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technical note*

Nucleus 22-channel cochlear implant: Preliminary observations

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Abstract—A carefully designed study was undertaken in 1982 to evaluate the performance of individuals who received the Nucleus 22-channel cochlear implant. All patients were profound-totally deaf, adults with a postlingual onset of impairment. The preoperative evaluation, prosthesis fitting, training, and postoperative testing were consistent across clinics. Single-subject studies, where each patient acted as his/her own control, revealed that of the 37 subjects, 16–24 obtained significant improvement ($P \leq 0.001$) on unpracticed, unfamiliar recorded speech tests from the Minimal Auditory Capabilities (MAC) Battery, when using hearing alone (no lipreading). In addition, virtually all patients showed improvement in recognition of speech material with lipreading. The data support the efficacy of a feature extraction coding system where specific formant and amplitude information are transmitted via direct electrical stimulation to the cochlea.

INTRODUCTION

Profound deafness is a very severe handicap for which, until recently, very little treatment has been available. Since the 1970's clinical studies of several different designs of cochlear implants have been undertaken to provide sound to the profoundly deaf and have yielded promising results. The objective of these devices has been to bypass the damaged hair cells of the cochlea and stimulate the cochlear nerve endings directly.

The two most common approaches have been to stimulate the cochlea with one electrode (single channel) or more than one electrode (multichannel). Both systems can be divided into those that deliver the speech signal without speech specific processing or those that extract the speech features in some way (2). The primary rationales for multichannel stimulation are to provide more information and to take advantage of the tonotopic organization of the cochlea.

The purpose of this paper is to provide a description of a technologically advanced 22-electrode speech feature extraction type cochlear prosthesis and to present some preliminary results of the clinical study to date.

THE CLINICAL PROGRAM

This 22-electrode system, which has been designed specifically for enhancing speech understanding, has now been implanted in over 68 patients worldwide including 32 in North America, 28 in Australia, and 8 in West Germany.

Preoperative Patient Selection

The primary criteria for selection of cochlear implant candidates are *1)* postlingually deafened; *2)* profound deafness, bilaterally; *3)* 18 years of age or older; *4)* no benefit from any sensory device (tactile or hearing aid) as defined by less than 1 percent open-set discrimination when aided; and *5)* positive CAT scan or tomogram demonstrating patency of the basal turn of the scala tympani.

There are three stages of evaluation. If the patient is considered suitable after completing the first stage, he or she progresses to the next. The initial steps (stage I) are

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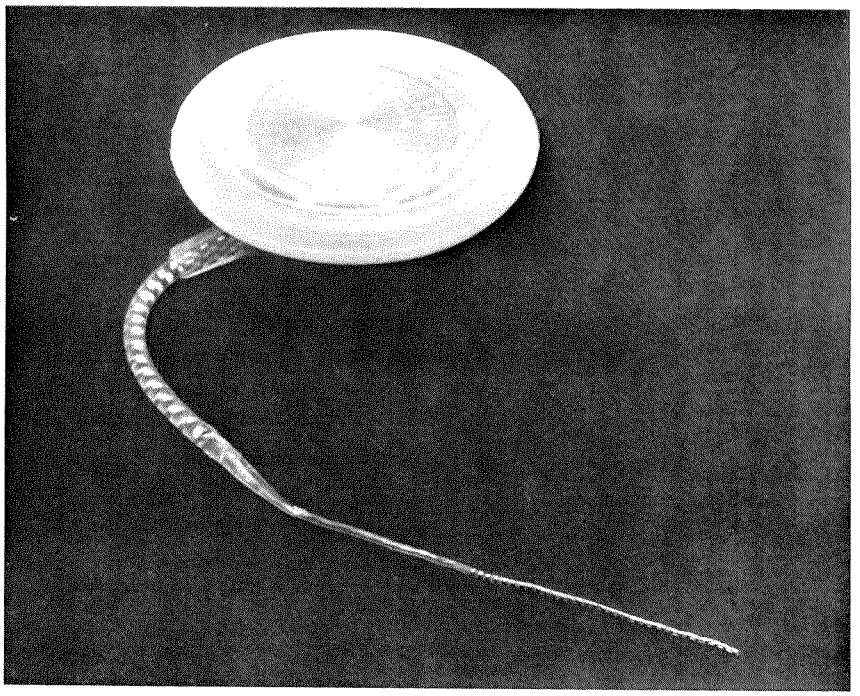

FIGURE 1
Implantable receiver/stimulator.

those taken to evaluate patients before they are considered as implant candidates. During this stage the degree of hearing loss is established and trials with new hearing aids are conducted if inappropriate amplification has been provided in the past. It is in stage I that promontory stimulation is performed. It is administered by placement of an electrocochleography needle electrode on the promontory. Those patients who do not obtain any sensation of sound in response to electrical stimulation are not considered candidates, at this time.

