorial membrane. Because of its strategic location, the tectorial membrane plays an important role in the mechanical stimulation of hair bundles. However, there have been few direct observations of the tectorial membrane, and many of its critical properties remain obscure.

Based on its biochemical composition and ultrastructure, the tectorial membrane is a polyelectrolyte gel similar to those found in many connective tissues. The mechanical properties of such gels are intimately connected to their electrochemical properties. As a step toward understanding its physiochemical properties, we have investigated the effect of the ionic environment on the size and structure of the tectorial membrane of the chick cochlea. In our experiments, the cochlear duct was dissected, placed in an ionic solution, and opened to expose the sensory receptor organ. The tectorial membrane was lifted off the organ and attached to the glass floor of an experimental chamber. Latex beads (2-5 μm in diameter) were allowed to settle on the tectorial membrane. Video images of the tectorial membrane were obtained, and the positions of beads were measured as a function of time while the ionic composition of the solution perfusing the tectorial membrane was systematically altered. These measurements indicate how changes in the dimensions and geometry of the tectorial membrane were caused by changes in composition of the solution.

Measurements of the tectorial membrane were obtained in both high potassium (endolymph-like)

[8] S.N. Merchant, M.E. Ravicz, and J.J. Rosowski, "The Acoustic Input Impedance of the Stapes and Cochlea in Human Temporal Bones," Abstracts of the 15th Midwinter Research Meeting of the Association for Research in Otolaryngology, forthcoming.

and high sodium (perilymph-like) solutions at a number of calcium concentrations. At a fixed calcium concentration, the dimensions of the tectorial membrane change if the sodium and potassium concentrations are changed. For example, when the calcium concentration was maintained at a low value (20 μmol/L), substitution of sodium ions for potassium caused swelling of the tectorial membrane. The swelling had a large magnitude, often increasing the thickness of the tectorial membrane by more than a factor of two, and a slow time course, often continuing for hours. Subsequent perfusion with a high potassium solution caused the tectorial membrane to shrink. The time course of shrinking was almost an order of magnitude faster than that of swelling. Generally the shrinking did not completely reverse the previous swelling. Permanent changes in the structure of the tectorial membrane tended to persist after a long exposure to a high sodium solution.

For both high potassium and high sodium solutions, the tectorial membrane shrunk as calcium was increased from μmol/L to mmol/L concentrations. When calcium concentration was held constant at 2 mmol/L, substitution of sodium for potassium had little effect. For both high potassium and high sodium solutions, addition of the calcium chelator EGTA, which reduced the calcium concentration to levels appreciably below 1 μm/L, induced swelling. If the perfusate contained 1 mmol/L EGTA, substitution of sodium for potassium had little effect.

Many of the exposures to perfusion solutions that were long enough for the changes in dimensions of the tectorial membrane to come to steady-state led to irreversible changes in the tectorial membrane. Therefore, we began to study the effects of brief (15 minute) exposures to test solutions. The responses for brief exposures are consistent with those for long exposures. However, the effects of brief exposures are more nearly reversible, and we have been able to measure responses to brief exposures of as many as 20 different ionic solutions in a single preparation. Thus, we should be able to characterize more fully the dependence of dimensions of the tectorial membrane on ionic composition of the perfusion solution. Such a characterization is necessary if we are to understand the gel properties of the tectorial membrane.

The initial experiments with the isolated tectorial membrane preparation revealed that its microstructure changes systematically and reversibly in different ionic solutions. To capture these differences in microstructure and quantify changes in the volume of the tectorial membrane, we are developing a system for analyzing effects of lymph composition on the three-dimensional structure of the tectorial membrane using video-enhanced microscopy and computer-aided image reconstruction. The image of the tectorial membrane is magnified using a compound microscope equipped with differential interference contrast (Nomarski) optics. The magnified image is projected onto a video camera connected to a video digitizer. A sequence of images is recorded at different focal planes of the microscope. This sequence of two-dimensional images contains information about the three-dimensional structure of the tectorial membrane.

Although Nomarski images are sensitive to variations in the refractive index of the specimen (i.e., the tectorial membrane), Nomarski images are not simple maps of refractive index. Implicit in the optical system are a number of systematic transformations of the underlying variations in refractive index. We have implemented numerical algorithms to undo these transformations and recover the underlying variations in refractive index. The optical transformations are characterized by measuring a sequence of video images at different focal depths of a microscopic (0.25 μm diameter) plastic sphere. This sequence, which approximates the point-spread function of the optical system, is used to implement a "deconvolution" system that reduces optical blurring in the plane of the images and also removes out-of-focus information (from nearby planes) that contaminates each image. The enhanced two-dimensional images will be used to construct a three-dimensional representation of the tectorial membrane. This representation will allow measurements of the dimensions of the tectorial membrane (including its volume, thickness, length, and width) as well as its microstructure.

