Chapter 25: Cochlear implants

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In July 1983, the Council on Scientific Affairs of the American Medical Association recommended endorsement of cochlear implants for postlingually deaf patients. The Council recognized that cochlear implants could enhance lip-reading ability and bring an awareness of environmental sounds which give benefit to the deaf. The recent developments in multichannel devices have exceeded these expectations as speech recognition is often possible.

Cochlear implants are now a routine clinical procedure for postlingually deaf patients in many countries. It is to be hoped that a similar statement regarding those who are prelingually deaf will be made within the next decade.

These simple statements conceal the immense amount of work and perseverance which have been required to establish the cochlear implant. House (1976) wrote 'There have been many and varied pressures to abandon the project. If it had not been for the encouragement and stimulation from the deaf patients who are the centre of this project, it would have died long ago'.

**Historical background**

Benjamin Franklin has been attributed as the first to suggest, in 1751, that electricity could produce hearing sensations in the deaf. Later Alessandro Volta (1800) placed metal rods into both his ears and connected them to a source of electricity. Apparently he heard the sound of bubbling water before he lost consciousness!

Much later at the end of the 19th century, many famous otologists, including Politzer, Ritter and Gradenigo were interested by the finding that passing an alternating current through electrodes applied around the ear produced sounds. In reality this produces 'electrophonic effects'. The impedance of the electrode interface with the skin, in or near the ear canal, causes the surface to act like the plates of a capacitory causing a slight movement (rather like the diaphragm of an earphone). The sound waves generated in the ear canal are transmitted to the cochlea. Thus a normal hearing person hears a sound at a maximum intensity of 30-40 dB HL with a frequency range of 30-15.000 Hz. Deaf subjects cannot hear anything.

At the end of the 19th century, unscrupulous doctors and charlatans made money by using this technique as a supposed means of preventing or curing deafness. At the same time there was much controversy over electrical therapy for other ailments, including treating the sexual organs for impotence and electrotherapy became so disreputable that established doctors dared not become associated with it.

It is difficult to be certain who succeeded first in producing true direct stimulation of the auditory nerve. Perhaps the Russians led the way. In 1934, Andreev, Gersuni and Volokhov published their paper entitled, 'Electrical stimulation of the hearing organ'. They placed an electrode near the round window and described various hearing sensations ranging from separate short noises to a smooth buzzing sound. Later Jones, Stevens and Lurie (1940)
reported similar findings on placing a saline-soaked cotton ball electrode on the round window in nine subjects. Sounds like 'the chirping of a cricket' were described.

The next significant event was in France when Djurno and Eyries (1957) reported the first 'cochlear implant'. They inserted a single copper wire inside the cochlea of a 50-year-old man who was totally deaf. The electrode was attached to an induction coil placed under the skin and the indifferent electrode was placed in the temporalis muscle. After healing, the induction coil was stimulated by currents produced by a second coil placed against the overlying skin. These investigators initially used an electrophrenic stimulator producing pulsed stimuli at a rate of 100/s. Later, a second implant was performed on a girl suffering from a total hearing loss after streptomycin therapy; this time, the electrode was placed in the round window niche against the membrane. In long-term studies, neither subject developed speech discrimination, although they could perceive speech rhythm and with training could distinguish between simple words such as 'allo', 'maman', and 'papa'. Both subjects claimed the devices helped them greatly with lip-reading. According to Zollner and Keidel (1963), the implants in Djurno's patients were still functioning 4-5 years later and the auditory sensations remained unchanged.

This was a remarkable report and it stimulated further research. In particular, it stimulated two groups in the USA: Blair Simmons and his group in San Francisco, and William House and his group in Los Angeles.

In 1961, House implanted two subjects with a single gold electrode placed in the scala tympani. These subjects were tested for several weeks. Later in 1961, a multiple electrode system was inserted for 2 weeks in one of the subjects but removed as a possible allergic reaction occurred (House, 1976).

In 1964, Simmons et al reported the results of bipolar stimulation of the acoustic nerve in an 18-year-old male undergoing surgery for a recurrent posterior fossa tumour. They stimulated the nerve for only 25 minutes but obtained clear evidence that a wide range of auditory sensations were heard. Later, in May 1964 (Simmons, 1966), they implanted a six-electrode array directly into the modiolus of a 60-year-old man. The patient was investigated extensively until October 1965 when the device was removed for fear of infection. He could distinguish a wide range of sounds. Auditory sensations were reported then 0.1 ms square waves were used at frequencies from 20-4000 Hz. Pitch varied according to the electrode stimulated. The research faced an unforeseen difficulty when the patient's vision was lost due to retinitis pigmentosa and he could no longer lip-read adequately. This report caused consternation among leading specialists who felt the patient's life could have been at risk; they urged no further studies of this kind until much more basic animal research had been completed.

