Section of Otology

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Papers

A New Approach to the Cochlear Implant

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It is now twenty years since Djourno & Eyries (1957) implanted an electrical stimulating device into the cochlea of a deaf person. Since then interest in the possibility of helping totally deaf patients in this way has never waned. The work has been done primarily in California, initially at Stanford (Simmons 1966) and then at San Francisco (Michelson 1971, Merzenich *et al.* 1973, Merzenich *et al.* 1974) and Los Angeles (House & Urban 1973). In Paris Chouard (Chouard & MacLeod 1973, Pialoux *et al.* 1976) have pioneered a surgically more ambitious approach.

There is little doubt that these studies have remained experimental and that no device which is practically useful has become available in general use as a help to the deaf. It is the purpose of this paper to describe a new approach to this problem, which though more modest in its aims may offer the possibility of more immediate clinical use on a scale large enough to produce scientific information as well as to be of social value.

To clarify the theoretical considerations which have led to these studies it is necessary to refer back to cochlear physiology.

Normal cochlear function

Although we are far from having a complete knowledge of cochlear function, or indeed of its anatomy and exact innervation, a considerable amount has been learned from detailed studies of the hydrodynamics of the inner ear and from microelectrode studies of single-cell units.

Von Békésy's experiments suggest that a travelling wave appears along the basilar membrane in association with vibration in the inner ear fluids. This wave has a maximum displacement whose position depends on the stimulating frequency. The travelling wave produced by high frequency sounds peaks towards the basal end whereas for lower frequencies it peaks towards the apex.

It is important here to examine the manner in which pitch is recognized and one tone distinguished from another, since on this are based all attempts to understand how speech is processed. There are two basic theories to account for this, which with continuing modification from ongoing research appear to present a reasonably accurate description of what actually happens.

(1) *The 'place' theory:* According to this theory the pitch of a pure tone is determined by the nerve fibres which are most active. This is related to the point of maximum displacement of the travelling wave. The theory does not provide a satisfactory explanation for all psychoacoustic and neurophysiological findings (Moore 1972, 1973*a*, *b*, 1975; Moore & Raab 1975, Evans 1975). For frequencies above 4–5 kHz, however, the evidence is in favour of a place theory (Henning 1966, Moore 1972, 1973*a*, *b*, Attneave & Olson 1971, Schouten 1970).

(2) *The temporal theory:* According to this theory pitch perception is determined by the time pattern of the neural impulses. Temporal information depends on phase-locking; the nerves fire at a particular phase of the stimulating wave-form so

that for sinusoids the time intervals between firings are approximately integral multiples of the period of the wave-form. In experimental animals phase-locking is limited to frequencies below 4–5 kHz. This limit is imposed by the temporal 'jitter' which accompanies the phase-locking. At higher frequencies the jitter becomes comparable with the period of the stimulating wave-form so that nerve firings become blurred over the whole period of the stimulating waveform.

Analysis of these Theories

In simple terms and if we are dealing with the mechanism of determining the pitch of pure tones, the place theory postulates that pitch is determined by those nerve fibres which are most active. The temporal theory on the other hand postulates that it is the time pattern of neural impulses which is basic to the pitch percept.

It is likely that both types of neural information contribute to the perception of pitch but their relative effectiveness differs in different parts of the frequency range. There is, however, considerable doubt with regard to the relative efficiency of the two mechanisms for the important mid-range frequencies. The upper frequency limit for temporal encoding is all important for any work involving single-channel electrical stimulation of the auditory nerve, since with a single channel no place coding is possible and information about the stimulus can only be carried in the rate and time-pattern of neural discharges.

Considerations Leading to the Present Work

Previous workers referred to earlier had not been able to report enough pitch recognition in the higher tones to suggest that the place mechanism was in action. The low tones heard were not adequate for speech discrimination and multiple electrodes are now considered. The problem there is the lack of insulation between different parts of the cochlea and attempts have been made by Chouard to introduce elements of insulating silastic. With each of these progressive steps greater problems and risks are introduced, and few advantages over a single-channel electrode have emerged.

In our present work we have decided to employ the simplest and least invasive type of electrical stimulation using an entirely extracochlear electrode placed in the round window and in contact with but not penetrating its membrane. The speech pattern information (Fourcin 1975) which can be transmitted by this means relates primarily to voicing and timing. With proper training, both of these could be of crucial help to a deaf lip-reader and are briefly reviewed below (p 382).

Clinical Tests

A fine, insulated steel electrode was used, ball-ended (diameter 1 mm) so that it did not perforate the window.

