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Review Article

Cochlear implantation: a review of the literature and the Nijmegen results

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Abstract

The field of cochlear implantation is developing rapidly. In subjects with bilateral profound deafness who gain no benefit from conventional hearing aids the aim of cochlear implantation is to provide a means for them to receive auditory sensations. Throughout the world, most cochlear implant centres are still continuing their research efforts to improve the results with this technique. Although it is still difficult to predict how an individual will perform with a cochlear implant, the success of cochlear implantation can no longer be denied. In this paper, we review some recent papers and reports, and the results of the various Nijmegen cochlear implant studies. Data about subject selection, examinations, surgery and the outcome are discussed. Our results were in good agreement with those of other authors. It can be concluded once again that cochlear implantation is an effective treatment for postlingually deaf adults and children, and for prelingually (congenital or acquired) deaf children with profound bilateral sensorineural deafness.

Key words: Cochlear implant; Deafness, pre and postlingual; Adult; Child

Introduction

During the past three decades, remarkable progress has been made in the application of cochlear implantation, from a research stage to regular clinical application. As a result of the pioneering work of House and coworkers, the American Food and Drug Administration (FDA) approved the single-channel 3M/House device in 1984 as a safe device for implantation. Later on, in 1990, the FDA also approved the multi-channel device developed by Clark and coworkers at the University of Melbourne. About 20,000 subjects have received a cochlear implant (CI) throughout the world up to the present time. The main goal of CI application is to restore hearing in subjects with profound hearing loss and thus enhance their ability to participate in aural-oral communication.

Studies have revealed that the majority of CI users, with a prelingual or postlingual onset of deafness, obtain significant benefit from this prosthesis. However, speech perception abilities vary widely, ranging from the simple detection of sound to the recognition of normal open speech (Tyler, 1993; Waltzman *et al.*, 1994; Hinderink *et al.*, 1995; NIH Consensus Statement, 1995; Snik *et al.*, 1997b).

Most users benefit more from their CI than from conventional hearing aids (House *et al.*, 1987; Miyamoto *et al.*, 1995; Summerfield and Marshall, 1995; Snik *et al.*, 1997a). The problem of variable speech perception abilities post-implant continues to challenge research teams and efforts are being made to find a means of predicting the result prior to cochlear implantation. So far, no single pre-operative factor has been found that can predict the outcome of cochlear implantation (Tyler, 1993; Summerfield and Marshall, 1995; Van Dijk *et al.*, 1995). However, it is known that some biographical factors, such as age at the onset of deafness and the duration of deafness, play a role (House *et al.*, 1987; Hinderink *et al.*, 1995; Maillet *et al.*, 1995; Summerfield and Marshall, 1995; Waltzman *et al.*, 1995). To obtain a good result, it is generally reported that careful subject selection is necessary and that a rehabilitation programme should follow cochlear implantation. Success in this field can no longer be denied in spite of initial scepticism in the scientific world and the deaf community (Van den Broek *et al.*, 1995; Cohen and Waltzman, 1996).

TABLE I

BIOGRAPHICAL DATA ON THE SUBJECTS WHO RECEIVED A COCHLEAR IMPLANT IN NIJMEGEN UNTIL THE END OF JULY 1997

	Adults and adolescents	Children <14 yrs
Number of subjects	57	48
Sex: Male	32	19
Female	25	29
Age at onset of deafness (range, yrs)	0 – 62	0 – 6.5
Duration of deafness (range, yrs)	1.5–51	1–13.5
Age at implantation (range, yrs)	14 – 68	3–13.5
Prelingual No.	11	39
Mean age at onset of deafness (yrs)	0.4	1.3
Mean duration of deafness (yrs)	25.7	5.3
Mean age at implantation (yrs)	26.1	6.6
Postlingual No.	46	9
Mean age at onset of deafness (yrs)	27.8	4.1
Mean duration of deafness (yrs)	16.9	4.2
Mean age at implantation (yrs)	44.7	8.3

This paper presents an overview of the current concepts of cochlear implantation and reviews the results of CI studies at the University Hospital Nijmegen. In Nijmegen, the cochlear implantation programme was initiated in 1987 in close co-operation with the Institute for the Deaf in St Michielsgestel. Initially, 10 subjects received a single-channel device, later all subjects received a multi-channel CI. Until the end of July 1997, 105 profoundly deaf subjects have been implanted. For more detailed data, see Table I.

Selection criteria and pre-operative tests

Pre-operative assessments

The field of cochlear implantation requires medical, audiological and psychological evaluation. The principles of candidate selection are similar for adults and children. A routine ENT examination forms the initial part of evaluation. Previous radical mastoidectomy or tympanoplasty, without any long-term problems, are not considered as absolute contraindications (Gantz, 1989; Schwartzman, 1995).