The criticism effectively stopped any further clinical work for several years, although much work continued in the laboratory. Some important animal studies were undertaken: for example Michelson (1968) showed that intracochlear electrodes could be maintained safely in cats and would function over long periods of time.

Human studies began again in 1969 when House implanted a further patient and the following year, two more subjects were implanted. It was a bold move which caused
controversy. House used a six-electrode system designed by Jack Urban which was hard wired (connected percutaneously to the external stimulator device). The patients were tested extensively for 2 years in the laboratory as a wearable external stimulator was not available until 1972. The results were sufficiently encouraging that a further 10 patients were implanted in 1973 and despite much criticism the cochlear implant was established as a means of alleviating total deafness.

Other groups in San Francisco (Merzenich, 1975), France (Chouard et al, 1984), Germany (Banfai et al. 1984), and Austria (Burian et al, 1984) began clinical work during 1970s. In Australia, Clark (Clark et al, 1983) used a prototype 10-electrode system in 1979, which met with some scepticism initially as the technology was considered unnecessarily complex.

Soon commercial companies began to develop the cochlear implants and to provide a standard of product reliability which led to the Food and Drug Administration (FDA) in the USA approving the clinical use of the 3M House device in 1984 (House and Berliner, 1986), and the Nucleus (Clark) device in 1985 in postlingually deaf adults. Cochlear implants were first used in prelingually deaf children by House in 1980 and this group currently has the greatest experience (> 200 children as of May 1986). Children also were implanted by Chouard, Banfai and Burian during the early 1980s and by Clark since 1985.

The basic concept of cochlear implants

Although cochlear implants take many forms, they are all composed of similar basic elements:

1. a microphone which picks up sounds, including speech

2. a speech processor which analyses the signal from the microphone. Some devices relay the information in an analogue form, while others perform more complex tasks such as feature extraction

3. a transmitter coil is used in the transcutaneous device. This transmits the signal to the implanted coil without the need for any wires passing through the skin*

   * Percutaneous or 'hard-wired' devices, such as the Eddington (Symbion) device do not have a transmitter coil or receiver as the wire from the speech processor goes directly into a plug placed in the skull.

4. a receiver coil which is implanted into the bone of the skull behind the ear. It receives the signal and relays it to the electrodes

5. the electrodes which are usually placed within the cochlea inside the scala tympani.
Different cochlear implants in clinical use

There are reputed to be over 40 different cochlear implant devices. Table 25.1 lists some of these. The commercial availability of cochlear implants has enabled clinical centres to undertake this work.

The cochlear implants may be classified according to the following features.

**Number of electrodes**

The simpler devices have only a single electrode. Other devices may have several electrodes ranging from four (Hochmair, Eddington) to 22 (Clark). The number of channels depends on how many electrodes are used and whether they operate in monopolar or bipolar modes (similar to the diathermy in surgery). For example the intracochlear Hochmair (3M) has four electrodes but only one is selected and used as a monopole with a reference electrode inserted into the temporalis muscle. The Eddington (Symbion) device has four channels which are all activated simultaneously with a common reference electrode. The Clark (Nucleus) device has 22 electrodes which are stimulated as bipolar pairs, with two channels giving F1 and F2 frequency information according to position and both firing at the rate of the fundamental frequency, F0.

**The electrode position**

The electrode may be placed on the round window membrane outside the cochlea (extracochlear); for example Hochmair, Banfai, Fraser and Douek devices, or inside the cochlea, invariably within the scala tympani via the round window (intracochlear).

**The speech processor strategy**

Most devices use an analogue signal strategy which is usually filtered (for example frequencies outside the 50-4000 Hz range are excluded). The information may be further divided by a filter bank into frequency ranges which are fed to different electrodes according to a place/pitch principle. The Eddington/Symbion device relays information to all four electrodes simultaneously building up excitation patterns within the cochlea.

Other devices such as the Clark and Douek devices use feature extraction. Usually the voicing fundamental is extracted from the speech signal (the voicing fundamental or F0 is the main spectral peak of voice pitch - males 80-150 Hz, females 100-300 Hz). Other spectral peaks occur with speech which are divided up according to their spectral range. Usually the first such spectral peak or formant (F1) lies between 200-400 Hz for males and 250-500 Hz for females. Most vowels can be recognized from F0 and the first two formant frequencies (F1, F2). Consonants usually three formant frequencies to be recognizable. The Clark/Nucleus device relays F0, F1, F2 and fricative (high frequency sibilant) information.

