New Ears for Old:
Auditory Implants and Frequency Transposing Hearing Aids

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Man's original method of aiding defective hearing was to cup his hands behind his ears. This earliest of sound funnels was followed by the use of animal horns and large sea-shells, and culminated in the eighteenth and nineteenth centuries in the development of ear trumpets of many different kinds. The first electronic hearing aids, which appeared in the 1920s, provided far greater amplification but were bulky, weighing in some cases over 100 lb. The subsequent development of miniature valves, transistors and integrated circuits led to progressive miniaturisation and the ready availability of 'behind-the-ear' aids and even 'within-the-ear' aids[1,2].

Although modern hearing aids may provide a number of additional options such as a 'bass-cut' switch or the use of 'amplitude gain compression', their design does not differ in principle from the first hand cupped behind the ear. In essence, such techniques compensate for lowered efficiency in the mechanical transducers of the outer and middle ear (the tympanic membrane and ossicles) by increasing the energy that drives the transducing system. Alternatively, if the mechanisms that conduct sound energy from air to inner ear are too severely impaired, they may be bypassed by use of a bone conduction hearing aid. In this way patients with hearing loss that is mainly 'conductive' generally get some benefit from conventional amplification.

In sensorineural deafness, in which structures in the cochlea or the auditory nerve are damaged, conventional hearing-aids may no longer be effective. No amount of amplification can assist if destruction of neuromechanical transducers in the cochlea is total. There are many pathologies, however, in which cochlear destruction is accompanied by at least a partially functioning auditory nerve[3-5] and in such cases it may be possible to provide auditory sensation by direct electrical stimulation of the sensory neurons.

The suggestion that electricity may be used to provide auditory sensation in the deaf dates back to Benjamin Franklin[6], and experimental investigation of the effects of stimulating the auditory apparatus by electrodes external to the inner ear has been in progress since Alessandro Volta (1800)[7]. Nevertheless, it was not until 1957 that the Frenchmen Djourno and Eyries[8] made the first attempt to stimulate the auditory nerve directly by means of an implanted electrode. Since that time, extensive efforts have been made to develop auditory prostheses that will mimic, at least in part, the normal functioning of the cochlea[3,9-15]. Experimental work has taken place with both single-channel implants[12,13,15] and multi-channel implants[16-20]. Evaluations of patients fitted with single-channel implants, however, have made it clear that such prostheses in isolation are not capable of conveying intelligible speech. The information they provide should be regarded chiefly as an aid to lip-reading[3,10]. Indeed, consideration of the rate of 'information transmission' in the speech code, and of the frequency analysing capacity of the unimpaired cochlea, has led various workers to conclude that at least 10, and perhaps as many as 20, channels may be needed to transmit sufficient speech 'information' to allow comprehension without lip-reading[9,21].

In spite of extensive investigations of the possible 'mappings' of the speech code into electrical stimuli, and enthusiastic reports by a few workers[16,22], the consensus view is that multi-channel implants have as yet no significant advantage over single-channel implants[3,5]. Nevertheless, the potential utility of even single-channel implants should not be minimised. Ballantyne et al.[3] conclude, for example, that 'single channel implants demonstrably have brought the following benefits to the totally deaf patient:

(a) Psychological: release from auditory isolation.
(b) Aid to lip-reading: improvement in speech scores compared with a similar group of patients with their hearing aids.
(c) Aid to identification of important environmental sounds including warning sounds.
(d) Aid to improvement in articulation and intonation.
(e) Relief of tinnitus in some cases.'

Furthermore, a number of promising developments have taken place in single-channel prostheses. In earlier work, both single-channel and multi-channel implants have been intracochlear. In multi-channel implants, electrodes are typically positioned along the length of the cochlear partition in the hope of restoring something of the 'place principle' of frequency analysis in the impaired ear. For single-channel implants, a less invasive extra-cochlear electrode positioned on the middle ear promontory or round window now appears equally effective[12,23]. Advances have also been made in selecting those 'information-rich' but nearly invisible speech cues most likely to assist with lip-reading. For example, it is
possible to extract the frequency of vibration of the vocal folds, which provides voice pitch and allows lip-readers to discriminate between otherwise indistinguishable pairs such as 'vat' and 'fat' (the vocal folds vibrate throughout the v but not the f) and also supplies cues relating to the intonation, stress and even syntax of sentences[12]. Furthermore, under conditions of simulated deafness, subjects with normal hearing increased lip-reading speeds by 55 per cent to 146 per cent when visual cues were supplemented by vocal fold vibration information presented in auditory form[24]. This compares with percentage gains of at most 30 per cent which have been found in simulated deafness studies when lip-reading is supplemented by information presented in a tactile form[25,26].