In general, pre-operative audiological assessment is considered as the major factor to determine the suitability of a subject for cochlear implantation. The audiological test batteries for adults consist of audiometry, tympanometry and speech perception tests. For younger children, play audiometry or visual reinforcement audiometry, tympanometry and speech perception tests are used. Audiological assessment should confirm profound, bilateral sensorineural hearing loss, without useful residual hearing. To determine the potential of any residual hearing, the use of powerful hearing aids with an appropriate auditory rehabilitation period is essential. Generally, speech perception tests quantify a candidate's ability to use his/her residual hearing effectively. Such data obtained pre-operatively are also valuable as a reference for comparison with post-implant scores. To confirm the results of behavioural hearing tests in children, objective electrophysiological tests, such as auditory brain stem response (ABR) and/or electrocochleography measurements, are often used (Shallop, 1993; Van den Broek *et al.*, 1995).

The radiological evaluation includes high resolution computed tomography (HRCT) scanning which is a prerequisite to determine possible ossification of the cochlea and congenital anomalies as well as anatomical landmarks (Wiet *et al.*, 1990; Gray *et al.*, 1991; Phelps, 1992; Dahm *et al.*, 1995). Generally, ossification of the cochlea is not considered as a surgical contraindication for cochlear implantation (House *et al.*, 1987; Wiet *et al.*, 1990; Lambert *et al.*, 1991; Hartrampf *et al.*, 1995; Schwartzman, 1995). However, in such cases full insertion of the electrodes is not always possible and the results of implantation might be less than optimal (Cohen and Waltzman, 1993). Magnetic resonance imaging (MRI) has proved to be very useful for the pre-operative evaluation of cochlear patency. With this technique, it is possible to assess in more detail the inner ear spaces and fluids, and to image the cochlear nerve in its meatal portion (Gray *et al.*, 1991; Phelps, 1992; Dahm *et al.*, 1995; Hinderink *et al.*, 1997). Usually, in the younger children these measurements are performed under general anaesthesia.

Subjects undergo psychological testing as part of the pre-operative assessment, to rule out any severe problems. The expectations and motivation of the subject and, in the case of children the parents, have to be realistic. Parents and/or relatives share a major responsibility with regard to rehabilitation after implantation (House *et al.*, 1987; Ramsden *et al.*, 1993; Vermeulen *et al.*, 1994).

Evolution in the selection criteria

Over the years, the selection criteria have changed as greater insight has been gained into the effect of several biographical factors upon CI performance. Various studies have revealed that postlingually deaf adults perform better with their CI than prelingually deaf adults (Tyler, 1993; Hinderink *et al.*, 1995). Therefore, nowadays prelingually deaf adults are usually discouraged from receiving a cochlear implant (Tyler, 1993).

The difference in performance between pre- and postlingually deaf children is far less pronounced (Gantz *et al.*, 1994; Dowell *et al.*, 1995; Snik *et al.*, 1997b). prelingually deaf subjects who received an

implant during childhood achieved a higher level of performance than those who received CI during adulthood (NIH Consensus Statement, 1995; Waltzman *et al.*, 1995). In deaf subjects, not only the time of onset of deafness has an effect on performance, but also the duration of profound deafness. The shorter the duration of deafness, the better the auditory performance (Gantz, 1989; Summerfield and Marshall, 1995; Van den Broek *et al.*, 1995; Waltzman *et al.*, 1995).

Dowell *et al.* (1995) reviewed the speech perception results of all the children and adolescents (up to 19 years of age) implanted in Melbourne and Sydney. In agreement with other authors, they observed that the range of speech perception performance was wide. Their results indicate that the age of onset of hearing loss and the age at the time of cochlear implantation do not have any significant effect on speech perception. However, the duration of deafness and the duration of implant use had a highly significant effect. A recent Dutch study on 34 postlingually deaf adults (Van Dijk *et al.*, 1995) has shown that all the subjects had better scores with their CI than with their previous conventional hearing aids. Neither age at the onset of deafness nor the duration of deafness as such proved to be useful as predictors of success or for selection purposes. However, the duration of deafness was related to the amount of rehabilitation that was needed after implantation.