**Pathophysiology**

It is probable that cochlear implants function best in profoundly deaf ears which have a large number of surviving peripheral neural elements capable of receiving and transmitting
electrical impulses to central nuclei. Studies show (Clopton, Spelman and Miller, 1980) that the neural elements most likely to be stimulated by cochlear electrodes are the spiral ganglion cells. Hinojosa and Marion (1983) have counted spiral ganglion cells in temporal bone specimens. Normal ears had an average of 33,915 spiral ganglion cells. In profoundly deaf ears, despite the presence of severe degeneration of sensory epithelium within the cochlea, only three out of 15 temporal bones examined had ganglion cell counts of less than 10,000 and the majority of counts were over 15,000. These findings completely refute earlier worries that loss of inner ear hair cells would cause massive retrograde degeneration of ganglion cells (Spoendlin, 1975). In another study (Otte, Schuknecht and Kerr, 1978) 34 out of 62 temporal bones were estimated to have fewer than 10,000 ganglion cells.

There appears to be no clear correlation between the duration of the deafness or the pathological aetiology and the number of surviving ganglion cells. Even congenitally deaf ears had high numbers; for example Scheibe's dysplasia resulted in counts of 8626 to 23,912 (Hinojosa, Blough and Mhoon, 1986).

Successful cochlear implants have been reported after all types of acquired deafness affecting the cochlea (for example trauma, labyrinthitis, meningitis, otosclerosis, Ménière's disorder). Cochlear implants cannot be used for eighth nerve disorders (after acoustic neuroma surgery) or for central problems such as bilateral temporal lobe damage.

After infection inside the cochlea, neo-osteogenesis especially in the basal coil may occur causing a bony obliteration (Suga and Lindsay, 1977). It is commonly seen after labyrinthitis and meningitis. In exceptional cases it may prevent the insertion of an intracochlear electrode.

**Otological selection of patients for cochlear implant**

The audiological selection of candidates for cochlear implant surgery is discussed in Volume 2. The final decision to perform surgery rests with the otologist.

It is helpful to classify potential cochlear implant subjects into the following groups:

1. acquired postlingually deaf adults
2. acquired postlingually deaf children
3. acquired prelingually deaf children
4. congenitally deaf children
5. acquired prelingually deaf adults
6. congenitally deaf adults.

The order in which these categories are given gives some indication of the increasing difficulty in auditory rehabilitation.
Acquired postlingually deaf adults

Patients who became deafened after 12 years of age usually retain language and have easily recognizable speech. Such subjects need little auditory rehabilitation compared with the subsequent groups.

There are no age limits providing the patient is medically fit; the author has successfully implanted a 79-year-old woman. The patient should be geographically accessible so that rehabilitation and programming of the device are possible and should speak the same language as the audiologist undertaking the rehabilitation.

The following evaluations are undertaken prior to implantation.

**Audiometry** (for details see Volume 2)

All candidates must be audiometrically profoundly deaf (greater than 90 dB HL at any audiometric frequency) and unable to gain any recognition of ‘open set’ speech using a powerful hearing aid without lip-reading (speech score 0%). Any speech recognition is an absolute contraindication. All patients must undergo a trial with a suitable hearing aid before they are considered.

The audiologist will also undertake other tests of sound recognition (usually the minimal auditory capabilities (MAC) battery of tests). If the patient scores better on these tests than the average for a patient after a successful cochlear implant, then he or she is not suitable for implantation.

**Otological examination**

The tympanic membrane in the intended ear must be intact and there must be no active infection (except for the Douek, EPI implant which has an active electrode which fits on to the end of a hearing aid mould and can be placed through a perforation). It is possible to implant a device despite the presence of a mastoid cavity providing the cavity is stable and dry and has a strong lining. The author has successfully implanted one such patient (Scrivener and Gibson, 1987).

Any chronic active infection of the nose or throat must be eradicated prior to surgery.

**Medical examination**

The patient must be well enough to undergo a 4-hour surgical procedure.

**Psychological evaluation**

The patient must be realistic. All patients must accept that they may not be able to understand any speech at all through the device. In Sydney, Australia a patient self-help group exists (CICADA group) and all potential implant patients and their immediate families spend an evening together with an implanted patient of similar age and his or her family. Some
implant groups ask a psychologist of psychiatrist to see all patients, but the author doubts that this is necessary.

**Laboratory investigations**

The following blood tests are carried out on all patients:

- full blood count
- liver function tests
- serological tests (when appropriate, AIDS antibody testing).

**Radiological investigations**

All patients must have the patency of the cochlear duct assessed. Using polytomography, the cochlear duct should be visible on at least three consecutive films taken at 2 mm intervals. Alternatively, a computerized tomographic (CT) scan may be employed (Ball, Miller and Hepfner, 1986). If there is any suspicion of a pathological condition which could cause central changes, then a CT scan of the head is needed.

