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THE PERFORMANCE OF POST-LINGUALLY DEAFENED ADULTS WITH COCHLEAR IMPLANTS

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INTRODUCTION

Profound deafness has a serious impact on the communication abilities of adults and children. Recent advances in electrical stimulation of the cochlea has provided new hope for deafness.[1,2] Many recipients of cochlear implants can now understand a considerable amount of speech without watching a person's lips; many more can combine this auditory information with lipreading to achieve very high levels of communication.[3,4,5] This article will review our recent clinical and experimental experience with cochlear implants in post-lingually deafened adults.

PRE-LINGUAL AND POST-LINGUAL DEAFNESS

First it is important to distinguish between pre- and post-lingual deafness. A person born deaf or deafened within the first 2–3 years who does not learn language through hearing has no, or a very limited, representation of speech sounds in the brain. A person who has learned language from audition but later becomes deaf should have some memory for speech sounds. These are respectively termed pre- and post-lingually deafened. Intermediate instances, corresponding to loss of hearing from about one and a half to five years old are termed peri-lingual. The longer they had been exposed to speech and the more recently they have become deaf, the greater will a person's memory be for speech sounds. It is also an advantage if the person has developed knowledge and user skills in the structural aspects of language. This knowledge can be put to use in understanding speech when the signal is not perfect, as is the case with cochlear implants.

As well as not having an auditory speech memory, pre-lingually deafened adults usually rely on sign language and have developed strong ties with other deaf people whose social and educational world is non-auditory. There are thus two large difficulties for pre-lingually deafened adults. Although they can 'hear' something from electrical stimulation of

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the ear. they have more difficulty assigning meaning to these sounds. and they are usually not highly motivated to learn this strange and imperfect code. Indeed pre-lingually deafened adults turn out not to be good users of cochlear implants and therefore they are typically not implanted. It is possible that in the future pre-lingually deafened children might be helped considerably by implantation.

Options for postlingually-deafened adults

Most profoundly deafened. and some severely deafened individuals receive only rather limited benefit from hearing aids. Some can hear gross loudness or pitch changes over time, and this can be very helpful to lipreading. However. the range of lipreading skills varies enormously both among normal and among hearing-impaired people. and the average level is generally insufficient to have an effortless conversation. Recently, wearable tactile aids have been shown to be beneficial to many profoundly-deafened children and adults.[6,7] However, the information provided is limited. It does not allow speech understanding without lipreading, and provides only a small advantage over lipreading alone. In addition, it can also require lengthy practice.[8] Therefore. cochlear implants have emerged as the most viable treatment for most post-lingually totally and profoundly deafened adults. However, it is critical to determine how much benefit a patient is receiving from an appropriate hearing aid before deciding what the chances are that the person will perform better and receive other forms of benefit with a cochlear implant.

The selection of appropriate patients

We have already mentioned the two most important criteria for an implant candidate: the adult should be post-lingually deafened and should receive only limited benefit from a hearing aid. These are readily established and could even form the basis for referral, but the determination of benefit should have a second, more precise stage. We typically implant only patients who have less than 4% correct recognition of open set monosyllabic words using a hearing aid. We do not recommend implanting patients who show a large enhancement in their lipreading score (say, 30%, depending on the test material) from using their hearing aid. The above remarks apply to mono aural performance on the better-hearing ear. However, it is uncertain how we should counsel a patient who has, say, 0% recognition of words in one ear and 8% in the other.

At present it is very difficult to predict how well a given patient will do with an implant. Post-implantation performances range from 0 to 7% correct on word recognition tests. A list of predictors is emerging, but the confidence intervals on such prediction are still rather wide. Therefore we are not able to tell the patient with any degree of certainty how much benefit they should expect from the auditory prosthesis. In marginal cases a calculated risk is acceptable, but the ultimate decision can be made by the informed patient, who is judged professionally (ie psychologically) able to appreciate and accept that risk.

Cochlear Implant Designs

The various cochlear implants share some common design characteristics. They all require:

1. a microphone—to receive and transform the sound wave to electricity;
2. a speech processor—to change the electrical waveform in some optimum way so that it can be transmitted to the electrodes and be perceived as speech;
3. an external/internal interface—to transfer the information coded by the speech processor to the internal electrodes;
4. internal electrodes—to transmit electrical current to the nerve fibres in the cochlea.