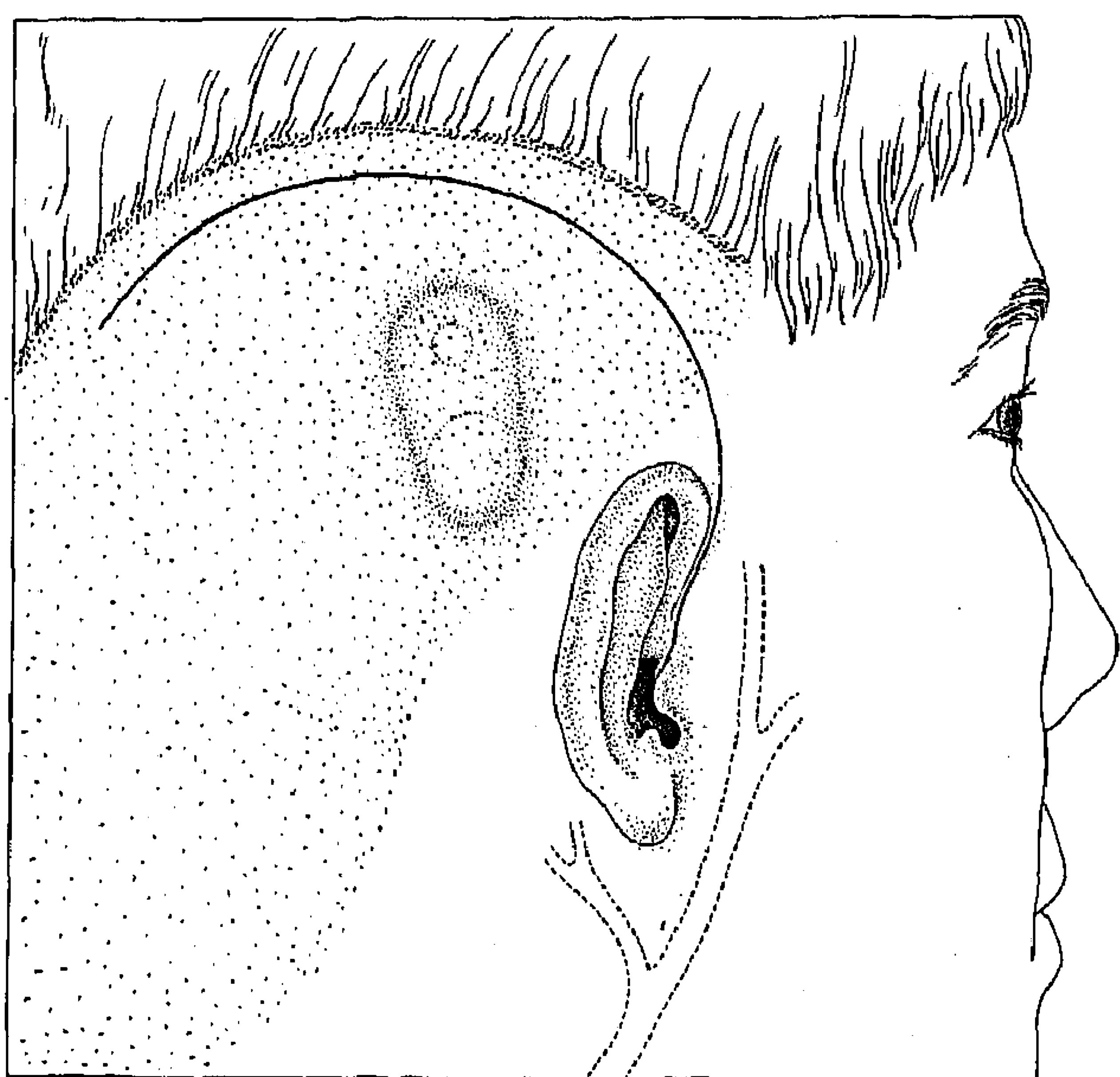
Originally, the audiological criteria were defined by total deafness and absence of any discrimination of speech sound. During the last years a shift is observed towards accepting subjects with limited speech discrimination (less than 30 per cent) in their optimally aided condition (NIH Consensus Statement, 1995; Summerfield and Marshall, 1995).

In the recent literature, the youngest children implanted were younger than two years. Implantation at such a young age is only feasible if profound bilateral sensorineural hearing loss can be diagnosed with complete certainty and the child has no benefit from conventional hearing aids. Cochlear implantation at a young age will diminish the negative effect of auditory deprivation. In the case of meningitis, if implanted very soon it might help to prevent labyrinthitis ossification which would impede later implantation. Cohen and Waltzman (1996) reported that eight children of younger than two years received a CI at their institute. They all showed significant benefit. The Hannover group has also implanted such young children, with encouraging results. Nevertheless, more data are required to show the benefits of early implantation and these may help to guide future policy.