**Evoked response audiometry**

The author performs electrocardiography on all candidates to ensure that no useful cochlear function exists. One patient with a non-organic hearing loss has been encountered. Brainstem audiometry can also be used, although the traces are more difficult to interpret when little or no hearing exists.

**Promontory and round window stimulation**

The usefulness of the promontory stimulation test is still disputed as House (personal communication, 1984) reported that several patients who failed to hear on promontory stimulation have received successful cochlear implants. At present there is no clear correlation between the promontory stimulation results and the results after implantation. Nevertheless, all patients who have a positive promontory stimulation test should hear using an implant so investigators may prefer to perform this test early in their series.

**Promontory stimulation**

Promontory stimulation is performed by placing a transtympanic needle electrode on the promontory as close as possible to the round window membrane and a reference electrode is placed on the earlobe or over the mastoid process. Usually electrocochleography is performed first to check the absence of cochlear action potentials. The electrodes are then connected to an electrically isolated (battery operated) supply to ensure patient safety. The optimum stimulus is a constant voltage (or constant current) source which supplies square wave bursts; the subject usually hearing the transition from an anodal to a cathodal current at the slower presentation rates. (Anodal current may suppress tinnitus if present.) The longer the duration of the square waves, the less current required to evoke a hearing sensation (Gibson, Game and Pauka, 1987). Sadly, any differences observed using different frequencies of stimulation are the result of changing in duration of the stimuli and do not reflect
remaining neural activity in the corresponding frequency ranges. Hope that the growth of loudness versus current levels (Smith and Simmons, 1983) is related to the number of surviving ganglion cells appears unfounded (Van den Honert and Stypulkowski, 1986). The period between two consecutive stimuli needed for the subject to hear two separate sounds rather than one may relate to central processing and may be a useful measure of the ability to utilize an implant.

Many attempts have been made to record the brainstem auditory evoked potentials following electrical stimulation (Van den Honert and Stypulkowski, 1986). There are major problems; first a massive artefacts has to be overcome; second, the responses are very inconsistent from the promontory. The author (Game, Gibson and Pauka, 1987) has only recorded two convincing electrically-evoked brainstem evoked potentials from over 20 patients tested.

**Round window stimulation**

If a tympanotomy is performed and the active electrode is placed directly on the round window membrane, then brainstem evoked potentials can be recorded consistently (Chouard, Meyer and Donadieu, 1979; Black et al, 1987). This test may be useful for confirming the intactness of the auditory pathways especially in prelingually deaf subjects.

**Acquired, postlingually deaf children**

Children who lose their hearing after acquiring speech are assessed in a similar manner to adults. Generally, without a cochlear implant, if hearing is lost before the age of 6 years, recognizable speech is lost; after age 6 until age 12 years, gross voicing errors result; and after age 12 years, recognizable speech remains with some errors as a result of loss of monitoring.

The commonest cause is meningitis. X-rays to exclude neo-osteogenesis of the basal cochlear turn are important (Eisenberg et al, 1984).

**Acquired, prelingually deaf children**

These children will behave as congenitally deaf children, but it can be assumed that the central auditory pathways are intact and there has been some 'priming' of the auditory cortex to sound.

Careful audiometric assessment is needed to avoid the possibility of implanting a potentially hearing ear.

**Congenitally deaf children**

These children may be further classified into two groups - hereditary and acquired. If the deafness was acquired at birth, then it is likely that the cochlea and auditory pathways are anatomically normal. Children who lose their hearing during the first trimester of pregnancy and those with hereditary deafness may have abnormalities of the otic capsule: for example,
a Mondini deformity with a limited number of cochlear turns or a Michel deformity with no cochlear development. Radiology is essential.

The intactness of the central auditory pathways is unknown. Animal studies (Bock, Horner and Steel, 1985) showed larger than normal responses from the inferior colliculus. Brainstem responses in human infants show maturation over the first 6 months of life (Schulman-Galambos and Galambos, 1975); perhaps without auditory input, this maturation cannot occur.

It is important to exclude any hearing before considering implantation. The author suggests testing by electrocochleography and acoustic reflex in addition to careful behavioural investigation.

Electric brainstem 'auditory' evoked potentials are theoretically very useful. Simmons and Black (personal communications) both advocated tympanotomy and placing an electrode on the round window membrane as part of the preoperative assessment.

**Acquired prelingually deaf adults and congenitally deaf adults**

There is a high rate (approximately 30%) of non-use of cochlear implants in this group (Eisenberg, 1985) as patients are accustomed to a world without sound and often only perceive sound sensations as a feeling or vibration in the head.

Thus they have difficulty in understanding sound and only gain limited prosodic information (duration and rise/fall of frequencies and intensity rather than detailed information which allows speech recognition). Extensive and arduous rehabilitation is needed to utilize even this simple information. Very careful counselling of the patient and especially the relatives is needed to avoid a disappointment.