Particular implants differ in the details of all these characteristics, but probably the most important differences are introduced in the speech processor. We shall now briefly discuss some of these differences. Although the first two are not now commercially available they have contributed much of the information we have on benefit from signal processing in implants.

House Implant

The single-channel implant processor developed by House[9] is schematized in Figure 1.[10] In the example shown, the input signal 'ma' amplitude modulates a 16-kHz carrier frequency. Severe peak clipping is used to limit the level.

Vienna Implant

The single-channel implant processor designed by Hochmair and Hochmair-Desoyer[11] is represented schematically in Figure 2. It functions like a hearing aid, in that it provides high-frequency amplification that can be adjusted to suit the individual. In the figure, the spoken word 'sat' (lower left) has the high-frequency energy characteristic of /s/ and /t/ amplified, to make the higher-frequency components of speech audible. The emphasis can be seen in the output waveform (lower right).

'Nucleus' Implant (Cochlear Corporation)

The 21-channel processing scheme designed by Clark and Tong[12] is shown in Figure 3. The fundamental frequency (FO) is extracted and determines the pulse rate. The first (F1) and the second (F2) formant

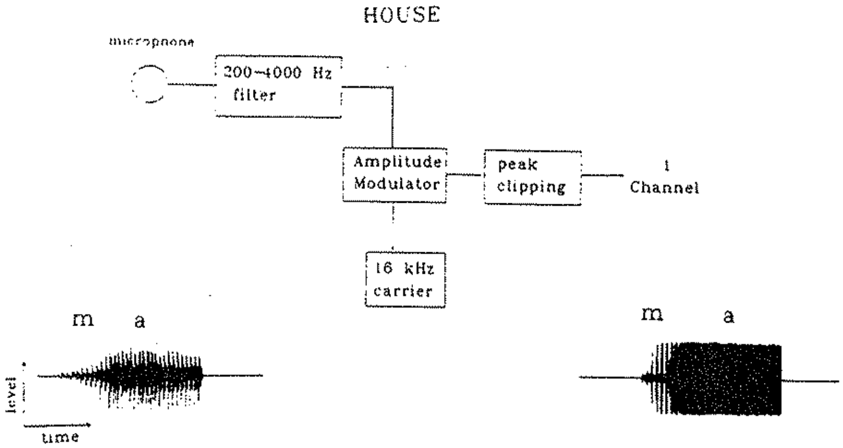

Figure 1 Schematic representation of the House cochlear implant. An example of the input (lower left) and output (lower right) waveform is shown for the word 'ma'. Adapted from Tyler and Lowder.[10]

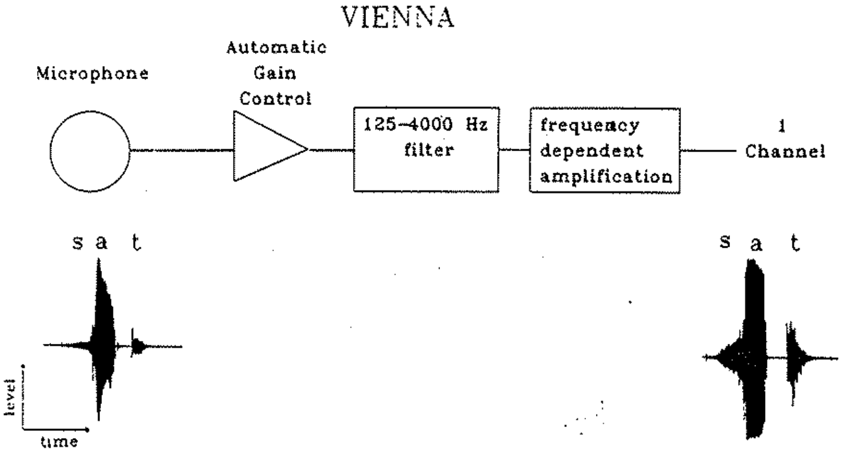

Figure 2 Schematic representation of the Vienna cochlear implant. An example of the input (lower left) and output (lower right) waveform is shown for the word 'ma'. Adapted from Tyler and Lowder.[10]

frequencies and their amplitudes (A1, A2) are also extracted and are used to determine the particular electrodes that are stimulated (one at a time), and the level at which they are stimulated. In this figure, the word 'heard' is the input, and the output is shown by designating the electrodes that would be stimulated by pulse trains, their levels and rate, as a function of time. Many combinations are possible, allowing the