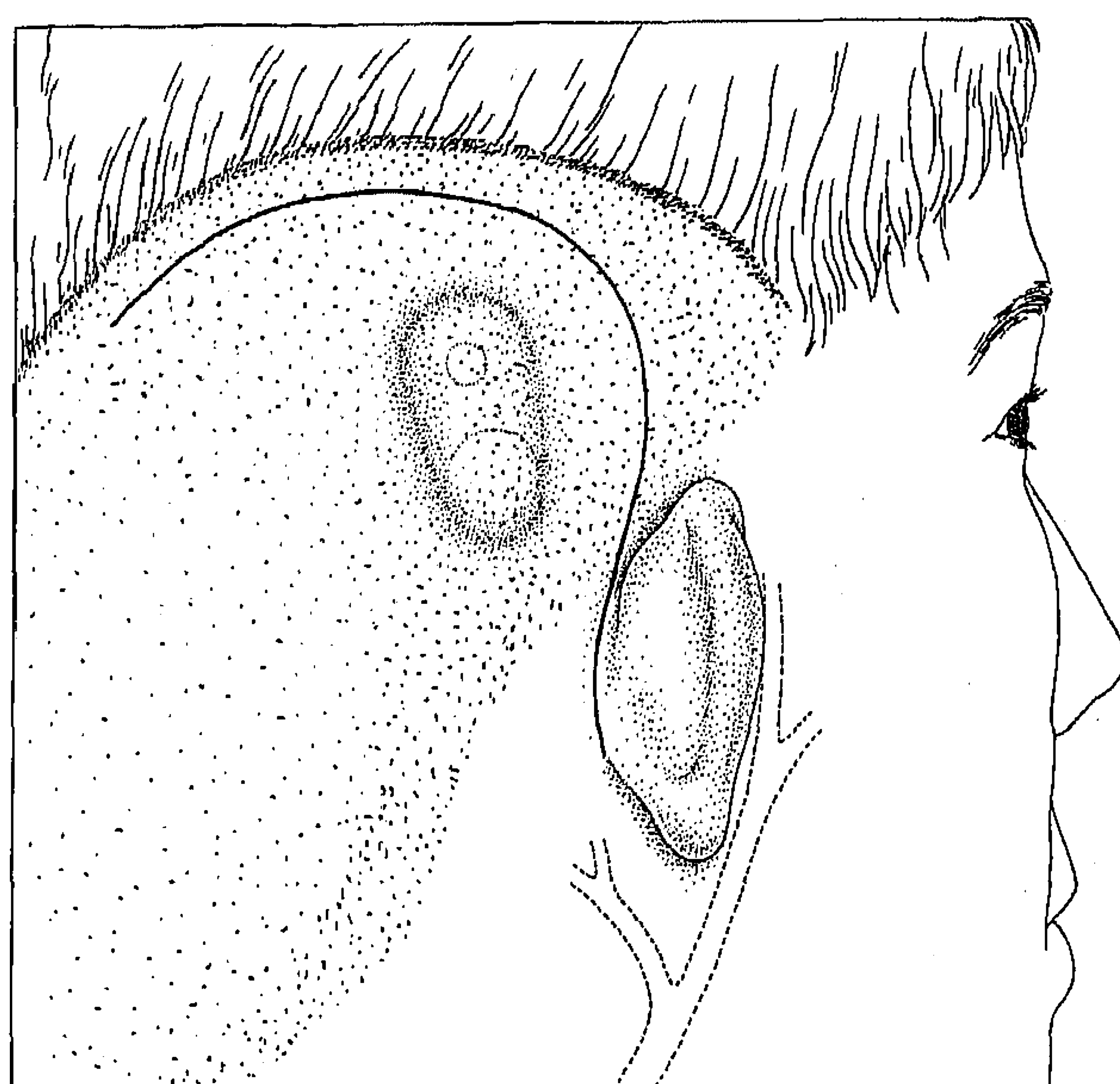
Surgery

Surgical technique

CI surgery can be performed successfully in adults and children, in spite of some difficulties, particularly with an ossified cochlea (Luxford and House, 1987; Graham *et al.*, 1989; Lambert *et al.*, 1991; Hartrampf *et al.*, 1995). Access to the cochlea is obtained through a mastoid and facial recess approach, as is also used in surgery for chronic otitis media. In adults, the receiver-stimulator is positioned just above and behind the pinna. In young children, the position is moved slightly downwards, in order to reach a more suitable flat part of the skull. The incision should be made at least 1 cm away from the planned site for the internal receiver. Several types of skin flap design have been advocated; the basis for the designs is to maintain a good vascular supply to the flap.



(a)



(b)

FIG. 1a and 1b

Diagram of an endaural incision (Fig. 1a) and retro-auricular incision (Fig. 1b) employed for cochlear implantation. Condensed dots indicate the site of placement of the receiver.

In Nijmegen, two types of incision are used. An endaural incision (Figure 1a) or a retro-auricular incision (Figure 1b); both curve upwards and backwards, high over the parietal region. In children, the surgical procedure for cochlear implantation differs slightly (Luxford and House, 1987; Clark *et al.*, 1991; Van den Broek *et al.*, 1995). This is due to the smaller dimension of a child's skull, the thinness of the skin and the later growth of the skull. Therefore, the incision is made right down to the bone. The temporal muscle is lifted from the parietal portion of the temporal bone with the subcutaneous tissue and skin as a single layer flap, rather than separating and removing the muscle from the tissues as is done in adults. This surgical modification minimizes problems with wound healing and possible electrode extrusion.

After elevation of the skin flap, the dura mater is sometimes exposed when drilling the well for placing the receiver-stimulator, especially in young children. It is usually necessary to gently push the dura mater down with a thin piece of bone to accommodate the receiver coil. After mastoidectomy, a facial recess approach is used to gain access to the middle ear and round window niche (Luxford and House, 1987; Graham *et al.*, 1989; Clark *et al.*, 1991). The facial recess is opened, and the facial nerve is skeletonized avoiding exposure of the nerve sheath. Cochleostomy can be performed in two ways: through the promontory anterior to the round window membrane or through the round window membrane itself (Clark *et al.*, 1991). Care should be taken not to mistake hypotympanic cells for the round window niche. This is necessary to avoid insertion of the electrode array into hypotympanic cells rather than into the scala tympani, which is an unacceptable complication. The electrode array should be inserted gently to prevent damaging to the delicate cochlear structures as much as possible. Rogowski *et al.* (1995) introduced the technique of soft surgery minimizing the damage to the inner ear structures.