Before 1978, corresponding studies comparing the abilities of deaf patients using auditory implants with their abilities using high-power hearing-aids or alternative non-invasive devices such as tactile and/or visual aids, had not been carried out and Ballantyne et al.[3] accordingly concluded that even single-channel implants must be regarded as experimental. Since that time, however, encouraging results have been found at a number of centres. Recent (unpublished) studies by House et al. at the Walt Disney Hearing Rehabilitation Research Centre in Los Angeles indicate that lip-reading performance with a single-channel implant is significantly better than with a high-powered bone-conduction hearing aid (see also work in Vienna by Hochmair et al.[27]). In a recently revised version of their 1978 report Ballantyne et al.[28] therefore express cautious optimism about the future of the implant programme.

Nevertheless, considerable technical, surgical and even theoretical difficulties remain, particularly with multi-channel (intracochlear) implants[3,5]. Notable among these are difficulties in estimating the proportion and location of auditory neurons surviving after loss of cochlear function, difficulties in achieving electrical isolation of electrodes in multi-channel arrays, with attendant problems of confining electrical stimulation to distinct neuron groups, uncertainty about how best to transform the speech wave form into some optimal form of electrocochlear stimulation (although ‘vocoder’ techniques are promising) and even lack of complete understanding of how the unimpaired auditory nerve codes basic stimulus dimensions such as intensity and frequency. The hope of providing intelligible speech by means of a multi-channel implant alone therefore remains somewhere in the future.

It must be remembered that patients with total bilateral hearing loss constitute about 2 per cent only of the sensorineural deaf population and, for reasons of insufficient residual nerve function, excessive age or other contra-indications of a medical, emotional or intellectual kind, the number suitable for implantation is fairly small; for example, estimates of the minimum number of patients in the UK who are currently suitable for implantation range from roughly 3,000[5] to 5,000[3], although this number could rise considerably if the benefits were shown to be great and the surgery not hazardous.

This leaves a very large number of the sensorineural deaf who, by virtue of possessing usable residual hearing, are excluded from the implant programme, but are nevertheless not adequately helped by conventionally amplifying hearing aids. Such patients usually have residual hearing in the low frequencies but little or no residual hearing in the high frequencies, producing what is known as a ‘ski-slope’ hearing loss (Fig. 1). As vowel

![Fig. 1. Pure-tone audiogram of a potential FRED user.](image)

![Fig. 2. Mean identification scores for the consonants /s/, /ʃ/, /t/, /t/, /tr/, /t/, /z/ and /dʒ/ (combined with the vowel /i:/) presented at comfortable listening level through TDH 39 headphones. (Data for 54 ears abstracted from Velmans and Marcuson,[30].)](image)
shows the average identification scores for such consonants under ideal listening conditions, with amplification adjusted to a comfortable listening level, by a group of adults with acquired sensorineural losses. As can be seen, patients whose losses deteriorate to no measurable hearing above 2 or 3 kHz have average identification scores of around 50 per cent, whereas scores in the 80-90 per cent region generally require measurable hearing of at least up to 6 kHz[30].

Various workers have therefore explored ways of lowering the frequency of high frequency speech cues, thereby mapping them on to the residual hearing range. The possibility of such a ‘frequency transposition’ was first suggested by Perwitzchky in 1925[31] and the earliest working devices were produced at the Karolinska Institute in Stockholm by Johansson[32,33] in the late 1950s. Since that time many transpositions have been tried[34] but few have been shown to be superior to conventional amplification, largely because recoded high frequency ‘information’ may in fact be treated by the ear/brain system as ‘noise’ and, furthermore, may interfere with low frequency information available in the residual hearing range[35,36]. Until 1980 the only transposer to be produced as a commercial hearing-aid (the Oticon Tp64/ Tp 72) was one of Johansson’s original devices.