Two patients were selected for tests, AS and WT. AS had two 'dead' ears following chronic infection and labyrinthitis and WT had a similar, unilateral condition – making three ears in all. These patients were selected because they had had radical mastoidectomies and therefore the round window area was exposed. This allowed us to place the electrode without anæsthetic and remove it at the end of the test. The results in all three ears were entirely consistent and this encouraged us to test a third patient CF, who had totally lost his hearing as a result of a skull fracture during a road traffic incident a year previously. Electrocochleography had confirmed his complete neurosensory hearing loss. Although there was a possibility that the deafness was due to an acoustic nerve section, this was thought to be unlikely as a bilateral injury of this type would have involved considerable, probably fatal damage to the brainstem. The injury was more likely to be due to cochlear damage.

An electrode was inserted through an endomeatal incision. The ball end was positioned comfortably and painlessly under a bony overhang protecting the round window. The electrode was brought out through the meatus and firmly packed to reduce mobility. The results were consistent with those of AS and WT but more tests could be done as the electrode was kept in for two days.

Results of Cochlear Stimulation (Patient CF)

(1) *Threshold determination:* Sine-wave pulses of 300 msec duration and rise/fall times of 20 msec were presented at a rate of about 1 per second. The patient was asked to tap in time with the sounds as long as he could hear them. The current was slowly decreased until the patient stopped tapping, then increased until he started again. This was repeated several times and the mean value taken as threshold. Thresholds were actually measured in terms of dB attenuation but converted to electrical values. They gave the following readings at various frequencies; they are plotted in Fig 1.

20 Hz	17 μA	30 Hz	13 μA
40 Hz	18 μA	60 Hz	20 μA
100 Hz	28 μA	150 Hz	71 μA
200 Hz	119 μA	250 Hz	133 μA
300 Hz	140 μA	400 Hz	315 μA

(2) *Dynamic range:* For low frequencies sounds were reported as uncomfortably loud at about 300 μA i.e. 25 dB above threshold or seventeen times its electrical value. It was not entirely clear whether this limit was imposed by loudness or by the feeling of an electric shock. Above 500 Hz the dynamic range approached zero (Fig 1).

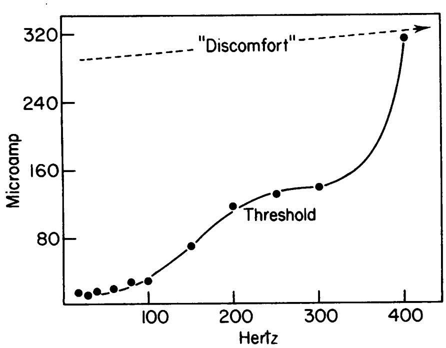

Fig 1 *Dynamic range of electrical stimulation of the cochlea*

(3) *Frequency discrimination:* Pairs of 300 msec tone pulses with silent intervals of 700 msec and differing in frequency were presented. The subject was asked to say which was higher and, despite some difficulties at first in understanding what was required, consistent judgements were obtained. Correct estimates of high/low and low/high were made, for example, between 70 Hz and 100 Hz.

For tones approximately 10 dB above threshold the frequency change which could be reliably detected was roughly: at 100 Hz, 30 Hz; at 60 Hz, 20 Hz; at 40 Hz, 20 Hz.

(4) *Periodic-aperiodic discrimination:* Noise, band-pass filtered between 20 Hz and 200 Hz, was described as 'rapid tapping' or 'brrr, brrr'. Noise filtered between 20 and 500 Hz at the same level produced a feeling of 'electricity in the jaw'. At a lower level it was 'like a cricket'. Noise filtered between 20 and 60 Hz was detected at 20 microamps and described as 'a pulley-chain being pulled'. With pairs of sounds, one being a sine-wave, the other filtered noise, the latter was described as 'bubbly'. This discrimination was made

