Reprint from THE LARYNGOSCOPE, Vol. LXXXVI, No. 11, pp. 1743-1751, November, 1976.

IMPLANTATION OF MULTIPLE INTRACOCHLEAR ELECTRODES FOR REHABILITATION OF TOTAL DEAFNESS: PRELIMINARY REPORT.*

CLAUDE H. CHOUARD, M.D.,
and
PATRICK MACLEOD, M.D.,
Paris, France.

ABSTRACT.

Many instances of total deafness are due to destruction of the organ of Corti but with partial or complete preservation of the function of the cochlear nerve. In such cases, it is possible to restore some hearing by electrically stimulating the fibers of the cochlear nerve with the help of implanted electrodes.

Preoperative testing with electric shocks applied to the round window have aroused sensations of noise in 45 cases of total bilateral deafness with a great variety of etiologies. The only negative results were in two cases of operated acoustic neuromas.

Our operation places up to eight intracochlear electrodes, each with a separate fenestration opening into an electrically isolated compartment of the scala tympani. Stimulation of each electrode yields a different sound sensation of a pitch that depends on its location along the cochlea. Electric filters direct different frequency bands to the appropriate electrodes, with the necessary compression of dynamic range.

In three experimental cases of unilateral deafness, pitch matches to the normal ear were made. In seven therapeutic operations on adult cases of acquired total bilateral deafness, speech recognition was usually relearned within a month or two. Improvement of voice quality was also dramatic.

The intracochlear electrodes have been well tolerated for months, but the method of connection to the external equipment still presents difficulties.

——— O ———

INTRODUCTION.

Proposed as early as 1957 by Djourno and Eyries[1] for the saccular nerve, then tried by Simmons[2] for the cochlear nerve, electrical stimulation of the cochlea through implanted electrodes was recently resumed with the use of a single electrode and developed simultaneously by Michelson and Merzenich[3] in San Francisco and by House and Urban[4] in Los Angeles.

However much the auditory gain thus provided to these patients is appreciated, nevertheless, it remains restricted by the poverty of frequency

*From Service O.R.L. du Centre Hospitalo-Universitaire Paris-St-Antoine and Laboratoire de Neurophysiologie sensorielle de l'Ecole Pratique des Hautes-Etudes.

information. For the improvement of these results, the implantation of several electrodes was deemed to be indispensable by all participants in the Symposium held on this subject in San Francisco in June, 1973.

Since then we tackled this problem personally. This enabled us to gather some physiological observations and results that appear to be worth reporting, for they may help to clarify the difficulties and requirements of such rehabilitation by implantation of multiple electrodes.

PHYSIOLOGICAL CONSIDERATIONS.

A sound stimulus normally results in electrophysiological activity whose topography within the nerve depends upon its frequency (von Békésy[5]). Frequency information is wholly contained in this topographic distribution, which is found also in the diencephalon and cortex; however, at low frequencies, below 300 Hz, the spikes of the nerve fibers arise as bursts whose rhythm reproduces the frequency of the stimulus. As the frequency is increased, the bursts merge, the rhythm becomes lost and is no longer recognizable subjectively. At 1,500 Hz, despite this psychological non-recognition, the rhythm can still be identified by a computer, but beyond frequencies of 4,000-5,000 Hz, the distribution of the spikes becomes wholly random (Rose[6]). The increase in the number of spikes when the intensity of a pure tone increase is first achieved by an acceleration of the small contingent of fibers electively sensitive to this frequency; but the refractory period of the nerve fiber prevents this acceleration from proceeding beyond 1,000 spikes per second. Any further increase in intensity results in bringing into play adjacent fibers, which are most sensitive to somewhat different frequencies.

MATERIAL AND METHODS.

a. Selection of Patients.

It would not be conceivable to operate on patients without having ascertained that they have at least a partially functional auditory nerve.