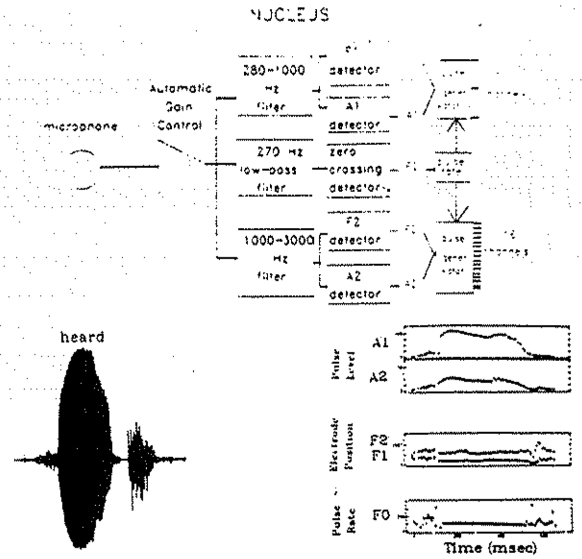

Figure 3 Schematic representation of the Nucleus cochlear implant. An example of the input (lower left) and output (lower right) waveform is shown for the word 'heard'. Adapted from Tyler and Lowder.[10]

stimulation to be geared, in theory at least, better to the electrodes giving best response, and to patterns, eg frequency-lowering, that best match information to residual capacity.

'Symbion' Implant (Richards Ineraid Cochlear Implant)

A schematic of the processing of the 4-channel Symbion implant based on the design of Eddington[13] is shown in Figure 4. Four filters separate the input, here shown as a complex waveform, into bands. The output shows how a complex waveform has been simplified, separated into three component sine waves. These sine waves (or the analagous bands of speech, if that were the input) are presented to different electrodes.

Other Implants

The principles behind other implants are mostly variants of those mentioned. Two have been developed in the United Kingdom. Fourcin et al[14] developed a single-channel device that codes only the F0, and improves patients' lipreading ability. Fraser and colleagues[15,16] have developed for extra-cochlear implantation a single-channel device similar to the Vienna processor, which shows improvements in lipreading and some limited word recognition.[17] The 12-Channel Chorimac implant[18] is based on peak-picking, presenting a pulsatile stimulus only to the electrodes associated with filters that currently have high levels of energy.

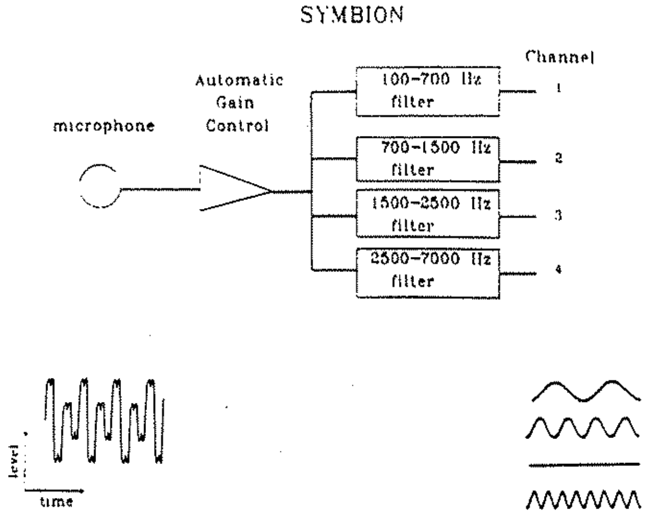

Figure 4 Schematic representation of the Symbion cochlear implant. An example of the input (lower left) and output (lower right) waveform is shown for an artificial stimulus of three sinusoids. The input waveform is divided among four channels depending on their frequency content. Adapted from Tyler and Lowder.[10]

The level of the pulse is fixed, but the pulse width varies with input level. The Durn/Cologne implant[19] is an extra-cochlear device that provides pulsatile simulation on from 1 to 16 electrodes, corresponding to spectral peaks. The pulse amplitude is fixed but the interpulse interval depends on the channel that has the highest energy. The device is typically programmed to send the same information to all electrodes (single channel), although in some subjects (for example, D4 and D7 reported here) it functions as 8 or 16 separate channels.