Ossification of the cochlea, as is often found in post-meningitis cases, needs drilling to open the scala tympani for electrode insertion. In the majority of cases, limited drilling in the basal turn will result in an open scala tympani and full insertion of the electrode array. In some cases the scala vestibuli will be open and allow a full insertion. In some cases with severe ossification, extensive drilling is necessary. If no lumen is found, only partial insertion will be possible (Gray *et al.*, 1991). Hartrampf *et al.* (1995) reported that in cases with cochlear ossification, at least seven electrodes of the Nucleus 22-channel system can be inserted. The problem of the completely obliterated cochlea has not been resolved. Balkany *et al.* (1996) described a technique using a complete drill out of the cochlea, however this does not seem to be the ultimate solution. Recently, Med-El introduced a two-array system for the ossified cochlea.

After insertion, the cochleostomy is sealed with bone dust or soft tissue and glue. In general, the electrode lead is placed in a groove created in the

superior part of the mastoidectomy fossa and fixed in the fossa incudis. This is because the distance from there to the round window does not change after birth. The receiver-stimulator should be tied down securely.

Complications

The surgical complication rate of the implant procedure is low, both in adults and children. Largely, the complications are comparable with those of middle-ear surgery. In addition to surgical complications, device migration or failure may occur. No major complications necessitating removal of the implant occurred in any of the 105 subjects who received a CI in Nijmegen. However, a few minor post-operative complications were found. A mild post-operative wound infection occurred in one child, necessitating prolonged use of antibiotics, while another child had a surgical haematoma which was aspirated, one adult had a transient facial nerve palsy and two adults developed post-operative dizziness, one due to inadvertent anterior canal opening. All these complications resolved satisfactorily by conventional medical treatment, the CIs were all functioning correctly. In four children and one adult, only partial insertion of the electrode array was possible due to severe ossification of the cochlea.

Revision surgery can be performed either to upgrade the CI system or to replace a failing device. Several studies have shown that it is possible to explant and re-implant without damage to the cochlea or the auditory nerve (Luxford and House, 1987; Clark *et al.*, 1991; Saeed *et al.*, 1995).

In Nijmegen, four out of the 105 subjects were re-implanted: one because the electrode was inadvertently placed into hypotympanic cells and three to upgrade the system from a single-channel device to a multichannel one. Time interval between first and second implantation in the latter three patients was four to six years. Re-implantation was uneventful and the speech perception performance was better than with the previous CI. This is illustrated in Figures 2a and 2b which show the one-year follow-up speech perception results with the first and the second implanted devices. One-year post-operative results are not yet available from the third re-implanted patient.

Pre-operative imaging and surgical results

HRCT scanning has proven to be a valuable tool for the pre-operative assessment of cochlear patency. However, (minor or major) cochlear ossification encountered during surgery is not always visible on pre-implant radiological studies (Wiet *et al.*, 1990; Dobie *et al.*, 1995; Schwartzman, 1995). If the HRCT scan seems to be normal in subjects with a history of meningitis or otosclerosis, the surgeon should suspect obliteration of the round window and part of the basilar turn. A Dutch study on the predictive value of HRCT scanning carried out in 100 subjects with a CI showed a relatively large number of false negatives, when compared to the intra-operative