During the last decade, a recoding device known as FRED (Frequency REcoding Device) has been studied, whose output is highly ‘speechlike’ in character[35,37,38]. The device has two channels, a transposing and a non-transposing channel. The transposing channel selects only the fricative and stop consonant cues in the 4 to 8 kHz region for recoding, ‘shifts’ these down the frequency axis by 4 kHz (thereby mapping them on to the 0 to 4 kHz range) and then combines the transposed information with conventionally amplified speech in the non-transposing channel (Fig. 3). Because of a perceptual ‘blending’ effect that occurs when recoded and non-recoded cues are combined[35], those with normal hearing the output sounds like normal speech with fricative and some stop consonants emphasised. Transposed environmental sounds, such as gas hissing, water running and bells ringing, also sound very similar to the originals, although lowered in frequency.

An initial evaluation study[38] with the FRED device established that a group of subjects with normal hearing were able, under simulated deafness conditions, to imitate transposed consonants more accurately with transposition added to conventional amplification, than a control group using amplification only. This effect, obtained without formal training or prior familiarisation with transposition, gave an initial indication of the ‘speechlike’ nature of transposed sounds.

A study of six sensorineural deaf children found they learnt to articulate the sounds / s, f, t, tr and t’/ more quickly when transposition was added to selective amplification than when selective amplification only was used (the experiment employed a double-blind, split-plot repeated measures design, balanced for order effects)[36].

In recent years an extensive evaluation programme using sensorineural deafened adults with a wide range of sloping losses has also been completed[30].

Phase 1 of the programme directly compared the ‘speechlike’ nature of FRED transposition with transposition supplied by the Oticon Tp72 (the only commercially available alternative system). Thirty-six subjects, who had no prior experience of transposition, were required to maximise the ‘clarity’ of each of eight CVC syllables containing transposed consonants by adjusting the ‘balance’ of conventionally amplified and transposed information for each syllable. The procedure was repeated for each ear using both FRED and Oticon Tp72 transposition in a design balanced for order effects. Transposing system characteristics were carefully matched on all variables other than the mode of transposition used (in contrast to FRED, which preserves the spectral envelope of transposed signals, the Oticon Tp72 converts all speech and environmental signals in the 4 to 8 kHz range into low frequency ‘noise’—see Fig. 3). The main question of interest was whether untrained subjects would opt for supplementing conventional amplification with transposition (of either kind) to improve the ‘clarity’ of individual CVC syllables, or whether they would judge the syllables to be ‘clearer’ with conventional amplification only, i.e. with the transposition gain control set to zero. Differences in the use of FRED and Oticon Tp72 transposition were highly significant; subjects opted for supplementing amplification with FRED transposition on 365 out of 576 ‘settings’, whereas they chose to supplement amplification with Oticon Tp72 transposition on only 32 out of 576 ‘settings’. Subjective preferences for FRED (over the Oticon Tp72) elicited at the end of the experiment were also highly significant. These results confirmed published findings regarding the subjective ‘acceptability’ and/or ‘speechlike’ nature of the two systems[36,38-40].
Phase 2 of the study focused on the ability of sensorineural deafened adults to identify transposed consonants with both conventional amplification and varying amounts of FRED transposition added to conventional amplification. It had become apparent from Phase 1 that the effects of transposition were likely to vary with the nature of the hearing loss, from consonant to consonant, and even with the ‘balance’ of transposed to non-transposed information. A ‘consonant identification profile’ was developed to chart these variations (Table 1). Two

| Consonants | Left ear | Comfortable listening level: 10 |
|------------|---------|-----------------------------|
|            | FRED transposition settings | -12 dB | -6 dB | 0 dB | +6 dB | +12 dB |
| s          | ? ? ? ? ? s ? s s s s s s s |
| d3         | ? s ? ? d3 d3 d3 d3 d3 d3 |
| t          | ? p ? t t t t t t t t t t |
| j          | ? ? s ? d3 s s s s s s d3 |
| t          | ? ? ? ? t p t t t t t t t |
| z          | d ? d ? b ? d ? d3 d3 |
| f          | s t s ? s t t t t s ? |
| z          | ? ? ? ? ? ? s s s s d3 |