RESULTS

The remainder of this presentation discusses results from two different studies evaluating performance with implants. At the University of Iowa we tested all patients implanted there as well as a group of patients implanted elsewhere but sent to Iowa City for evaluation.[20,21,22] In the first study patients were not especially selected for their level of performance. Nine patients with the House implant were available, 32 patients with the Nucleus implant and 25 patients with the Symbion implant. In the second study[23] we tested some of the better cochlear implant patients in Europe and the United States. We shall discuss the performance of both groups in four areas: everyday sound recognition, word recognition, sentence recognition and lipreading enhancement.

Everyday Sound Recognition

Everyday sound recognition was tested in the unselected group with a test of 36 sounds, tested in two lists of 18 items, ie an 18-alternative closed-response set, randomised without replacement. The patients know that each sound will be one of 18 that is written in front of them. The results are shown in Figure 5. The House patients averaged 24%, the Nucleus patients 35%, and the Symbion patients 47% correct.

In the second study, the better patients were tested with an 18-alternative set of sounds chosen so as not to be dependent on the country of the patient. The results in Figure 6 indicate that the Chorimac and Duren patients scored lowest, and the Symbion patients highest. It is clear that most of these patients are able to recognize some environ-

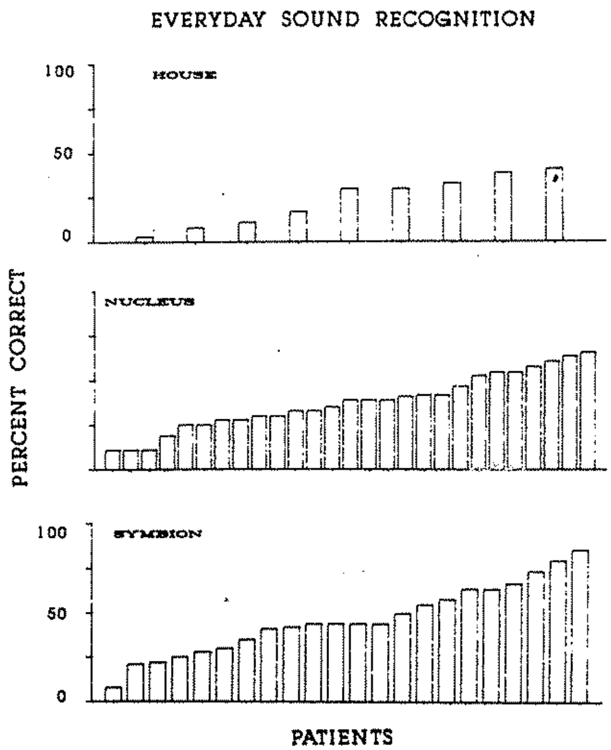

Figure 5 Results obtained on the Everyday sound recognition test from the unselected group of patients.