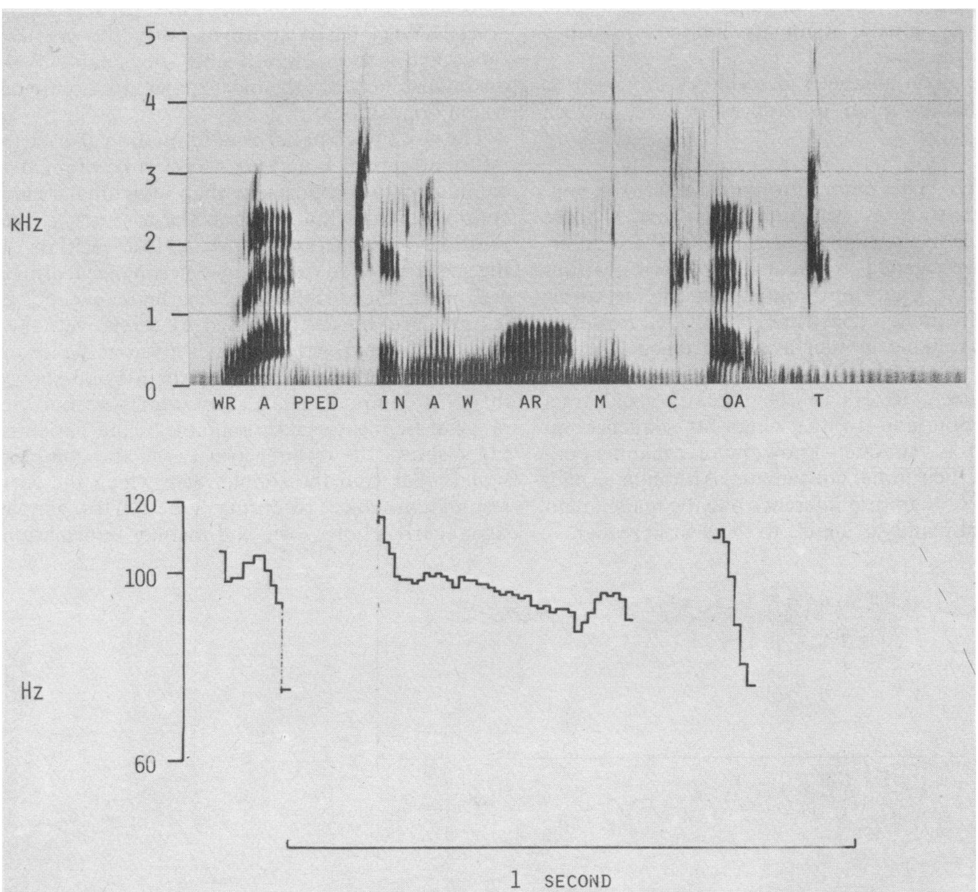

Fig 2 *Above, wide band spectrogram based on an analysis of the speech pressure waveform, spoken by JB (Ballantyne 1977). Below, analysis derived from the synchronously recorded laryngograph waveform, which makes it possible to show larynx frequency variation period by period. The hearing mechanism is able to extract a correlate of this pattern to provide the sensation of voice pitch*

correctly ten times out of ten for pairs presented in random order.

(5) *Intensity discrimination:* There was no difficulty in discriminating intensity as loudness. The smallest difference which could be reliably detected (in 80–90% of presentations) was 2 dB (a change in current of about 25%). It was roughly constant both for different frequencies (30, 50 and 100 Hz) and levels (5–20 dB above threshold).

Relationship with speech

It is clear that single-channel extracochlear stimulation will only provide low frequency information. The speech frequencies which are important to a normal listener ordinarily cover a far greater range; an example is shown in the upper half of Fig 2. When the communication needs of the profoundly deaf and the essential nature of speech sound differences in English are considered, however, a low frequency channel appears capable of providing assistance to an extent which is disproportionally greater than its limited frequency bandwidth.

Three main phonetic descriptors are used to define the essential differences between speech sounds.

(1) *Place:* This refers to vocal tract shaping: contrasts such as bet – debt – get have a place difference in their initial consonants. Place differences are carried by acoustic pattern features which have important components in the whole energy-frequency spectrum. They are, however, partly available in the facial movements of the speaker.

(2) *Manner:* Refers to the type of vocal tract constriction and to the temporal sequence required: toe – so; doe – know; involve manner contrasts in their initial consonants. Although a small amount of temporal inference may be made, manner is not readily available to the deaf lipreader.

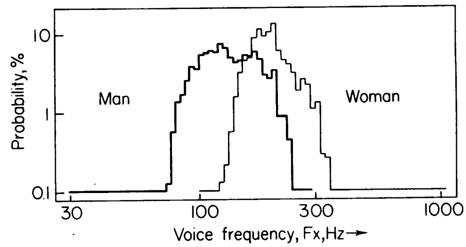

Fig 3 *Two voice-frequency distributions are shown. The lower one is for a man. The upper distribution is for a woman. These histograms show how an important aspect of normal speaking voices can be accommodated by the frequency response possibilities which are made available by the direct, external, electrical stimulation of the cochlea*

(3) *Voice:* refers to the laryngeal excitation which may be applied to the vocal tract: to – do; Sue – zoo; involve voice contrasts since (t) and (s) are voiceless fricative consonants whilst (d) and (z) are voiced. Voice-based contrasts carry the greatest functional load in English since they enable us to distinguish between the most frequently occurring sound oppositions.