Scores 1.5 3.5 12 11 15.5 13

Table 1. Consonant identification profile for the subject with the audiogram shown in Fig. 1.

identification responses were obtained for the eight consonants shown (recorded on tape and combined with the vowel /i:/), (a) with gradually increasing amounts of transposition, and (b) with gradually decreasing amounts of transposition, i.e. with conventional amplification only, and with the transposing to conventional amplifying channel ‘balance’ set to -12dB, -6dB, 0dB, +6dB and +12dB respectively in both an ascending and a descending series. The subject’s identification responses are shown in the cells of the profile and the overall performance at each level of transposition is obtained by adding the columns[30]. The column totals were also used as a means of distinguishing those likely to benefit from a transposing hearing aid (‘users’) from those unlikely to benefit (‘non-users’). For the purposes of the study, ‘users’ were taken to be subjects whose total score at any one of the five transposition ‘balance’ settings was at least 3.5 points greater than the total score using conventional amplification only; this criterion of improvement was arbitrarily set to be just greater than 10 per cent of the maximum possible score of 32.

The profile in Table 1 shows one of the most dramatic improvements obtained so far, an improvement from 1.5/32, using conventional amplification only, to 15.5/32 with the transposing to conventional amplifying channel balance set to +6dB (i.e. an increase of 14/32 or 43 per cent of the maximum possible score). In fact, the improvements obtained in Phase 2[30] were somewhat less, ranging from the arbitrary minimum of 3.5/32 (10.9 per cent) to a maximum of 9.5/32 (29.7 per cent). Of the 28 subjects tested, 9 were diagnosed as ‘users’, 5 on both ears and 4 on one ear only. Inspection of the 14 ‘user’ audiograms indicated that they fell within the dotted area shown in Fig. 4. Roughly speaking, they had residual hearing at least up to 1 kHz but little or no residual hearing above 4 kHz. As can be seen from Fig. 4 there were also two clear ‘non-user’ categories. In some cases hearing was too poor to benefit (immediately) from transposed information, and in other cases hearing in the high frequencies (particularly above 4 kHz) was sufficient to identify the tested consonants without transposition. There were also some subjects who had both ‘user’ audiograms and problems with transposed consonants but who did not obtain immediately improved identification scores of at least 10 per cent with transposition. Although there is a possibility that such subjects may benefit from transposition after training, they were categorised as ‘non-users’.

Phase 3 consisted of a field trial using wearable FRED hearing-aids and involved six of the nine subjects diagnosed as potential ‘users’ in Phase 2. The main aim of the field trial was to establish whether subjects diagnosed as likely to benefit from transposition would in fact turn out to do so. In addition, the field trial made it possible to determine the long-term effects of transposition in naturalistic settings. The trial was broadly based, involving both ‘objective’ tests and extensive ‘subjective’ evalua-

Fig. 4. The range of audiograms for potential FRED users. ‘User’ audiograms fall within the dotted area.
tions, under both ‘blind’ and ‘informed’ conditions. In
the initial four to six weeks the effect of a short training
programme on the identifiability of transposed conso-
nants was examined. Each subject was given a consonant
identification test before and after a four-session imitation
training programme, under two experimental conditions,
i.e. with their FRED aids operating as conventional
amplifiers, and with transposition supplementing conven-
tional amplification. Subjects were not informed of the
conditions of the experiment and the experimental design
was balanced for order effects. Although imitation scores
improved with training under both transposition and
non-transposition conditions, overall group scores under
transposition were significantly higher, by 24 per cent.
Identification scores after training with transposition
were higher by 33 per cent than after training without
transposition.