An electric square wave signal can be delivered to the membrane of the round window; the cochlear liquids carry the current to the fibers of the auditory nerve and arouse a sensation of sound, providing some fibers are still functional. How many fibers are necessary to give this sensation is still undetermined.

Contrary to House and Brackmann,[8] who claim that round window stimulation through the intact eardrum is feasible, we think that anatomical variations of the round window are so frequent that this diagnostic test must be performed through a surgical procedure. The eardrum is removed at its lower edge and folded up. This gives a clear view of the round window, which often varies in shape and size, especially in deaf mutes who may have birth defects. The bare tip of an insulated electrode is placed in good position against the membrane of the round window.

In adult patients this test is performed under local anesthesia, with all necessary instructions to the patient written on cue cards beforehand. With frightened subjects, such as children, the electrode can be placed under general anesthesia and the test performed on the following day. Auditory evoked responses may be recorded from the scalp, allowing the test to be performed on very young deaf children (Fig. 1).

We have performed the preliminary test 59 times: on the deaf ear in five cases of unilateral conductive hearing loss; on both ears of four cases

Fig. 1. Diagram of the auditory evoked response of a three-year-old deaf mute child to an electric stimulus supplied to the round window membrane (x100).

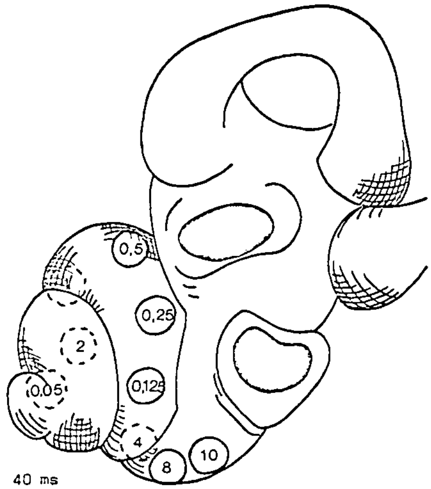

Fig. 2. Schematic map of the frequencies localization in the human cochlea.

of bilateral total deafness, and on only one ear (37 right and four left) of 41 cases of bilateral total deafness.

b. Surgical Procedure.

We used teflon-coated microelectrode wire of 10 percent iridium, 90 percent platinum, bare diameter .005", (0.127 mm). The reference electrode was platinum iridium wire, bare diameter .007" (0.178 mm), whose insulation has been removed from a 3 cm length. It was inserted in the temporalis muscle.

As it is difficult to stimulate directly and separately the fibers within the nerve trunk into which they are gathered and condensed, we preferred to make use of their spreading along the lamina spiralis of the cochlea by implanting the electrodes at the level of the scalae.

In our three first patients only one electrode, then two and then five were implanted in the cochlea. These patients were experimental patients with facial paralysis and unilateral deafness. They had no indication for a supra-petrosal approach. We implanted them only through a middle ear approach in the second turn and in the basal turn of the cochlea.

Our patients with total and bilateral deafness received seven electrodes; two surgical approaches are necessary for this implantation:

a. Middle ear approach with resection of the bone of the external auditory meatus and conservation of the skin and of the eardrum. If the malleus muscle is removed this provides a good access to the basal turn, second turn and apex.

b. Trans-temporal supra-petrosal approach, which gives access to the highest internal portion of the first turn of the cochlea, between the geniculate ganglion and the internal auditory meatus. This approach is indispensable because the conversational frequencies lie in this upper portion of the first turn.

This operation was performed on seven cases of total bilateral deafness.

Each electrode was introduced into the cochlea through a separate fenestration of the scala tympani. An electrically isolated compartment was made in the scala for each electrode by means of little pieces of silastic. Each electrode was fixed to the bone around the fenestration with methylmethacrylate. According to their positions in the cochlea, the electrodes were connected with the corresponding channels of the external apparatus through teflon plugs, to provide transmission from external to the internal circuits.

c. Electrophysiological Procedure.