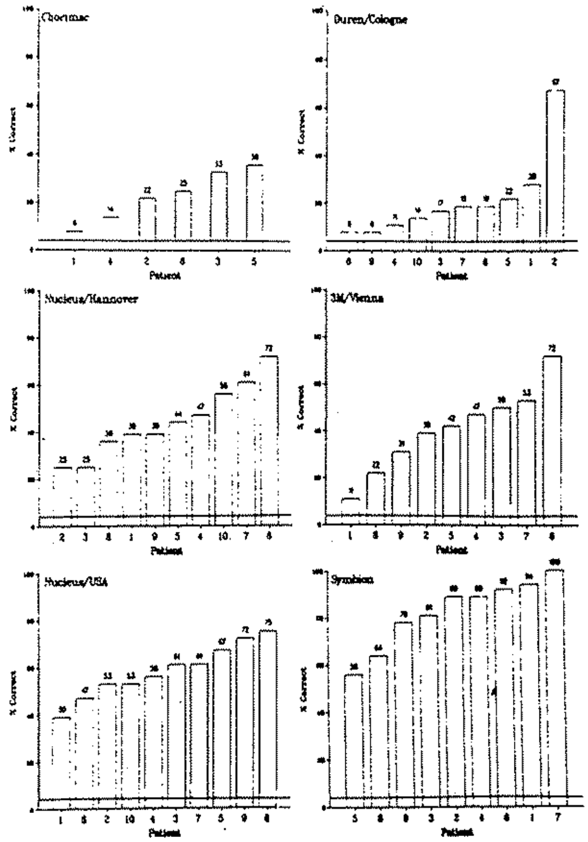

Figure 6. Results obtained on an everyday sound recognition test from the 'better' patients. From Tyler et al.[23] (With permission)

mental sounds. In natural surroundings of everyday life, where contextual information is available on the likelihood of certain sounds, the effective performance could be much higher.

Word Recognition

Word recognition was tested in the unselected group with 50-item lists of monsyllabic words. The effective vocabularly size is somewhat over 1,000 and the patients did not know what the words were before the text, ie an open-response set test. The results are shown in Figure 7 with the words scored by both words correct and phonemes correct. The House patients average 1%, the Nucleus patients 17%, and the Symbion patients 12% correct. The better patients were tested with 35-item word lists. Three

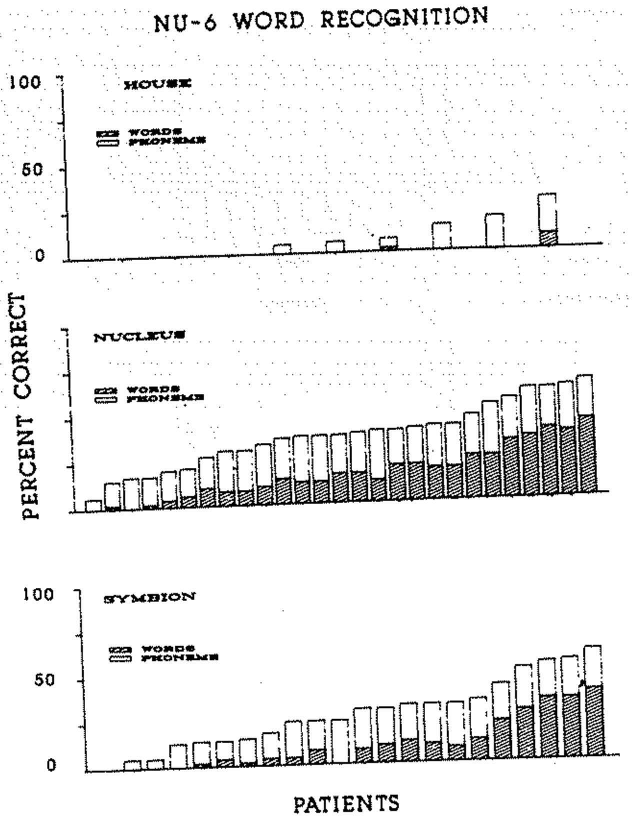

Figure 7 Results obtained on the NU-6 word recognition test from the unselected group of patients.

word lists were used: one spoken in English, one in French and one in German. The same talkers (a male and a female) recorded each test and the words had the same meaning in each language. The results, shown in Figure 8, indicates that the Chorimac patients averaged 2.5% correct on the French list. The Duren patients averaged 17%, the Vienna patients averaged 15% and the Nücleus/Hannover patients averaged 10% on the German test. The Nucleus/USA patients averaged 11% and the Symbion patients averaged 14% on the English test. Some of these patients are thus able to recognize words without visual clues. In everyday life, with familiar speakers, effective performance can be much higher than the scores on this difficult test suggest.[24,25]