**Preoperative counselling**

The importance of counselling preoperatively cannot be over-stressed. Common patient misconceptions are as follows:

1. An implant will provide recognizable speech sounds - untrue! Even patients who gain 'open set speech recognition' admit that sound is distorted and unlike their previous recollection of speech. If a patient has any 'open set speech recognition' using a hearing aid, her or she is not a candidate for implantation.

2. An implant works better than a hearing aid in a noisy environment - untrue!

3. As the device is 'implanted' it is less noticeable than a hearing aid - untrue! The speech processor looks like an old-fashioned body-worn hearing aid. This seems to upset prelingually deaf teenagers and adults in particular.

4. Once the implant is fitted, no further hospital visits are required - untrue! Several visits are needed to adjust the outputs to obtain the best speech processor settings or 'programmes', especially with multichannel devices. Levels can fluctuate requiring further
adjustments. Several other visits are needed for rehabilitation and assessment if maximum benefit is to be obtained by the patient. These factors and the fact that device breakages occur (broken leads, etc) mean the patient must be prepared to revisit the cochlear implant team many times. Geographical accessibility of the patient is important.

The surgeon and the audiologist should ensure that the patient understands all these facts. A tape recording of a cochlear implant simulation is useful to convey to relatives the limited hearing which will be gained by the patient. It is very helpful to arrange for the patient and his/her family to spend an evening together with a patient who has already received an implant.

Cochlear implant surgery

The standard approach now employed by most cochlear implant teams is to embed the body of the implant in the skull behind the mastoid and to trail the electrodes via the mastoid through a posterior tympanotomy to the round window. The following steps are undertaken.

Access

The hair should be shaved with a wide margin around the intended incision. The incision should not be placed over the implant. The intended site of the transmitter coil may be marked before incision and a stab incision is made in the centre. A small hole may then be drilled into the skull through the incision and labelled with gentian or some other similar dye. The draping of the wound need not leave the external meatus uncovered; usually the pinna is pushed forwards and an adhesive drape is used.

The scalp incision is made at least 1 cm behind the posterior edge of the transmitter coil site. The limbs of the incision are kept wide to avoid any necrosis of the middle third of the scalp flap. The scalp is raised in two layers: a skin and subcutaneous tissue layer, and a periosteal layer. There is no need to cut into the sternomastoid muscle.

Mastoidectomy

A cortical mastoid operation is performed. The edges should be kept overhanging (that is they should not be saucerized as in conventional mastoid surgery) as the electrode lead will fit snugly underneath overhanging edges.

Posterior tympanotomy

It is usually possible to make the approach via the facial recess in the hypotympanum without disturbing the incus. Theoretically, this affords better support for the tympanic membrane and makes retraction less likely. To gain a sufficient view of the round window niche, the facial nerve has to be skeletonized, but if possible some bone is left to protect it during electrode manipulation and in case revision surgery should be required. The bone anterior to the facial nerve on the edge of the middle ear has to be cautiously removed. With care the chorda tympani nerve can often be preserved. The commonest error which must be avoided is to damage the annulus by making the posterior tympanotomy too laterally. If the ear has been cleaned with povidone-iodide (Betadine) preoperatively, Betadine from the
external meatus will appear on making the posterior tympanotomy - the dreaded 'Betadine sign'.

**Siting the body of the implant**

A circular area of bone is removed from the skull around the initial siting mark. The implant should have the external edge approximately 5 mm above the surface of the skull to allow the patient to site the transmitter coil. When the skull is thin, the author recommends drilling an outer circle completely down to the dura leaving thin bone in the centre ('Scriv's oasis'). Then, on pressing the implant into position, the dura can be safely moved medially averting the need to have the implant sited too externally causing an obvious postauricular lump. The trail of electrodes leaving the implant should be sited in a bony groove leading to the mastoid as this avoids movement on temporalis muscle contraction which could eventually break the electrode lead. Several holes are drilled about the bony groove and around the bony overhang of the mastoid cavity to provide a means of placing sutures to secure the implant.

**Inserting the electrode**

After preparing the site for the body and tail of the implant, the round window can be opened. The anterior bony overhang of the round window niche must be removed. The round window membrane lies anterosuperiorly. It is very easy to mistake a hypotympanic air cell for the round window and basal cochlear turn in a well pneumatized ear. The round window is kidney-shaped lying mostly in the horizontal plane, although the anterior portion is more vertical. The membrane arises from a bony annulus. The inferomedial portion of this annulus projects as the crista semilunaris (or 'scutum'). The round window can be opened by a central cruciate incision and the crista semilunaris has to be drilled. If there is any doubt concerning the location of the basal turn or its patency, the anterior lip of the round window should be drilled to visualize the interior of the cochlea. Care should be taken not to damage the osseous spiral lamina which projects inferiorly.