1. Preoperative Testing. The stimulus is a square wave of negative polarity. The reference electrode is a metal plate held in the hand. We use a radio-frequency insulation unit for maximum safety. The pulse duration is 0.3 ms. The amplitude varies between 0 to 5 and exceptionally 10 volts and the pulse frequency varies from 0 Hz to 1,000 Hz. The patient is instructed to describe every sound sensation he may experience.

2. Postoperative Testing. We use the same stimulating apparatus in order to determine the subjective threshold frequency and the maximum stimulation amplitude for each implanted electrode. The reference electrode in this case is a platinum iridium wire, 0.007", (0.178 mm) diameter, whose insulation has been removed from a 3 cm length. This reference electrode lies in the temporalis muscle.

Special attention is devoted to obtain from the patient an accurate report on the subjective frequency range of each effective electrode.

3. Chronic Stimulation. We constructed an apparatus that divides the sound message, by means of filters, into eight bands of frequency at octave intervals, from 125 to 8,000 Hz. Due to the very narrow dynamic range of the acoustic nerve, a drastic dynamic compression is necessary to prevent the patient from being disturbed by intense sounds. That is the reason why the sinusoidal signal received in each channel is converted into an impulse whose frequency varies with intensity. According to our observations, this particular difficulty is well eliminated if constant-level impulses, whose frequency increases with stimulus intensity, are used as stimuli.

RESULTS.

a. Electrophysiological Findings.

1. Preoperative Testing. In total deafness the threshold level averaged 1.42 volts with a standard deviation of $\pm$ 1.02. During a progressive increase of stimulating current intensity, the uncomfortable level was reached very soon above the perceptual threshold. In cases of very low perceptual thresholds the uncomfortable level was reached at approximately twice the threshold. Such a dynamic range of 6 db was seldom obtained and never exceeded.

We did not find any correspondence between the level of the audiometric curve, the etiology of the deafness, and the threshold level of the sound sensation. Even in five subjects with pure transmission deafness of 30-50 db with quite normal bone conduction, the threshold level was within the standard deviation, providing the thick mucosa of the promontory had been removed.

The sound sensation depends on the frequency. With frequencies higher than 300 Hz the result is a white noise in which high sounds are somewhat predominant; probably because the greater width of the scalae at the beginning of the cochlea favors the diffusion of the current in this area, in contrast to the narrowed areas at the apex of the cochlea. This white noise is perceived, regardless of the frequency of the electric stimulus, except that frequencies under 300 Hz present in this stimulus are perceived. When the frequency of the signal is varied below this figure, a false impression of tonal discrimination can be felt, analogous for instance with the noise of the explosions of a motorcycle engine, first idle, then accelerating, until giving the impression of a continuous sound when the frequency of 300 Hz is reached; but the analogy is not complete. Contrary to the sound shocks of an engine, the electric stimuli, when further accelerated, merely induce within all nerve fibers an increased intensity of the white noise obtained by fusion.

2. Postoperative Testing. If the cochlea is divided into several electrically isolated compartments it becomes possible to perform a local stimulation involving only one compartment. Stimulating each electrode one by one, we obtained for each of them nearly the same values for threshold level and uncomfortable level. In two cases one out of seven implanted electrodes gave no response. After 20 months our first patients have always experienced sound sensation with a constant threshold, when their electrodes were stimulated.

For a given stimulus over 300 Hz, applied in succession to each electrode, the perceived sound depended on the location of the electrode. Experimenting on implanted patients with unilateral deafness it has been possible with an audiometer to match the sound perceived in the implanted ear with sound perceived in the normal ear.