Throughout this period subjective data were collected
regarding the performance of the aid (operating both as a
conventional amplifier and as a transposer) and at the end
of the ‘objective testing’ period there was a debriefing
session at which subjects were made fully conversant with
the operation of the aid and with their own performance
in all previous experiments (in Phases 1, 2 and 3). Provided
they felt, on the basis of experience so far, that
transposition might be of benefit to them, they were
invited to become their own experimenters for two to
three weeks. In this period they would be required to
compare the effects of transposition on speech intelligibil-
ity and environmental sounds with those of conventional
amplification (achieved by turning the transposition gain
control to zero). Five of the six subjects agreed to
continue and were issued with a detailed list of situations
in which to assess the aid. After the ‘informed subjective
evaluation’ period, subjects delivered their final ver-
dict[30] and, at this time, an important indirect measure of
the subjective value of transposition was obtained.
Subjects were informed that the evaluation project was
now over. However, if they wished to retain the aids for
everyday use in place of (or supplementary to) their own
behind-the-ear aids, they could do so. By comparison
with the subjects’ own aids (such as the NHS BE11, BE12
and BE13) the FRED aids (in their initial form) were
highly inconvenient, consisting of a behind-the-ear aid
connected by a cord to a body-worn box, with two
batteries (one of which required daily charging) and
controls fashioned more by experimental considerations
than for ease of use. Arguably, if subjects were willing to
tolerate the inconvenience, the benefits of transposition
would be more than marginal. In fact, the final verdict of
all five subjects was that transposition provided signifi-
cant benefit both in the perception of speech and in the
identification of environmental sounds. They opted to
keep the aids and after a period of 15 months were still
using them regularly. There were, however, considerable
individual differences between subjects in the pattern of
benefit obtained, ranging from one subject, a medical
physicist, who found the aid particularly useful in hearing
warning bells and arcing in a centrifuge (indicating a
malfunction), to another subject, a receptionist, who
found the aid particularly useful in conversation. Subjects
also differed, usually for reasons of convenience or social
acceptability, in their degree of resistance to wearing a
body-worn box and cord.

To date, evaluation studies with the FRED aid have
been highly encouraging. The field trial with sensori-
nearl deafened adults was, however, a small one and a
much larger trial involving 48 subjects is currently in
progress at six independent centres in the UK.

Conclusions

(a) Patients who appear to benefit from FRED transposi-
tion have residual hearing at least up to around
1 kHz but little or no residual hearing above 4 kHz
(transposing the 4 to 8 kHz region to the 0 to 4 kHz
region potentially doubles the range of detectable
frequencies for such patients).

(b) ‘Recoded’ versions of speech and environmental
sounds produced by the FRED aid are subjectively
very similar to the originals (to those with normal
hearing and to those with acquired sensorineural
hearing losses).

(c) Transposition may produce an improved ability to
imitate and identify transposed speech sounds and to
identify a wider range of environmental sounds,
although the pattern of benefit is variable.

(d) The main disadvantage of FRED transposition ap-
pears to be that in excessive amounts it makes speech
sound ‘shoochy’. There may also be occasional un-
wanted environmental noise in the 4-8 kHz region.
Both problems may be eliminated by turning down
the gain of the transposing channel. Provided that the
transposition ‘balance’ is properly adjusted, infor-
mation normally made available by conventional
amplification remains available.

There are, of course, many questions yet to be an-
swered. The effects of transposition on those with conge-
ital hearing losses have not yet been systematically
explored and further work is required with children,
particularly in the context of learning to articulate. The
effect of training on subjects who have ‘user’ audiograms
but who do not show immediate improvement when
transposition is supplied also needs investigation. Initial
surveys indicate that if all subjects with ‘user’ audiograms
turn out to benefit from transposition, the potential
number of beneficiaries would be large, perhaps 25 per
cent of the hearing aid user population.

Technical research and development are required. It is
clear from user resistance to a body-worn box and cord
that the FRED aid needs to be miniaturised into a
behind-the-ear aid. Furthermore, patients with severe
and profound hearing losses may have problems in
identifying phonemes, other than those with major ener-
gy components in the 4 to 8 kHz region, transposed by
FRED. So research is required into means of providing
‘speechlike’ low frequency transformations of such ad-
ditional, inaccessible speech cues.

This article is based on a paper read at the Conference on
Assessment and Management of Complex Disability held at the
Royal College of Physicians in November 1981.
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