The electrode should be inserted smoothly and without force. Studies show that at approximately 8-9 mm depth, the tip of the electrode contacts the spiral ligament as it rounds the first cochlear turn (Clifford and Gibson, 1987). Undue force at this stage may buckle the electrode or force the tip through the basilar membrane. If the electrode insertion halts at this point, it may be possible to progress by gently rotation the electrode in the appropriate direction. Usually the Nucleus electrode can be inserted approximately 20 mm and, with this device, the depth of penetration is recorded according to the number of stiffening rings left outside the cochlea.

The round window niche should be filled with soft tissue (usually fibrous tissue) to prevent a perilymph leak postoperatively.

**Closure**

The monopolar diathermy should not be used near the electrode assembly. The periosteal layer is sutured together thus stabilizing the electrode assembly. The author uses surgical staples to close the wound and does not use a drain for fear of infection.
Postoperative care

A prophylactic antibiotic (for example erythromycin) is given for 7 days. The patient may be vertiginous and requires suitable medication. Often the tinnitus is increased for a few days postoperatively. The wound should be inspected for any haematoma which can be removed if necessary by aspiration through the suture line. The patient is usually discharged on the third postoperative day. Often polytomograms are obtained to check the exact location of the electrodes.

Complications following surgery

Fortunately, serious complications after cochlear implant surgery are uncommon. The following complications have occurred in the author's series.

Immediate problems

(1) Haematoma under the skin flap.

(2) Poor blood supply to the edge of the skin flap. In one case, the skin edge became very dusky but, fortunately, there was no necrosis. It is wise to keep the limbs of the incision broad.

(3) Cerebrospinal fluid leak: one patient had a slight tear of the dura under the body of the implant. Postoperatively cerebrospinal fluid tracked along the route of the electrode leads into the mastoid and passed down the eustachian tube to the nose. A lumbar drain was inserted and the leak stopped without the need for further surgery.

(4) 'Airocoele': a patient coughed and air blew through the mastoid elevating the skin flap. A ventilation tube was needed temporarily to prevent continual recurrence.

(5) Facial palsy: no reports of permanent facial nerve palsy following cochlear implant surgery have been reported. The author had one patient who had undergone previous radical mastoid surgery in which the facial nerve had been exposed (Scrivener and Gibson, 1987). After cochlear implant surgery she had a partial facial palsy for 6 weeks.

(6) No cases of postoperative infection have been encountered. The author knows of one case where an implant did become infected and had to be removed some months after surgery (Morrison, personal communication, 1985).

Long-term problems

(1) Increased tinnitus has occurred in one out of 44 patients using a Nucleus multichannel implant. The majority of patients reported less tinnitus using a cochlear implant.

(2) No patient has reported persistent giddiness. Nevertheless, the importance of preoperative vestibular tests to foresee the possibility of implanting the only ear with surviving vestibular function is obvious.
(3) Numbness: although most patients complain of numbness of the ear postoperatively, no patient has complained of this in the long term.

(4) Palpable lump: one patient in the author's series has an obvious lump but she does not appear to find this upsetting (1/18).

(5) No patient has continued to complain of a taste disturbance.

(6) Using the multichannel electrode, several patients (4/44) have reported facial twitching presumably caused by the current spreading across thin or dehiscent bone between the cochlear duct and the facial nerve. This may necessitate programming out the function of the offending electrodes. This is most likely to occur when cochlear otosclerosis has caused defects in the otic capsule.

(7) House (personal communication, 1985) mentioned three patients with persistent perilymph leaks. The author has one such case (1/18). A perilymph leak may present as obvious fluid behind the tympanic membrane, but is more often merely associated with continual fluctuations of the thresholds.

Problems with the implants

(1) Device failure. The commonest cause of device failure with earlier models was breakage of the wires passing from the body of the device. This is much more likely to occur if the implant is not firmly embedded into the skull as the device may rock when the patient contracts his scalp musculature.

(2) Leakage of body fluids into the device has dogged some earlier implants. This seems to have been prevented by improved manufacture and the use of hermetic sealing.

(3) Electrical interference. Some of the single channel devices (for example the House sigma system) can be affected by nearby electromagnetic fields.