We could thus, for the first time, plot a frequency map of the human cochlea (Fig. 2). It corresponds fairly well to what could be expected on the basis of investigations. By stimulating separately one of the electrodes with a stimulus whose frequency was less than 300 Hz, the same phenomena of frequency variation, acceleration, then fusion, as with total stimulation were obtained, except that the sound resulting from the fusion, instead of being a white noise, approximated in this case a pure tone corresponding to the location of the stimulating electrode; in fact, at the frequency of 1 Hz, the sound heard was compared to either a gong or handbell stroke, according to the electrode concerned. More precisely, when an electrode lying close to the apex cochlea was stimulated, beginning with a frequency under 30 Hz, the gradual acceleration of the stimulus gave a sound whose pitch increased up to the frequency of 300 Hz. Here the fusion of the sound resulted suddenly in a new, much deeper sound — a rumbling in the case cited as an example.

We have already pointed out a special difficulty. During this electric stimulation of the cochlear nerve fibers, there is a very narrow margin between the perceptual and the uncomfortable thresholds. In volts, the latter is approximately twice as high as the former. The dynamic compression is enormous. This trouble is well overcome if impulses of adequate level are used as stimuli. The level of these impulses must be chosen between threshold level and discomfort level. The frequency of these impulses can be varied between 0 and 1,000 Hz to convey to the patients information as to sound intensity.

b. Clinical Findings.

1. Diagnostic Aspect. Patient selection with electrical stimulation of the round window through a surgical approach allows us to recognize among

TABLE I.

Audiometric Thresholds of Implanted Patients with Total Deafness.

Case	Sex	Age	Years Duration	Etiology		A.C. Hearing Level (Hz) (ANSI, 1969) 250	500	1,000	2,000	4,000
1	F	56	2	Meningitis	R	—	85	90	80	85
					L	80	90	85	95	—
2	M	42	39	Unknown	R	80	100	—	—	—
					L	90	—	—	—	—
3	M	20	10	Unknown	R	90	—	—	—	—
					L	85	110	—	—	—
4	F	70	8	Chronic labyrinthitis	R	—	—	—	—	—
					L	—	—	—	—	—
5	F	46	38	Meningitis	R	40	45	—	—	—
					L	45	50	—	—	—
6	F	43	5	Meningitis	R	40	50 } Bone conduction	Bone	—	—
					L	40	50	conduction		—
7	M	26	16	Bilateral petrosal fracture	R	—	—	—	—	—
					L	—	—	—	—	—

those who are totally bilaterally deaf, those to whom intracochlear implantation may be proposed

Using this preoperative test we obtained negative response in only one case of total unilateral deafness, secondary to removal of an acoustic neuroma. In all other cases we obtained positive responses, *i.e.*, all the five other cases of unilateral conductive deafness, and in 45 cases of total bilateral deafness, except one once again for a patient operated upon for bilateral acoustic neuroma. It is worth pointing out that, aside from 14 cases of undetermined deafness, this test showed that implantation was worth performing in eight cases of meningitis (meningococcal, mumps or of undetermined origin) six cases of labyrinth destruction due to petrosal fracture, 12 cases of congenital deafness, five cases of childhood deafness, four cases of bilateral labyrinthitis with cholesteatoma of undetermined origin, four cases of otosclerosis extended to the labyrinth and one case of severe long-standing Ménière's syndrome. Among the four cases of unilateral total deafness with positive response, were one case of undetermined deafness and three cases of skull fracture with facial paralysis.

Although the number of cases we have tested is still small, the results suggest that a majority of cases of total deafness retains at least partial neural function and is, therefore, eligible for implanting.

2. Therapeutic Aspect. During the last six months, we have implanted seven adult patients with total deafness: all had acquired speech before the loss of hearing.

The audiometric thresholds of these cases are summarized in Table I.

— A 56-year-old female who had been deaf for two years after meningitis (Case 1).

— A 42-year-old male who had been deaf for 39 years with no known cause (Case 2).

TABLE II.

Diagram of Folkloric Songs Discrimination, Stimulation Cochlea with Two Electrodes Only, Located in High and Low Frequencies (Case 1).