The voice pitch patterns of intonation also carry information which may on occasion be of greater communicative importance than individual sound contrasts. The whole structure of a sentence, the position of the stressed words and the attitude of the speaker are all carried by voice. Voice features are the least accessible to the deaf lip reader. These features are, however, carried by a relatively low frequency signal. An example is given in the lower half of Fig 2. Indeed the analysis in Fig 3 shows that this component lies substantially within the range of frequencies discriminable by our patients. Fig 4 shows the difference between the complex signal 'coat' and the simple form which the corresponding voice recording takes. This simple signal carries both voice and manner information

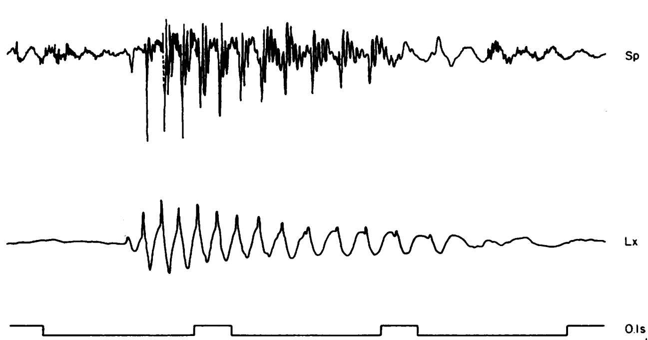

Fig 4 *The top trace is the speech pressure waveform for the word 'coat'. It has been taken from the recording used in producing the spectrogram and Fx analyses of Fig 2. The lower trace shows the synchronously recorded output from the speaker's larynx. This waveform, Lx, is much simpler than the pressure waveform, Sp, and subject to smaller amplitude variation. Lx is present only when voicing occurs, and provides a basis for direct cochlear stimulation*

to a useful degree. It follows from these considerations that a combination of lip-reading and the vocal, laryngeal, component of speech might give rise to a considerable improvement in speech intelligibility compared with lip-reading alone. This may be put to an initial test by the direct stimulation of the listener's cochlea by signals derived from the speaker's larynx.

Stimulation by laryngographic output

This was done in patient CF and can only be described anecdotally as only one subject was involved. Nevertheless the results were striking enough to merit report.

The laryngograph (Fourcin & Abberton 1971) output was connected via a 500 Hz low pass filter with the stimulating electrode. When the laryngograph electrodes were placed on his wife's larynx the patient claimed that he could hear 'her voice'. CF was a poor lip-reader and could only interpret his wife's speech. When the tester's laryngograph output was connected in the same way with the patient's electrode he demonstrated an immediate and remarkable increase in the ability to lip-read correctly.

Further work is in progress on the quantification of these findings and on the practical aspects of transducing voice frequencies into stimulating electrical impulses.

Conclusion

Five main conclusions may be drawn from these first observations:

(1) Extracochlear stimulation is capable of producing sound sensations which are sufficiently discriminable to be of communicative use to the lip-reader.

(2) A viable electrode may be inserted using essentially standard middle-ear surgical techniques; these are much freer from complications than intracochlear procedures.

(3) The frequency range over which changes in stimulating frequency can be detected corresponds well with the range of fundamental frequencies in the normal speaking voice. This provides an intrinsic match between a speech pattern input and listener capability.

(4) The laryngograph provides a simple, direct means of obtaining the voice pattern information which is necessary for the development of clinical tests and speech-training methods.

(5) On the basis of this work it should be possible to develop a practical acoustically-based portable prosthesis for single-channel extracochlear electrical stimulation capable of being adjusted to correspond to the needs and capabilities of the individual.

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The following papers were also read:

Otoadmittance Measurements in Patients with Rheumatoid Arthritis

Mr D A Moffat
(*The London Hospital, London E1*)
(submitted to *Journal of Laryngology and Otology*)

Grommets and Glue Ear: a Five-year Review of Controlled Trial

Mr Marcus Brown
(*University Hospital of Wales, Cardiff*)
(submitted to *Journal of Laryngology and Otology*)

Diagnosis of Multiple Sclerosis in the ENT Department

Mr P D M Ellis and Mr J V Jestico
(*see British Medical Journal* 1976, ii, 970–972)

Ototoxic Antibiotics: an Electrocochleographic Study

Mr Richard T Ramsden
(*The London Hospital, London E1*)