1.4.1 Stimulus Coding in the Auditory Nerve and Cochlear Nucleus

Project Staff

Dr. Bertrand Delgutte, Dr. Peter A. Cariani

The goal of our research is to understand neural mechanisms for the processing of complex acoustic stimuli at the level of the auditory nerve and cochlear nucleus. During the past year, we have focused on the coding of the pitch of complex periodic tones such as voiced speech and musical sounds. We have recorded the responses of auditory-nerve fibers to both harmonic and inharmonic stimuli similar to those used in psychophysical experiments on pitch perception. Neural responses were analyzed in the form of autocorrelograms, which display the probability distribution of all interspike intervals (1st, 2nd, 3rd, etc). Aggregate autocorrelograms were formed by adding the interval distributions for large numbers of auditory-nerve fibers innervating all regions of the cochlea. For harmonic stimuli which produce a strong pitch at the fundamental frequency, the most frequent interspike interval in the aggregate autocorrelogram always corresponded to the fundamental period of the stimulus. For inharmonic stimuli that have multiple, ambiguous pitches (such as amplitude-modulated tones), aggregate autocorrelograms showed multiple prominent intervals whose relative strengths corresponded roughly to the relative salience of the different pitches. For amplitude-modulated noise, which has a much weaker pitch than amplitude-modulated tones, interspike intervals were much less concentrated near specific values than for modulated tones. These results show that information for pitch determination is available in a relatively simple form in the interspike intervals of auditory-nerve fibers, and are consistent with pitch theories stating that pitch corresponds to the most frequent interspike interval in the entire auditory nerve.

If an interspike interval code is used for pitch, what neural mechanisms could be employed to discriminate between different pitches? One possibility is that cells in the cochlear nucleus with regular "chopper" firing patterns might preferentially synchronize to specific interspike-intervals in their auditory nerve inputs. An array of such elements tuned to different intervals could implement an autocorrelation-like periodicity detector. In order to test this idea, a simple model of a neuron exhibiting "chopping" behavior, preferred interspike intervals, and band-pass modulation transfer functions was developed. The integrate-to-threshold model has a nonmonotonic threshold recovery function with a "superexcitable" phase following a refractory one. The presence of a superexcitable phase implies that the neuron will have relatively higher discharge rates and modulation gain in response to amplitude-modulated tones whose modulation frequency is within a certain range. The model predicts that the peak of superexcitability should coincide with the interspike interval predominant at the onset of chopping. We are currently recording from cochlear nucleus units with chopper discharge patterns in order to test the model predictions.

Publications

Cariani, P., and B. Delgutte. "Interspike Interval Distributions of Auditory-nerve Fibers in Response to Variable-pitch Complex Stimuli." *Abstr. Assoc. Res. Otolaryngol.* 15 (1992).

Delgutte, B., and P. Cariani. "Coding of the Pitch of Harmonic and Inharmonic Complex Tones in the Interspike Intervals of Auditory-nerve Fibers." In *Audition, Speech, and Language.* Ed. M.E.H. Schouten. Berlin: Mouton-De Gruyter. Forthcoming.

Delgutte, B. "Fundamental Issues in Auditory Modeling." Proceedings of the IEEE ASSP Workshop on Applications of Signal Processing to Speech and Audio Coding, 1991.

1.5 Electrical Stimulation of the Auditory Nerve

Project Staff

Dr. Bertrand Delgutte, Scott B.C Dynes

This research studies physiological mechanisms of electrical stimulation of the auditory nerve with the expectation that such information will help design improved cochlear implants. For this purpose, we are recording the responses of auditory-nerve fibers to electric currents applied through electrodes inserted into the cochlea. Recent results[9] have shown that a speech processor in which brief current pulses are applied in rapid succession through different electrodes provides better speech reception in cochlear-implant patients than a processor delivering continuous analog signals. In the hope of better understanding the physiological basis for these improvements, we are studying the responses of auditory nerve fibers to pairs of brief rectangular electrical pulses separated by a delay. For delays smaller than 0.5 msec, the presence of a subthreshold first pulse either decreased (sensitization) or increased (masking) the threshold for the second pulse. The amount of sensitization was always greater than that of masking. The time course of these effects, as well as the asymmetry between sensitization and masking were predicted by a nonlinear, biophysical model of myelinated nerve fibers developed by J.T. Rubinstein. These physiological results resemble inter-pulse interactions found in behavioral thresholds of cochlear-implant patients. They suggest

[9] B.S. Wilson, C.C. Finley, D.T. Lawson, R.D. Wolford, D.K. Eddington, and W.M. Rabinowitz, "Better Speech Recognition with Cochlear Implants." *Nature* 352: 236-238 (1991).

that increasing pulse rate in interleaved-pulses speech processors may not lead to further improvements in speech reception because this would increase interactions between pulses applied through different electrodes.