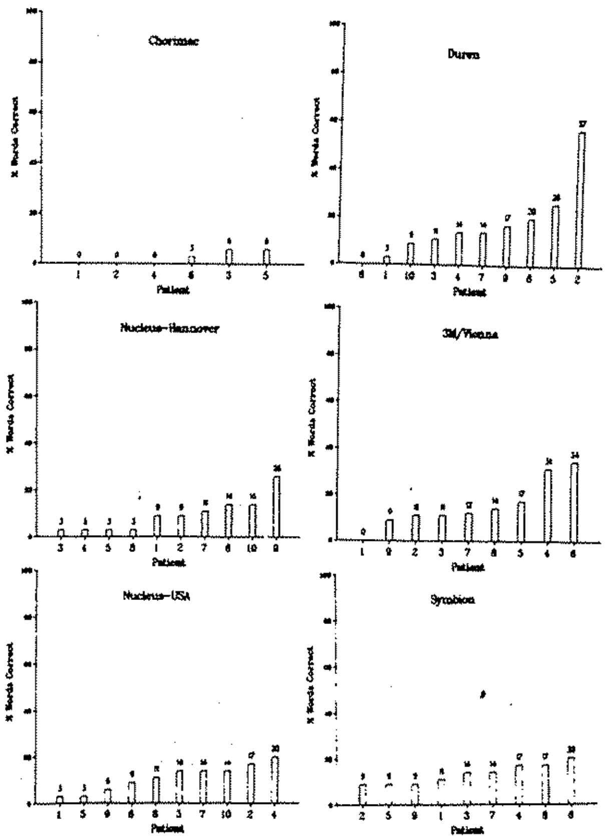

Figure 8 Results obtained on a word recognition test from the 'better' patients. From Tyler et al.[23] (With permission)

Sentence Recognition

Word recognition in sentences was tested in the unselected group using 100 sentences produced by 20 different talkers. There were 434 words in all the sentences, excluding the definite and indefinite articles ('the', 'a'). The test format involves an open set. The results are shown in Figure 9. The House patients averaged 1%, the Nucleus patients 38% and the Symbion 32% correct.

The better patients were tested with 30 sentences. Three sentence lists were used: English, French and German. Again the same talkers recorded each test, and the sentences had the same meaning in each language. There were 124 words in the English sentences, 152 words in the French sentences and 126 words in the German sentences, excluding articles. Figure 10 shows that the Chorimac patients averaged 0.7%

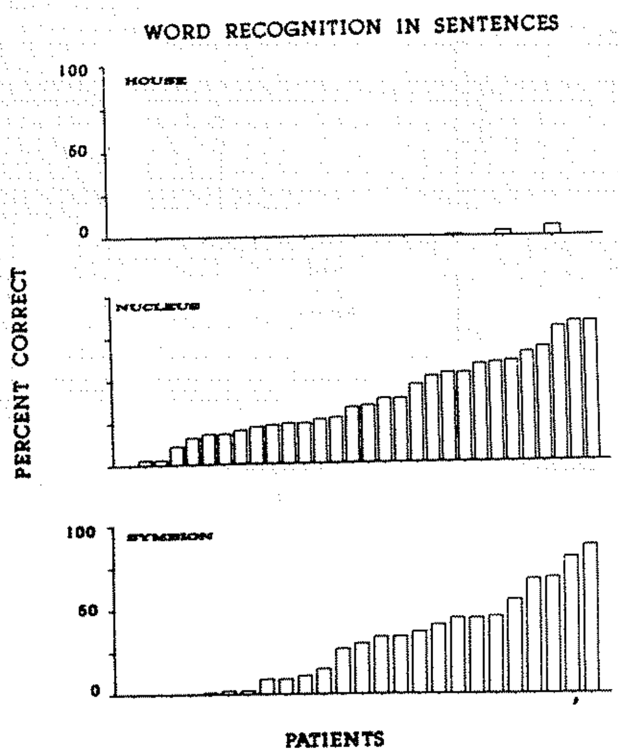

Figure 9 Results obtained on the word recognition in sentence test from the unselected group of patients.

correct on the French list. The Duren patients averaged 10%, the Vienna 16% and the Nucleus/Hannover 16% correct on the German test. The Nucleus/USA patients averaged 44% and the Symbion 48% correct on the English test. Again, with familiar speakers and in surroundings with contextual cues, effective performance can be higher than these figures suggest.