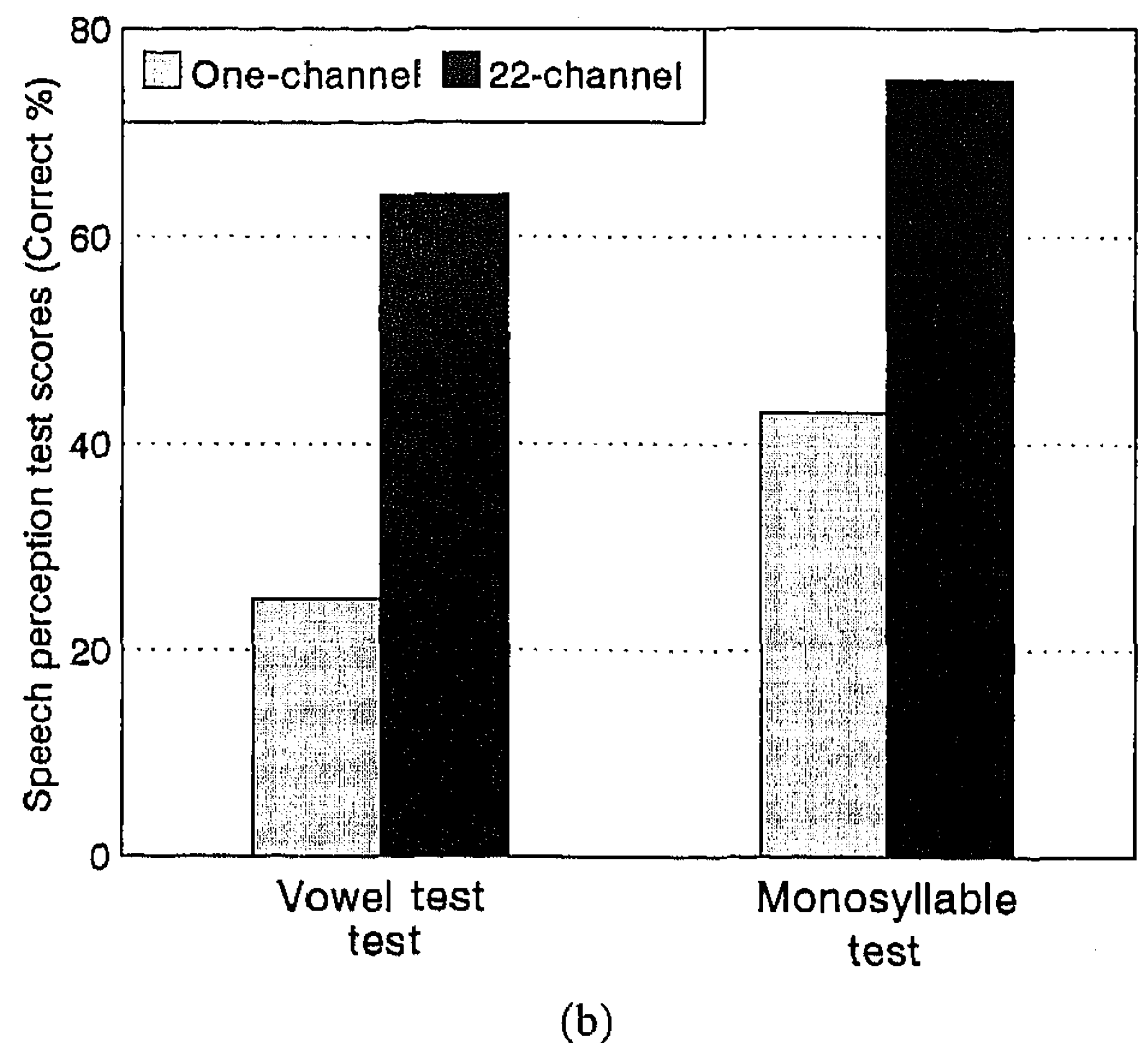
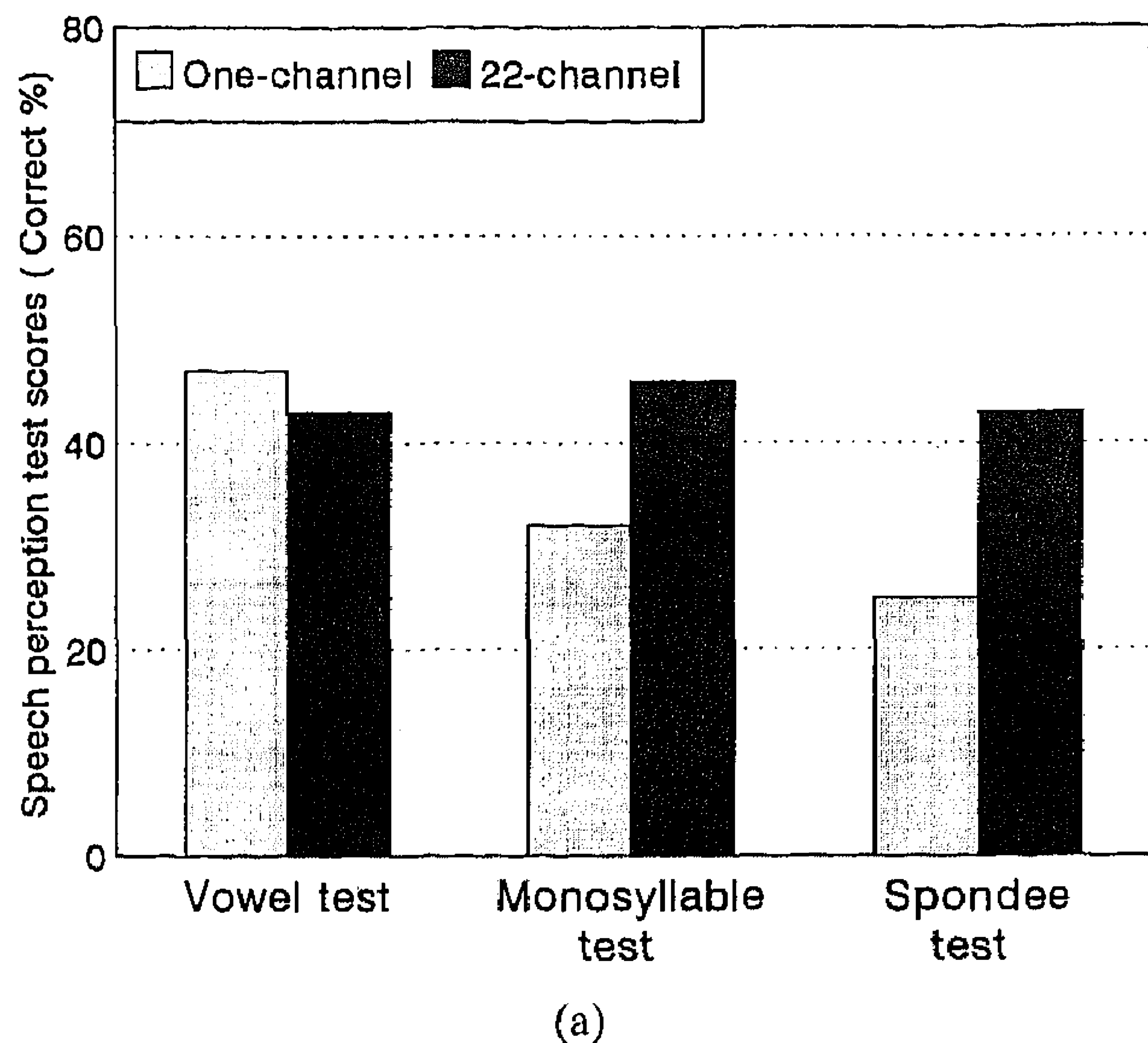


FIG. 2a and 2b

The speech perception scores of two CI users who were re-implanted. The gray bars indicate the scores obtained with the previous system; the black bars indicate the scores obtained with the multichannel Nucleus system. The data were obtained one year after the implantation.

findings (Hinderink *et al.*, 1997). The data are presented in Table II. This means that in spite of its value, the accuracy of pre-operative HRCT scanning is not optimal.