Title of the Song	Song Code	Responses: Device with Lip Reading	Device without Lip Reading	Device without Lip Reading and without Low Frequencies	Device without Lip Reading and without High Frequencies
Il pleut bergère	1	1	1	Nothing	Nothing
J'ai du bon tabac	2	2	2	2	2
Au clair de la lune	3	3	3	3	0
J'ai un problème	4	4	4	Nothing	Nothing
Auprès de ma blonde	5	5	5	5	5
Tiens voilà du boudin	6	6	6	6	6
Papa les p'tits bateaux	7	7	7	5	Nothing
Fais dodo Colas mon p'tit frère	8	8	8	Nothing	8
La Marseillaise	9	9	9	4	9
Ils ont des chapeaux ronds	10	10	10	Nothing	Nothing
	Results	10/10	10/10	4/10	4/10

— A 20-year-old male who had been deaf for 10 years; deafness had developed gradually over two years, with no precise cause (Case 3).

— A 70-year-old female who had been deaf for eight years as a result of bilateral chronic labyrinthitis (Case 4).

— A 46-year-old female who had been deaf for 38 years after childhood meningitis (Case 5).

— A 43-year-old female who had been deaf for five years after meningitis (Case 6).

— A 26-year-old male who had been deaf for 16 years as a result of bilateral petrosal fracture (Case 7).

As early as the day after implanting the electrodes, the discrimination of frequencies and the understanding of a few words were possible; these immediate performances imply lip reading, the more so as the patient has been deaf for a longer time. Anyhow, these performances were always superior to those obtained when only a single electrode was stimulated. Melodic recognition was variable from patient to patient; patients who had normal hearing before they become totally deaf were able to recognize popular melodies in almost 100 percent of cases even though they were stimulated by only two electrodes, providing these electrodes were located at the two ends of the cochlea, not too close to each other (Table II). In melomaniac patients the recognition of popular melodies was not so good and was no better if all seven electrodes were stimulated. As a consequence, complex melodies such as symphonies or concerto were neither identified nor appreciated; but in all cases music or songs were distinguished from speech.

Speech recognition improved very quickly with training, but tone reeducation was necessary. These patients must relearn to hear. After about a month, though the intelligibility of word lists remained poor, nearly 50 percent of a usual conversation could be understood without lip reading. After two months recognition of 30 disyllabic usual words uttered at random by a machine became possible. The criterion of 80 percent of intelligibility was usually reached with patients who were young and not tired.

In our three patients whose long-standing deafness had resulted in voice changes, the voice improved dramatically as early as the first weeks.

DISCUSSION.

a. Experimental Patients.

The justification of this part of our work must be stated first. We were obliged to use experimental patients in order to test our two starting hypotheses, namely, that dividing the cochlea into electrically isolated compartments is feasible and makes speech discrimination possible. We could not use animals for this experiment, because animals, even after a long conditioning, are not able to understand the human voice to such an extent as to give us enough information about the intelligibility of the received message. We could not use totally deaf patients either, because in such psychologically fragile patients no risk of failure could be assumed. On the other hand it would have been too severe an aggression to perform such trials in patients with unilateral deafness who generally do not need any surgical operation; however, when unilateral deafness is due to a skull bone fracture, and is associated with a facial paralysis, it becomes necessary to operate in order to rescue the facial nerve. In this case the surgical approach allows us to reach the cochlea, so with preoperative patient agreement, it became possible to perform, without further damage, the human experiments we needed. The results obtained[7] in this situation in three patients enabled us subsequently to operate on patients with total bilateral deafness.

b. Round Window Stimulation.

Because of the anatomical variations of the round window we think a surgical approach is necessary to perform this important diagnostic test; thus, the differences between our results and those reported by House, *et al.*,[8] find a possible explanation.

There is no relation between the threshold level giving sound sensation and the level of the audiometric curve or the etiology of the deafness. We think that the variations of the threshold level we obtained in our 59 cases are due to the variations of the round window, whose membrane is more or less distant from the margin of the window.