Lipreading Enhancement

To quantify the enhancement of lipreading, the recognition of consonants was measured in two conditions: vision-alone and audition-plus-vision. Only the unselected group of patients were tested. The consonants tested were /p, t, k, b, d, g, f, v, sh, s, z, m, n/ in the context /a/—consonant—/a/. Each of the 13 consonants was repeated 12 times for a total of 156 items from a laser videodisc. The patient is aware of all the response options; thus it is a 13-choice closed-set task.

The results are shown in Figure 11. Most of the patients have higher

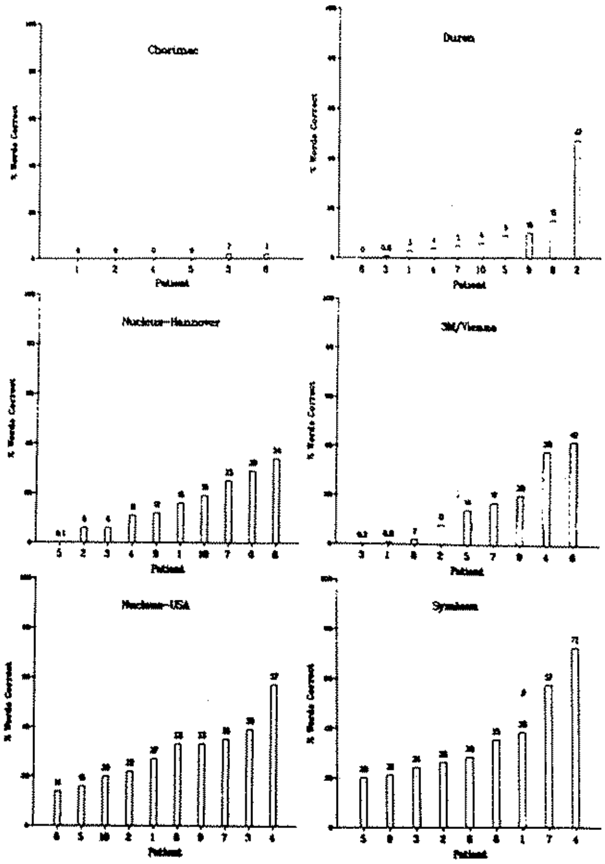

Figure 10 Results obtained on a word recognition in sentence test from the 'better' patients. From Tyler et al.[23] (With permission)

scores for audition-plus-vision than for vision-alone scores. Enhancement scores, computed by subtracting scores for vision-alone from those for audition-plus-vision, averaged 32% for the Nucleus, 21% for the House and 38% for the Symbion patients. Also shown are the results from 3 patients with the Vienna device who averaged 37%.

CONCLUSIONS

Cochlear implants have had an enormous impact on the rehabilitation of post-lingual profoundly deafened adults. A variety of devices are available, of which the multichannel Nucleus and Symbion devices usually yield higher scores. However, the single-channel Vienna and Duren/ Cologne implants have also assisted some patients in achieving some

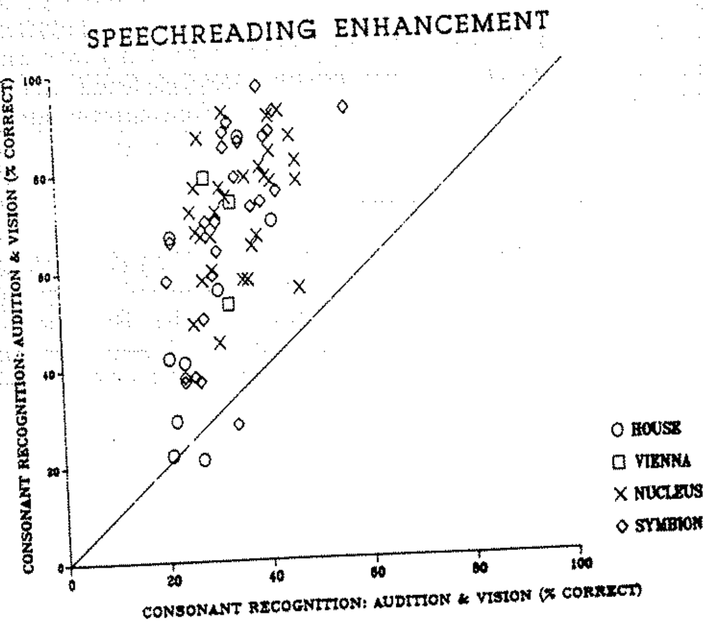

Figure 11 Results obtained on the consonant recognition test from the unselected group of patients. The results are shown for the audition-plus-vision and vision-alone conditions. All points above the diagonal indicate benefit to lip-reading.

degree of open-set word recognition.