MRI has been advocated by several authors to supplement the pre-operative evaluation of cochlear patency. In the Nijmegen study, MRI was performed in 28 CI subjects. MRI was found to be superior to HRCT scan with respect to predicting cochlear patency. This was especially the case in meningitis-deafened cochleas. Our results once more suggest that MRI can supplement the CT findings.

Electrophysiological measurements

To achieve the best results with a CI, it is important to adjust the processor output to the user's dynamic range. This may be a problem in young children (Mason *et al.*, 1995). To tackle this problem, several investigators performed measurements to assess threshold and comfortable levels directly after placement of the CI, while the child was still under general anaesthesia. For this purpose, electrically evoked ABR measurements (EABR) and/or electrically evoked stapedius muscle reflex (ESR) measurements were performed (Lambert *et al.*, 1991; Shallop, 1993; Mason *et al.*, 1995; Van den Borne *et al.*, 1996). A study was performed in Nijmegen to find out which measurement was the most sensitive. Therefore, post-operative EABR and

ESR thresholds were determined. It was found that the EABR thresholds vary widely within the patient's dynamic range, whereas the ESR thresholds lay in a more limited part of the patient's dynamic range (Van den Borne *et al.*, 1994). So, the determination of ESR thresholds seemed to be the better choice.

A technical restriction of the EABR measurement is that it is more susceptible to noise and electrical artifacts than the ESR measurement. A specific problem with intra-operative ESR measurement is that anaesthetic agents influence the outcome (Gnadeberg *et al.*, 1994; Van den Borne *et al.*, 1996). To illustrate this, Figure 3 shows an example of ESR thresholds recorded intra-operatively. During the measurement, the concentration of an anaesthetic agent (halothane) was increased and later readjusted to the original level. A significant effect of the halothane concentration was seen. Figure 3 also shows the post-operative value obtained at six months after device fitting. In general, post-operative ESR thresholds were lower than those measured during surgery (Van den Borne *et al.*, 1996). Owing to the technical restrictions and the poor relationship with the behavioural results, intra-operative EABR and ESR data should be used with caution for device programming.

TABLE II
PRE-OPERATIVE HIGH RESOLUTION COMPUTED TOMOGRAPHY FINDINGS IN 100 SUBJECTS (WITH DIFFERENT AETIOLOGIES) FOR COCHLEAR IMPLANTATION RELATED TO THE SURGICAL FINDINGS

Aetiology	HRCT				Total
	True positive	True negative	False positive	False negative	
Meningitis	9	19	0	17	45
Otosclerosis	1	1	0	2	4
Other aetiologies	0	51	0	0	51
Total number	10	71	0	19	100