Positive results obtained in cases of deafness of such diverse origin seem to be paradoxical. These positive results do not signify that the cochlear nerve was normal in every case. They mean only that there were enough fibers to give sound sensation when they were electrically stimulated all at once. These clinical results are in accordance with the findings of Schuknecht.[9]

In most cases this diagnostic test has been performed on one side only in order not to further injure the patient. Only the patients' choices determined that the right ear was more frequently tested than the left one.

c. Frequency Map of the Cochlea.

The frequency map of the cochlea we propose is only an approximate diagram. The frequencies we obtained stimulating one by one the electrodes of our unilaterally deaf patients, yielded approximately the figures of the diagram. It was not possible to determine precisely the distance of each fenestration from the round window; moreover, we cannot accurately know the exact length of the portion of the cochlea which is subjected to stimulation. On the other hand the localizations of the speech frequencies are only deductions.

Our experimental patients suffered from traumatic labyrinth destruction with facial paralysis. We had indications for a trans-labyrinthine approach to the facial nerve, which allowed us to reach the basal turn, the second turn, and the apex of the cochlea; but we had no indication for a supra-petrosal approach which would allow us to reach this higher part of the first turn in which, by deduction, we believe these conversational frequencies lie.

d. Clinical and Long-Term Results.

Despite the good results we obtained in speech intelligibility on our implanted patients, we think this procedure, using a teflon knob, is unacceptable for long term rehabilitation of total deafness. Probably due to the movements of the outside wires under the ear-packing after three to six months, we observed suppuration of the skin around the plugs, followed by a more or less rapid elimination of the teflon knob; however, the intracochlear tolerance of the electrodes seems to be excellent. Despite the skin infection we had no suppurative accident of the inner ear and moreover the physiological characteristics of every electrode remained constant. Presently our first patient, who was operated on 22 months ago, still keeps his electrodes in perfect condition.

It is necessary to discard this transcutaneous plug. We are working on a device that will transmit the electrical information through the skin to each electrode. As long as this apparatus is not available, this technique of rehabilitation of total deafness may not be considered as general surgical procedure.

This new device will be built in the near future, and the good results we have obtained make us believe that this technique may become a future treatment of profound deafness.

BIBLIOGRAPHY.

1. Djourno, A. and Eyries, C.: Prothèse auditive par excitation électrique à distance du nerf sensoriel à l'aide d'un bobinage inclus à demeure. *Presse Med.,* 35:1417-1423, 1957.

2. Simmons, F. B.: Electrical Stimulation of the Auditory Nerve in Man. *Arch. Otolaryngol.,* 84:24-76, 1966.

3. Merzenich, M. M., et al.: Neural Encoding of Sound Sensation Evoked by Electrical Stimulation of the Acoustic Nerve. *Ann. Otol.,* 82:486-502, 1973.

4. House, W. F. and Urban, J.: Long Term Results of Electrode Implantation and Electronic Stimulation of the Cochlea in Man. *Ann. Otol.,* 82:504-517, 1973.

5. von Békésy, G.: Experiments in Hearing (Research Articles from 1928 to 1958). McGraw-Hill Book Company, New York, N. Y., 1960.

6. Rose, J. E., et al.: Phase Locked Responses to Loco-Frequency Tones in Single Auditory Nerve Fibers of the Squival Monkey. *Jour. Neurophysiol.,* 30:769-793, 1967.

7. Chouard, C. H. and MacLeod, P.: La réhabilitation des surdités totales. Essai de l'implantation cochléaire par électrodes multiples. *La Nouvelle Presse Médicale,* 44:2958, 1973.

8. House, W. F. and Brackmann, D. E.: Electrical Promontory Testing in Differential Diagnosis of Sensori-Neural Hearing Impairment. The Laryngoscope, 84:2163-2170, 1974.

9. Schuknecht, H. F.: Congenital and Acquired Sensori-Neural Hearing Loss in Electrical Stimulation of the Acoustic Nerve in Man. Velo-Bind, Inc., San Francisco, Calif., pp. 37-46, 1974.