Stage II considers results obtained from speech discrimination testing using the Minimal Auditory Capabilities Battery and selected subtests from the Iowa Cochlear Implant Battery (4, 7). These tests are prerecorded by an unfamiliar speaker and are presented to potential candidates in a controlled fashion (i.e., using standard audiometric equipment in a sound field presentation). All tests are performed with a sensory device. For baseline purposes a measure of speechreading is also obtained.

Stage III is the final step in patient selection and occurs only if the candidate meets stages I and II criteria. It involves counseling for appropriate expectations, both with the patient and the family. Further, a tinnitus questionnaire is administered, the surgical procedure is fully explained, and the patient is scheduled for implantation. A more complete description of the patient selection process can be found in Mecklenburg and Primeccombe (3).

Postoperative Testing and Training

Typically, 2 to 2½ weeks after surgery, fitting of the speech processor, counseling, orientation, and training of the patient commences. Approximately 10 sessions of additional patient contact occur over the next 10 weeks.

The Patient System

The patient's device consists of the implantable receiver/stimulator (Fig. 1) with its 22-electrode array and the external electret microphone, transmitting coil, and wearable speech processor.

The smooth, flexible, free-fit electrode array carries 22 pure platinum electrodes and 10 support rings on a silastic carrier. Each electrode is independently programmable. The array tapers from a maximum of a 0.6 mm diameter to a 0.4 mm diameter; it may be inserted up to 25 mm. The equally spaced active electrodes are located on the distal 17 mm of the silastic carrier, and 10 support rings are located on the proximal 8 mm. The receiver/stimulator receives the externally coded stimulus information and generates charge-balanced, constant-current, biphasic stimulus pulses to selected bipolar electrodes.

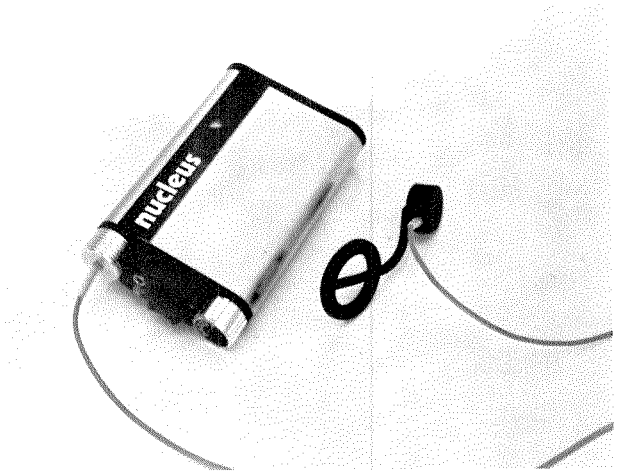

FIGURE 2
Wearable speech processor.

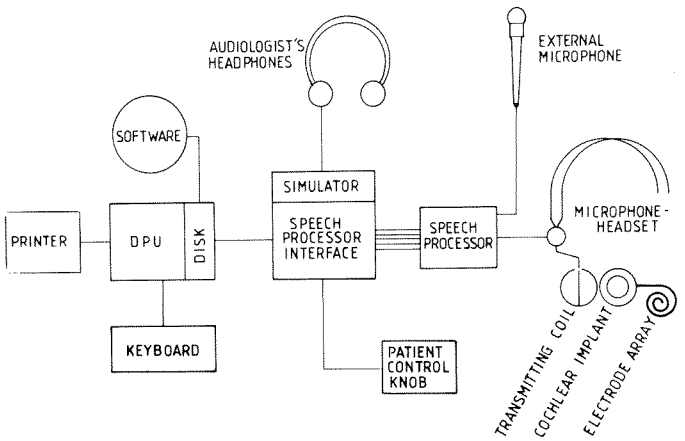

FIGURE 3
Block diagram of the complete Nucleus Diagnostic and Programming System. The modified microcomputer is called the Diagnostic Programming Unit (DPU).

Surgery

The surgery for implantation involves a 2- to 3-hour procedure which is essentially a modified mastoidectomy and posterior tympanotomy with the addition of the drilling of a bed for the receiver-stimulator in the mastoid and the insertion of the 22-electrode array into the scala tympani.