Publications

Dynes, S.B.C., and B. Delgutte. "Phase Locking of Auditory-nerve Discharges to Sinusoidal Electric Stimulation of the Cochlea." *Hear. Res.* Forthcoming.

1.6 Middle-Ear Muscle Reflex

Project Staff

Dr. John J. Guinan, Jr., James B. Kobler

Our aim is to determine the structural and functional basis of the acoustically elicited middle-ear muscle reflexes. During the past year, data analysis and writing have been done to prepare for publication our results on the sound-frequency selectivities of single stapedius motoneurons in ketamine-anesthetized and decerebrate cats. Stapedius-motoneuron tuning curves were very broad, similar to the tuning of the overall acoustic reflexes as determined by electromyographic recordings. The lowest thresholds were usually for sound frequencies between 1 and 2 kHz although many tuning curves also had a second sensitive region in the 6-12 kHz range. The broad tuning of stapedius motoneurons implies that inputs derived from different cochlear frequency regions (which are narrowly tuned) must converge at a point central to the stapedius-motoneuron outputs, possibly at the motoneuron somata. There were only small differences in tuning among the four previously described groups of stapedius motoneurons categorized by sensitivity to ipsilateral and contralateral sound. The thresholds and shapes of stapedius-motoneuron tuning curves support the hypothesis that the stapedius acoustic reflex is triggered by summed activity of low-spontaneous-rate auditory-nerve fibers with both low and high characteristic frequencies (CFs). Excitation of high-CF auditory-nerve fibers by sound in their tuning curve "tails" is probably an important factor in eliciting the reflex. In general, the most sensitive frequency for stapedius motoneurons is higher than the frequency at which stapedius contractions produce the greatest attenuation of middle-ear transmission. This is consistent with the hypothesis that the main function of the stapedius acoustic reflex is to reduce the masking of responses to high frequency sounds produced by low-frequency sounds. A manuscript describing these data has been submitted.[10]

Also during the past year, data analysis and writing have been done to prepare for publication our results on (1) the growth of simultaneous masking of cat auditory-nerve fiber responses to high-frequency tones by low frequency noise, and (2) the effects of stapedius-muscle contractions on the masking of responses in the auditory nerve.

Publications

Kobler, J.B., J.J. Guinan, Jr., S.R. Vacher, and B.E. Norris, "Acoustic-Reflex Frequency Selectivity in Single Stapedius Motoneurons of the Cat." Submitted to *J. Neurophys.*

1.7 Cochlear Efferent System

Project Staff

Dr. John J. Guinan, Jr., Michael P. McCue

Our aim is to understand the physiological effects produced by medial olivocochlear efferents which terminate on outer hair cells in the mammalian cochlea.

During the past year, work has been done on several ongoing projects: (1) a project which measures efferent effects on stimulus frequency otoacoustic emissions (SFEs) to test hypotheses about the role of outer hair cells in controlling the "cochlear amplifier," (2) a project in which efferent effects on SFEs are contrasted with two-tone suppression effects on SFEs (both of these agents appear to influence the "cochlear amplifier" but at different sites), and (3) a project to determine the correspondence between the number of medial efferents that fire and the magnitude of the effects produced.

During the past year, we have also begun work aimed at comparing the time courses of the many reported efferent effects. Preliminary work suggests that all of these effects may not follow the same basic time course which would imply that more than one mechanism is involved.