Programming

Usually approximately 3 weeks after surgery, the scalp flap has healed sufficiently to allow the cochlear implant to be activated. At the initial postoperative session, the current level which is most comfortable is determined for each channel. In single channel devices, the output is filtered to provide an even sensation throughout the frequency range of the device. Multichannel devices are more complex to programme as the output range for every channel has to be set individually. Once set, the channels in some complex devices (for example Nucleus implant) are tested to determine the rank order of pitch sensation. Theoretically the most apical electrode should provide the lowest pitch sensation and successively more basal electrodes should provide higher pitches. This is rarely the finding clinically. Often several electrodes either provide exactly the same pitch sensation or inappropriate pitches are encountered. This may be a result of damage to the spiral ganglion cells from the original pathological condition which caused the deafness, or of buckling of the electrode during insertion. These inappropriate electrodes can either be re-ordered or switched off.
Usually when the patient is first 'switched on', the dynamic range is minute. There is little difference in current terms between just hearing and the sound becoming uncomfortably loud (reduced dynamic range). Gradually over the following weeks, the dynamic range increases. On average, the patients require eight programmes, set at weekly intervals, before a final programme is reached. This means that the patient must be available for weekly programming for at least 2 months after implantation.

Programmes can suddenly change even some months after implantation. The author has three patients who have suddenly lost 'hearing', twice after viral infections. Fortunately the 'hearing' has always recovered within 2 months.

**Recording results**

There are no standardized tests for assessing the results of cochlear implants which makes cross comparison of data difficult. Furthermore, there is a significant learning effect if a test battery is used on several occasions. Nevertheless, despite these shortcomings some comparisons are possible.

The following tests, commonly employed, may be classified into various groups:

1. Measurement of the threshold of hearing for pure tones using the usual setting of the device. This cannot be compared to an audiogram as the levels can be altered by changing the device settings. Nevertheless, it shows how the device performs across frequencies and indicates the frequency limits of the device.

2. Prosodic or suprasegmental tests. These tests show if gross features of speech are perceived such as distinguishing one versus two syllables, a male or female speaker, a stressed word in a sentence, etc.

3. Vowel and consonant confusion tests. The patient is given a number of vowels or consonants by listening alone. He or she attempts to identify each sound which is charted, each response being charted against the vowel or consonant given. This test not only gives an indication of how many vowels or consonants can be detected using the implant but also gives an indication of where the main errors exist.

4. Closed set discrimination tests. The patient is given a list of alternative choices and has to select the correct answer. For example, the vowel test asks the patient to distinguish between hood, hid, heed, had, hud: there is a one in five possibility of guessing correctly, or the chance level is 20%. Similar tests use the initial and final consonants and a set of five every-day sentences.

5. Open set discrimination tasks. Open set means that the patient can have no hope of guessing the answer so the chance level is 0%. Open set tests must not have any contextual clues; for example, if a patient knows that the subject is 'railways', understanding sentences such as 'When does the next train leave?' is not true open set. Telephone conversations with an implanted patient are impressive but may not be a measure of open set discrimination as so many contextual clues occur.
True open set discrimination tests include the standard Central Institute for the Deaf (CID) sentences and everyday open set sounds (dog barking, telephone ringing, etc). The most difficult open set tasks are monosyllabic words and spondee recognition tests. These latter tests are difficult and usually compared with lip-reading alone and with lip-reading plus audition (through cochlear implant). Using some multichannel devices (for example Nucleus, Storz and Symbion devices) word recognition is possible in some patients with audition alone.

(6) Speech tracking. The patient has to repeat exactly each word read from a book by the tester. If the patient gives a wrong response, the word is repeated and then, if necessary, a careful hierarchy of clues are given until the correct answer is given. The tester cannot proceed until the patient has repeated the correct word. The number of correct words per minute is recorded. The results can be compared using lip-reading alone, lip-reading plus audition and audition alone. The number of contextual clues is often quite small so audition alone gives some indication of 'open set' function.

Results using different implants

Every series has a few patients who manage spectacularly well using cochlear implants and perform far above the average for the device - such individuals are called 'star patients'. Most groups have case reports of star patients who can perform telephone conversations, etc, and often 'open set discrimination' is claimed. It is important, however, that groups other than the development team should be able to substantiate the claims.

Both single channel and multiple channel devices can be of significant benefit in prosodic tasks and provide some 'closed set discrimination' (Gantz and McCabe, 1986). This provides a number of useful clues which help the ability to lipread.

To date only two multiple channel implants (Eddington, Symbio device and the Clark, Nucleus device) have been shown to give the majority of implanted patients true 'open set discrimination' by groups other than the development team (Gantz and McCabe, 1987; Pauka, Gibson and Game, 1987; Cohen, Waltzman and Shapiro, 1987). Other multiple channel implants (Banfai and Chouard devices) have been claimed to provide 'open set discrimination' by the development teams but these have not yet been substantiated. The House 3M device has never claimed to provide 'open set discrimination'. The Hochmair team have claimed some limited 'open set discrimination' for the extracochlear device but this has not yet been substantiated (Risberg et al, 1987; Rosen and Ball, 1987).

There can be no dispute that postlingually deaf patients gain significant benefits from the use of cochlear implants; especially the multichannel devices.