Figure 2 shows the speech processor, which is $130 \times 75 \times 18$ mm and weighs 210 gm when the batteries are included. There are controls for adjusting the sensitivity and applying a squelch feature available to the patient, as well as a variable LED output which provides both a means of estimating battery strength and the presence or absence of an input signal. Alignment of the external coil over the internal coil in the implant is facilitated by a continuous test tone when the speech processor sensitivity dial is switched to the "T" position.

Sound is picked up through the microphone and transmitted to the speech processor, where certain features of speech are extracted, passed through an analog-to-digital converter, coded, and sent along the headset cable to a transmitter coil which is located in close approximation to the internal receiver coil. Electrical power and the coded signals are transmitted through the intact skin to the receiver/stimulator by magnetic induction, where the signal is decoded and electrodes are selected for stimulation.

Speech Processing Strategy

The feature extraction coding strategy estimates three parameters of speech: *1)* The fundamental frequency (FO) determines the rate of stimulation at the electrode. *2)* The place of simulation is determined by an estimate of the frequency of the second formant. *3)* The overall amplitude of the speech sample is estimated and converted into current. For example, a high-frequency, second formant speech segment will cause a more basal electrode to be selected. This coding strategy is based on studies by Clark et al. (1) and Tong et al. (5). They demonstrated that patients were able to accurately associate place of stimulation with different vowels and to relate changes in the rate (frequency) of stimulation to the voice fundamental.

This strategy allows use of the normal frequency organization of the cochlea with its relative progression of high to low frequency sensitivity from the basal to the apical end. Bipolar stimulation allows for better control of the electrical stimulation site by passing current between two specific locations. When stimulation occurs at different points along the cochlea, different pitch percepts are elicited.

Computer-Based Testing

The audiologist's computer-based testing system, called the Diagnostic and Programming System (DPS) (Fig. 3), is used to determine optimum parameters and to program the patient's speech processor to his or her individual needs. The system consists of a specially modified microcomputer, a speech processor interface (SPI) designed to control the operation of the signal processor during psychophysical and speech testing, a patient control knob for altering the amplitude or rate of stimulation of a given electrode, a simulator which

provides a visual display of the electrode selected for stimulation and an acoustic simulation of the stimulus delivered, and a printer for providing hard copies of the data gathered for medical records.

Fitting the Device

The three primary psychophysical measurements needed to program the device are effective dynamic range for each electrode pair, loudness balancing, and place-pitch ranking.

Once these psychophysical measurements are obtained, they are compiled for programming and transferring onto the memory chip (EPROM: erasable, programmable, read-only memory) of the speech processor. All of the psychophysical testing is done with the same speech processor, which the patient takes home.

Specially designed subroutines of the software are also available which allow the device to be fine tuned. The purpose of "fine tuning" is to optimally adjust the stimulation parameters for each of the 22 electrodes for each patient; this satisfies quality judgment as patients gain more listening experience and become more descriptive reporters.

Psychophysical tests such as place-pitch ranking and loudness growth for each electrode allow for optimization of the speech processor program. In these tests, the speech processor is connected to the diagnostic and programming system and is directly controlled by the microcomputer keyboard or patient control knob. In the case of pitch ranking, the objective is to ensure that the patient perceives the pitch of the electrodes in order, from high to low, as they are stimulated from the basal to the apical end of the cochlea.

The objective of loudness growth programming is to give the patient the most natural speech perception. In other words, the stimulation amplitude which will occur for a given input signal can be adjusted. The effective dynamic range defines the limits of a patient's useable stimulation for sound sensation from the softest sensation (100 percent critical points) to the maximum comfortable loudness. Typically, this varies from electrode to electrode.

Training With the Speech Processor

To introduce the patients to the task of integrating and transferring newly received electrically stimulated sound patterns, exposure to normal listening conditions and participation in interactive communication is necessary. This is accomplished through structured listening tasks provided throughout a 40-hour rehabilitation program. During the training sessions patients are presented a variety of materials, both with and without the aid of lipreading. Careful introduction of specially designed speech materials provides the patient with the opportunity to associate words and sentences with patterns of electrical stimulation. Rehabilitation designed for multichannel implant systems differs from that used for single-channel devices. The primary difference is the increased number of channels of information available to the patient; these allow for more complex pattern recognition by the multichannel cochlear implant recipient.

The main elements of the training program are a formal program of counseling, follow-up checks of the equipment, appropriate level practice materials, and intensive practice in the use of the processed signals in a normal communication situation, with the telephone and with environmental sounds. Materials include closed sets of words and sentences; contextually based open-set sentences; and completely open-set presentations of words, phrases, and sentences.