[10] J.B. Kobler, J.J. Guinan, Jr., S.R. Vacher, and B.E. Norris, "Acoustic-Reflex Frequency Selectivity in Single Stapedius Motoneurons of the Cat," submitted to *J. Neurophys.*

1.8 Cochlear Implants

Project A: Models of Current Spread and Nerve Excitation during Intracochlear Stimulation

Project Staff

Dr. Donald K. Eddington, Dr. Jay T. Rubinstein

The basic function of a cochlear prosthesis is to elicit patterns of activity on the array of surviving auditory nerve fibers by stimulating electrodes that are placed in and/or around the cochlea. By modulating these patterns of neural activity, these devices attempt to present information that the implanted subject can learn to interpret. The spike activity patterns elicited by electrical stimulation depend on several factors: the complex, electrically heterogeneous structure of the cochlea, the geometry and placement of the stimulating electrodes, the stimulus waveform, and the distribution of exitable auditory nerve fibers. An understanding of how these factors interact to determine the activity patterns is fundamental to designing better devices and to interpreting the results of experiments involving intracochlear stimulation of animal and human subjects. As a first step towards this understanding, the goal of this project is to construct a software model of the cochlea that predicts the distribution of potential produced by the stimulation of arbitrarily placed, intracochlear electrodes and to use these potential distributions as inputs that drive models of auditory nerve fibers.

This year we directed effort at testing the three-dimensional, finite difference model of the human cochlea that predicts the potential distribution produced in this structure by electrical stimulation using model electrodes of arbitrary position and geometry. Both the measurements of scala tympani potentials and psychophysical measures of the interaction between two simultaneously stimulated electrodes made in subjects implanted with intracochlear electrodes and reported last year were continued and confirmed the asymmetric potential distributions predicted by the model.

We have continued the development of linear and nonlinear models of extracellular excitation of myelinated and unmyelinated nerve fibers by considering the case of terminated fibers. Cable models developed to simulate stimulation near the terminal of a passive fiber show that the predicted cathodal threshold can be an order of magnitude lower than predicted by the infinite length models used to date. In addition to the obvious relevance of such models to stimulation of the cochlea (where dendrites of auditory nerve fibers terminate), these models are also of general interest since they predict that in regions where some fibers terminate and others do not, cathodal electrical stimulation will tend to excite the fibers that terminate.

Publications

Eddington, D.K., G. Girzon, and P.A. Cuneo. "An Electroanatomical Model of Intracochlear Electrical Stimulation II: Tests of Model Predictions for Monopolar Electrodes." Submitted to *Hear. Res.*

Girzon, G., and D.K. Eddington. "An Electroanatomical Model of Intracochlear Electrical Stimulation I: Formulation, Solution and Predictions for Monopolar Electrodes." Submitted to *Hear. Res.*

Project B: New Sound Processors for Auditory Prostheses

Project Staff

Dr. Donald K. Eddington, Dr. William M. Rabinowitz

Our collaboration with colleagues at Duke University and the Research Triangle Institute in the development of new processing algorithms to improve the speech reception of cochlear implant users has resulted in laboratory-based systems that increase the average single-syllable word recognition scores by 20 percentage points for the seven subjects tested (Wilson et al., 1991). In order to make the continued development of new algorithms and their testing in our larger subject population more efficient, we decided to design and build a local, laboratory-based, real-time signal-processing system in collaboration with Joseph Tierney amd Marc Zissman of Lincoln Laboratory.

The resulting system includes a digital signal processing (DSP) board (Sonitech Corporation, based on a Texas Instruments TMS320C30 DSP chip) that connects to a SUN IPC workstation. The serial output port of the DSP board is connected to a custom I/O system that includes two channels of A/D conversion (50 kHz/channel) and eight channels of D/A conversion (>100,000 kHz/channel). Two channels of input provide the ability to investigate binaural processing and the eight channels of output allow for stimulation of up to eight intracochlear electrodes. The eight output channels are isolated from the 120V AC power and converted to current source signals by custom electronics before being connected to a subject's implanted electrode array. Custom software provides the flexible interface that enables the experimenter to specify the parameters and configuration of the processing algorithm to be implemented.

Initial tests of the system concentrated on simulating the subject's commercial, four-channel analog processor in which the analog output of each of four bandpass filters is directed to an implanted electrode. Tests of this system were made in our best performing subject and demonstrated equivalence in both subjective impressions and objective measures of word recognition. A new system designed to reduce the interference caused by simultaneously activating electrodes was also implemented. It uses the envelopes of bandpass filter outputs to modulate biphasic pulse trains that are interleaved and, therefore, delivered nonsimultaneously to as many as six electrodes. Initial tests of this system made use of a 24 consonant test (aCa context) in the same best performing subject. Scores measured using the commercial processor ranged between 73% and 85% and between 95% and 99% using the interleaved system.

Publications

Wilson, B.S., C.C. Finley, D.T. Lawson, R.D. Wolford, D.K. Eddington, and W.M. Rabinowitz. "Better Speech Recognition with Cochlear Implants." *Nature* 352: 236-238 (1991).