Cochlear implants have helped patients in a number of ways, including the perception of environmental sounds, the recognition of words and sentences and improvement of the audiovisual perception of speech. Virtually all patients obtain some form of benefit from their cochlear implant. This is remarkable because most of these patients could not even detect the presence of sound while using powerful hearing aids before receiving their cochlear implant. However, the amount of benefit obtained varies enormously across individuals, sometimes from 0 to 70% correct word recognition.

The enormous variation in performance makes the selection of appropriate candidates difficult. It is essential to determine accurately and thoroughly the amount of benefit the patient receives from their hearing aid before deciding whether an implant is appropriate. It is quite likely that improvements will be made in the design of cochlear implants in the forthcoming years. We will also improve our ability to fit and adjust accurately the devices to individuals. As a consequence of these advances the implantation of cochlear prostheses will extend to patients with severe, and perhaps even some types of hearing loss currently classified as moderate. Together with this increasingly sophisticated technology of hearing prostheses it will be important to provide the needed orientation and training of professionals providing hearing health care. Only then can we ensure that our patients get the best possible devices fitted in the optimal fashion, and that they are trained and counselled appropriately and efficiently.

ACKNOWLEDGEMENTS

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DISCUSSION

Audience Do you think that the differences in benefit relate to the aetiology of the hearing loss?

Professor Tyler Data are being collected by many centres around the world that we hope will eventually answer that question. There are many factors involved in patient benefit, such as the number of usable nerve fibres and the (central) ability to extract information from a limited code. (These people do not hear speech the way normal-hearing people do, but have to make educated guesses based on an imperfect signal.) Aetiology may have some bearing on neural capacity, but there will still be much variability within aetiological categories.

Audience Do you think that the time from onset of deafness in relation to insertion of the implant affects the outcome?

Professor Tyler Again, there are as yet insufficient data to answer this question. There is some evidence that patients who are implanted soon after becoming deaf do better than patients who have been deaf for a number of years. However, there are also some patients who have been profoundly deaf for 20–30 years who have achieved very good results. There may be some relationship, but it is not consistent enough to predict outcome or to exclude somebody just because they have been deaf for a number of years.

Professor Haggard Could I get your reaction to the apparent differences in some tasks between the Symbion and the Nucleus devices. We can take into account the fact that the analysis in the Nucleus device makes some assumptions about the stimulus, i.e. that there is one speaker, not two, and no noise. The apparently lower performance on the environmental sounds and on speech in noise are then much what we would expect. The Nucleus and Symbion patients are then, broadly speaking, performing at similar rather than different levels. Is that a fair conclusion, or could there be any difference in the selection of the subjects that were available to you that might undermine that conclusion?

Professor Tyler It is accurate to say that from our experience the Symbion patients' performance and the Nucleus patients' performance are very similar. There may be a slight benefit for some Symbion patients with environmental sounds. Patients implanted in Iowa are randomly allocated to receive either the Nucleus or Symbion device, and so there is no selection bias in this group.

The better patients that I tested in Europe and elsewhere in the United States were drawn from a biased pool. The Symbion patients were drawn from a pool of about 85 patients, while there were about 517 Nucleus patients in the United States at the time. However, the Nucleus patients were located over a much larger geographical area, and were therefore not all considered for inclusion in the study by the manufacturer. It is difficult to determine the extent of any selection bias. It is certainly remarkable that two devices that work on such different principles are able to achieve similar results. There is a new device being developed in the United States that will allow the selection of either pulsatile or analog stimulation, which can be adjusted to the patients' individual needs, and this may enable more specific answers to your question.