There are 6 to 10 3-hour sessions. Two to three sessions are concerned with providing patient-specific programming, introduction to sound sensation, and counseling as to the use of the device in different listening situations. The remainder of the sessions are directed toward specific sound experience exercises, speech tracking (with and without lipreading), continued equipment monitoring, and counseling.

RESULTS OF SPEECH DISCRIMINATION TESTING

Patient Profile

All patients were postlingually deafened adults, ranging in age from 22 to 74 years, who had bilateral, profound hearing loss. The onset of profound deafness was 6 months to 50 years for these patients. All patients had more than 90 dB loss unaided. None could receive any benefit from an alternate sensory aid. No medical or radiological contraindications to surgery were noted, and of those tested with promontory stimulation, all demonstrated positive results. Although 68 patients have been implanted to date, data from only 35 to 38 patients are presented here as not all individuals have undergone complete postsurgical evaluations.

TABLE 1
Paired comparison of mean minimal auditory capabilities (MAC) results for selected closed-set subtests.

	N	Presurgical, % correct		Postsurgical, % correct		*N* Subjects with Significant Improvement†
		mean	range	mean	range	
Noise/Voice	37	68	0–98	86*	34–100	21
Four-choice spondee	37	42	0–85	72*	0–100	21
Vowel	37	29	0–55	46*	0–68	18
Final consonant	37	32	0–63	49*	0–67	20

* Significant difference, $P < 0.001$.
† Binomial model, $P < 0.05$.

Results

Presurgical and postsurgical speech results for recorded materials with multichannel users were obtained from subtests of the Minimal Auditory Capabilities Battery (MAC Battery) and subtests of the Iowa Cochlear Implant Battery. Essentially three categories of tests were used: those that emphasize prosodic features in a closed-set format, closed-set speech tests, and open-set speech tests. The test conditions for the pre- and postsurgical evaluations were the same. Detailed results of seven selected subtests of the MAC Battery are found in Tables 1–3.

All postsurgical data were obtained at three months of experience with the speech processor. Mean data for one prosodic test and three speech measures of the MAC Battery are shown in Table 1; all are in a closed-set format. The noise/voice test was selected as being representative of prosodic elements as it appears to assess the perception of the broad features of speech, such as amplitude variations and temporal cues. For this study, patients consistently scored above chance levels of 50 percent on such tests for both presurgical and postsurgical conditions. An example of patient group performance on these measures is shown by the noise/voice test. The mean score for 37 patients was 68 percent preoperatively (range, 0–98 percent) and 86 percent postoperatively (range, 34–100 percent). Most tests of suprasegmental (prosodic) features of speech can be performed by subjects who receive basic auditory or tactile cues.

Closed-set segmental tests present a more difficult task; in this case the subject is required to correctly identify an item from a group of selected alternatives. Each has a chance score of 25 percent since the task is to select the correct item out of a set of four. Although some patients demonstrate the ability to achieve high scores on these subtests, results are not necessarily indicative of discrimination of unfamiliar speech. Table 1 shows results of three closed-set segmental tests. The four-choice spondee test is included here rather than spondee same/different test as it may indicate the ability to make decisions based on changes in the fundamental frequency. Mean score on the four-choice spondee for 37 patients was 42 percent preoperatively, with a range of 0 to 85 percent; it was 72 percent, postoperatively with a range of 0 to 100 percent. Significant differences between the presurgical and postsurgical measures using a *t* test were found ($P < 0.001$).

The mean vowel test score for 37 subjects was 29 percent before implantation (range, 0–55 percent) and 46 percent postsurgically (range, 0–68 percent). The difference between the preoperative and postoperative conditions was found to be significant ($P < 0.001$). For 37 subjects, the final consonant subtest yielded a mean score of 32 percent preoperatively (range, 0–63 percent) and 49 percent postoperatively (range, 0–67 percent) with a significant mean difference of 17 percent (*t* test yielded $P < 0.001$).

A summary of the presurgical and postsurgical open-set speech recognition test results obtained from those patients who have completed their evaluations is presented (Table 2). These are most important measures as they not only provide a basis for patient selection during the presurgical evaluations, but they may be more indicative of patient's abilities to use electrically elicited auditory sensations for the understanding of some conversational speech, postsurgically. For these open-set subtests, recorded speech materials are completely unfamiliar, unpracticed items presented with no alternative choices. The patient repeats a spondee, monosyllabic word, or sentence.