Special considerations for prelingually deaf patients

Postlingually deaf adults require little active rehabilitation as they already understand the significance of speech as a language. Rehabilitation consists of a number of exercises to improve their recognition of components of speech and to improve their ability to follow speech.
Prelingually deaf patients have little or no concept of hearing. They have often developed their language based on signs coupled to lip-reading (for example total communication or cued speech). Prelingually deaf teenagers and adults will have grown accustomed to their own language and will find it a difficult and arduous task to learn a new language - rather similar to an English-speaking/hearing person learning Russian. Often it is the family of these patients who are eager to obtain a cochlear implant because they hope to improve the speech of their deaf relative. Unfortunately, even when a patient has been successfully implanted, the quality of the speech changes very little. Perhaps multiple channel implants coupled with intensive speech therapy can help in the future, but at present it would be misleading for any surgeon to offer this hope to families of deaf people.

There is more optimism regarding the use of cochlear implants in young children who may still have a capacity to learn naturally to utilize sound for hearing and learning speech. Nevertheless, as no cochlear implant device provides more than a shadow of normal speech sounds, it is unlikely that a child would gain sufficient information to learn speech by audition alone. Although children have gained benefit from single channel cochlear implants, there is still debate as to whether the same benefit could have been achieved using a vibrotactile device. Popelka and Gittelman (1984) wrote a most discouraging report of a child who received a single channel implant.

The hope is that multichannel implants will provide more information and better results. However, the programming of a multiple channel cochlear implant in a young prelingually deaf child will be a very difficult task. The author has implanted one prelingually deaf patient with a multiple channel (Nucleus) implant. This subject had a very limited dynamic range initially and was totally confused by the sensation of sound. It is likely that the dynamic range in children will change over the first few months and several programming sessions will be needed.

The difficulties of using cochlear implants in prelingually deaf patients are:

1. Radiology must show a normal otic capsule. Implants are not possible for Michel deformities. There may be a risk of meningitis if an ear with a Mondini defect is implanted.

2. It is essential that the brainstem auditory pathways are intact. This may be checked using electrically evoked brainstem potentials, but at present this requires a general anaesthetic and a tympanotomy operation to place the stimulating electrode directly on the round window membrane.

3. Total loss of auditory function must be confirmed. There is no satisfactory method of testing auditory evoked potentials available for low frequencies.

4. The child must have enough language to be able to cooperate with the implant team. Profoundly or totally deaf children are exceptional if they can communicate by a purely oral system. Most have to supplement their lip-reading by a sign system or by cued speech. The person undertaking the rehabilitation must be able to converse with the child.

5. At present most cochlear implant teams would not attempt to implant a child with other handicaps such as mental retardation.
(6) The programming of the device is likely to take many weeks of painstaking work. The child must be geographically accessible. It would be pointless to implant a child from overseas and for that child to have nobody available to programme the device and undertake rehabilitation.

(7) Even the most optimistic cochlear implant teams accept that a cochlear implant can only take a profoundly or totally deaf child into the severely deaf category (Eisenberg et al, 1986). Special help with education is still vitally important. The parents must accept this fact and be realistic regarding the role that a cochlear implant can play. The deaf child remains deaf, albeit no longer totally deaf. The deaf child does not become a normally hearing child.

False worries:

(1) The cochlear implant is not 'set in concrete'. It can be removed and replaced with a more sophisticated device should one become available at a future date.

(2) There is no evidence to show any deterioration of the spiral ganglion fibres in the long term after cochlear implant surgery.

(3) The operation requires skill but so far few, if any, serious complications have occurred. A cochlear implant operation is no more serious than any other operation to help a handicapped child, for example a hip operation.

Final conclusions

The usefulness of the cochlear implant in totally deaf (postlingual) adults is established. Single channel implants give limited benefit, which is confined to improving lip-reading skills, and provide limited environmental recognition. Multichannel implants can, in some patients, provide the ability to understand speech without the need for lip-reading. The results of multichannel implants are superior to those with a single channel and it is difficult to justify the continued clinical use of single channel implants. Despite early worries, intracochlear implants have not been shown to carry any risk to the patient and extracochlear implants appear only to be indicated when the access to the cochlea is blocked (for example by neo-osteogenesis) or could be hazardous (for instance in an ear with a Mondini defect).

The use of cochlear implants in prelingually deaf teenagers and adults is limited and much care has to be taken to ensure that the patient really wants an implant and is not having it forced upon him by his family (House, 1986).

The benefit of cochlear implants for the prelingually deaf child is uncertain, but there are many favourable findings which give grounds for optimism. Cochlear implants in children need a careful team approach which involves the otolaryngologist, the paediatrician, the audiologist, and the teacher of the deaf.