Table 2 shows the means and range of scores on three measures: spondee, monosyllabic, and phoneme recognition. For the 20-item spondee recognition test, the preoperative mean for the group was 0.9 percent with a range of 0 to 4 percent. Postoperatively, 17 of 37 showed

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TABLE 2
Paired comparison of spondee recognition and NU #6 subtests of minimal auditory capabilities battery.

	N	Presurgical, % correct		Postsurgical, % correct		N Subjects with Significant Improvement†
		mean	range	mean	range	
Spondee recognition	37	0.9	0–4	10.4*	0–36	17
NU #6						
word score	37	0.2	0–4	3.7*	0–22	16
phoneme score‡	37	4.1	0–13	16.6*	0–39	24

* Significant difference, $P < 0.001$.
† Binominal model, $P < 0.05$.
‡ Chance = 4.5 percent.

TABLE 3
CID sentences.

Condition	N	Mean	Range
Lipreading only	37	54.9	14–85
Implant only	37	12.4	0–58
Lipreading and implant	37	82.6	18–100

a significant improvement [binomial model, $P < 0.05$ (ref. 6)] with a mean of 10.4 percent and a range of 0 to 36 percent. The NU #6 word list is phonetically balanced and scored both by word correct (50 items) and phoneme correct (150 items); thus two sets of scores are obtained from one presentation of the NU #6 list. Patients were encouraged to guess at each item. The monosyllabic word test was the most difficult of the MAC subtests; patients typically were unable to obtain any score preoperatively, with a mean of 0.2 percent and a range of 0 to 4 percent. Postoperatively significant improvement was demonstrated by 16 out of 37 (binomial model, $P < 0.05$). The mean was 3.7 percent, and the range was 0 to 22 percent. The phoneme mean scores, derived from responses to the word test, represent results from an inherently closed-set task since there are a limited number of English phonemes from which to choose. The chance score is 4.5 percent and preoperative patients scored a mean of 4.1 percent with a range of 0 to 13 percent. These scores increased in the postoperative condition to a mean of 16.6 percent with a range of 0 to 39 percent. With the use of the binomial modeling of the test scores, 24 of 37 patients demonstrated a significant improvement when comparing the preoperative aided best-ear response to that of the cochlear implant (Table 2).

The results of testing when using CID sentence materials as the stimuli are found in Table 3. Three conditions are shown: lipreading alone, implant alone, and lipreading combined with the cochlear implant. The results demonstrate that 22 out of 37 were able to achieve a significantly higher score when comparing lipreading alone to lipreading with the prosthesis, with a mean of 54.9 percent and 82.6 percent, respectively. Most of the patients were unable to obtain any score preoperatively when using the implant only (mean, 0.2 percent), whereas postoperatively, 20 out of 37 obtained a significantly improved score (mean, 12.4 percent; range, 0–58 percent) with hearing only (no lipreading).

Of the patients reported here, none achieved presurgically a discrimination score on more than one of the four open-set tests (spondee, monosyllabic word, phoneme, and sentence recognition). Fifteen of the thirty-seven patients obtained scores on all four open-set measures, postoperatively. The preoperative results for the open-set measures show an ability to recognize speech for virtually all patients. Postoperatively, scores ranged from 0 to 58 percent, depending on the type of speech stimuli used.

Further, evaluation of the patients informally and with speech-tracking tests have also demonstrated that approximately 30 percent of the patients have significant speech understanding without lipreading.

CONCLUSION AND FUTURE DIRECTIONS

Severe and profound deafness is a very isolating handicap; its presence may have far reaching effects on the person's family, work, and social interaction. Today's advanced cochlear implant systems help to overcome many of the difficulties which result from such hearing impairments.

Presently, a 22-channel cochlear implant system designed to extract the most important features of speech has been designed and tested by Nucleus Limited and Cochlear Corporation. A standard evaluation program-

ming, training, and postsurgical evaluation protocol has been used by 13 centers on 68 patients. Of these patients, none failed to achieve hearing sensation and no device has failed to function. All but one patient listens with the device for an average of 10 hours per day. For virtually all patients who have completed the presurgical and postsurgical speech battery, speech recognition scores were found to be significantly improved. Particularly notable is the fact that approximately one-third of the patients were able to achieve significant speech recognition without lipreading.

In the future, more effective speech processing strategies and coding schemes will make it possible for even greater improvements in the recognition abilities of cochlear implant recipients for speech. Also, with advancing technology, it is likely that cochlear prostheses will become useful to a wider group of hearing-impaired individuals who obtain very limited benefit from hearing aids.

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