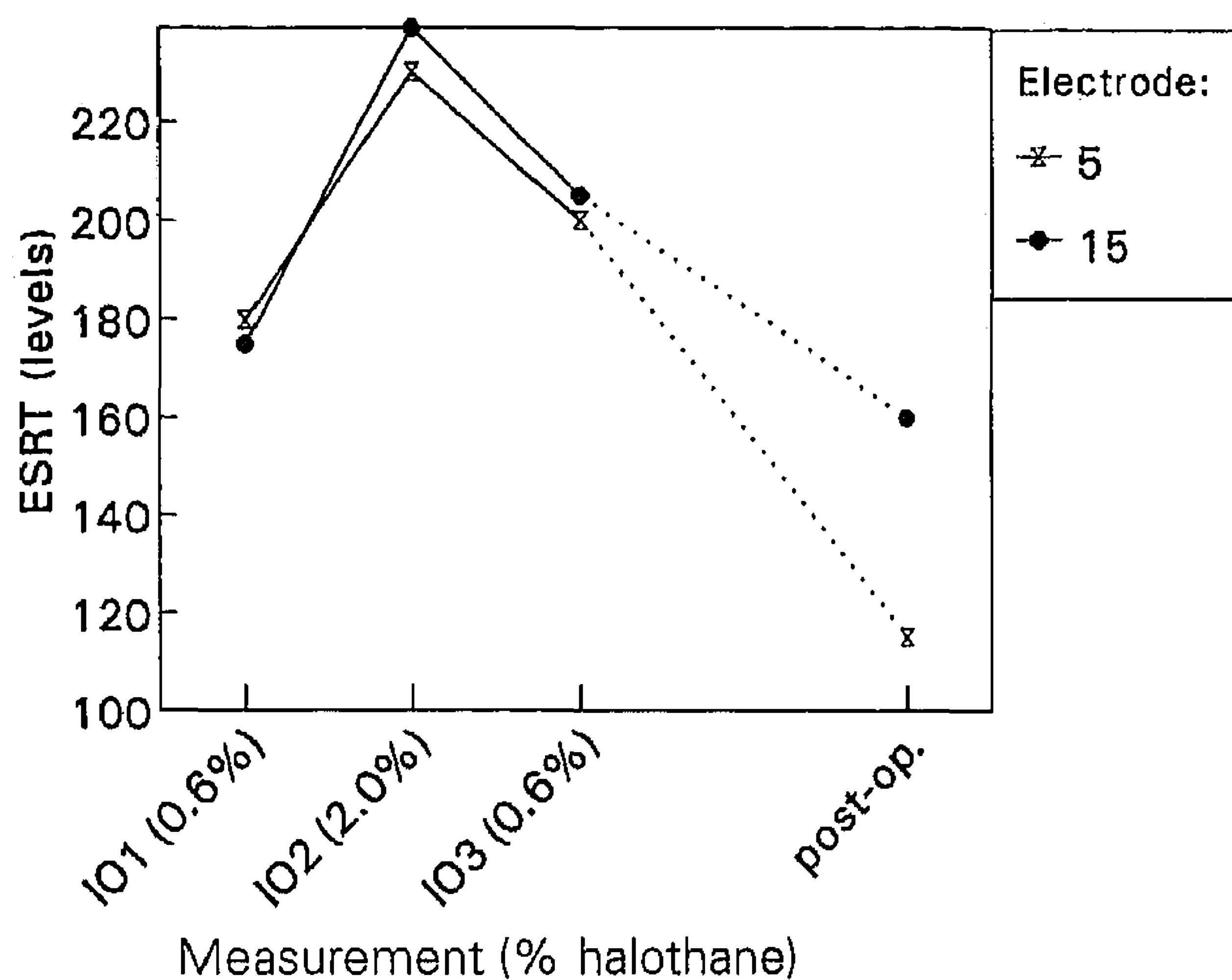


FIG. 3

A typical example of electrical evoked stapedius reflex thresholds (ESRT) recorded intraoperatively from electrodes 5 and 15, while the concentration of the anaesthetic agent (halothane) was varied from 0.6 per cent (IO1) to 2.0 per cent (IO2) and back again to 0.6 per cent (IO3). Post-operative results obtained 6 months after device fitting are also indicated.

Rehabilitation

The aim of the rehabilitation programme is to achieve optimal use of a CI. New auditory abilities should be used to develop new auditory and communication skills. Generally, speech perception skills improve after cochlear implantation. Continuation of learning in meaningful situations in daily life, also after the initial rehabilitation period, contributes to the optimal use of a CI (Vermeulen *et al.*, 1994).

Collaboration of the CI team with tutors in a setting for the deaf is essential for children. If a child does not receive rehabilitation and encouragement for spoken language, the outcome of cochlear implantation is likely to be disappointing. In cooperation with the Institute for the Deaf in St Michielsgestel, the initial rehabilitation period in Nijmegen takes two weeks. After this period, CI users return once every month for tutoring for at least one year. After rehabilitation, they should be able to continue learning at home and at school, at their own speed and in their own manner.

Evaluation

Outcome of cochlear implantation in adults

Summerfield and Marshall (1995) found that the majority of postlingually deaf adults who received a 22-channel CI at several CI centres in the United Kingdom experienced significant benefit. After two-years follow-up, the Iowa group (Maillet *et al.*, 1995) found largely a comparable result in their study on 82 postlingually deaf adults, with the greatest benefit in postlingually deaf adults with a short duration of deafness.

The Nijmegen CI team evaluated the speech performance of prelingually and postlingually deaf adults who had received either a single-channel or a

multi-channel CI (Hinderink *et al.*, 1995). Speech perception tests were performed at various intervals during a two-year follow-up period. The most significant improvement in speech perception performance was observed in the postlingually deaf adults who were using a multichannel CI. These users were the only ones to achieve open-set speech recognition. Nevertheless, the average performance of the prelingually deaf CI users with either a multi- or single-channel device was significantly above chance on both the pattern recognition and sound discrimination tasks. Nowadays cochlear implantation in prelingually deaf adults is discouraged because of the limited benefit. However, in special cases, for instance in prelingually deaf adults with impaired vision (Usher's syndrome) a CI may be an important supportive tool (Hinderink *et al.*, 1995). In a second study on a larger number of postlingually deaf adult CI users ($n = 34$), a sentence recognition test on a video was used. All the subjects were examined at six and 12 months post-operatively. The scores were recorded in three modalities: visual only, auditory only and audio-visually. Pre-implantation, the subjects were evaluated in visual mode only. (The auditory and audio-visual mode tests were excluded because some of the subjects were not using appropriate hearing aids due to a lack of benefit). The results are shown in Figure 4, which clearly indicates the improvement in speech perception with increasing follow-up. In summary, it can be concluded that adults with postlingual deafness experience significant benefit from cochlear implantation and they show better results than adults with a prelingual onset of deafness. This is in agreement with the conclusion drawn in the NIH report (1995).

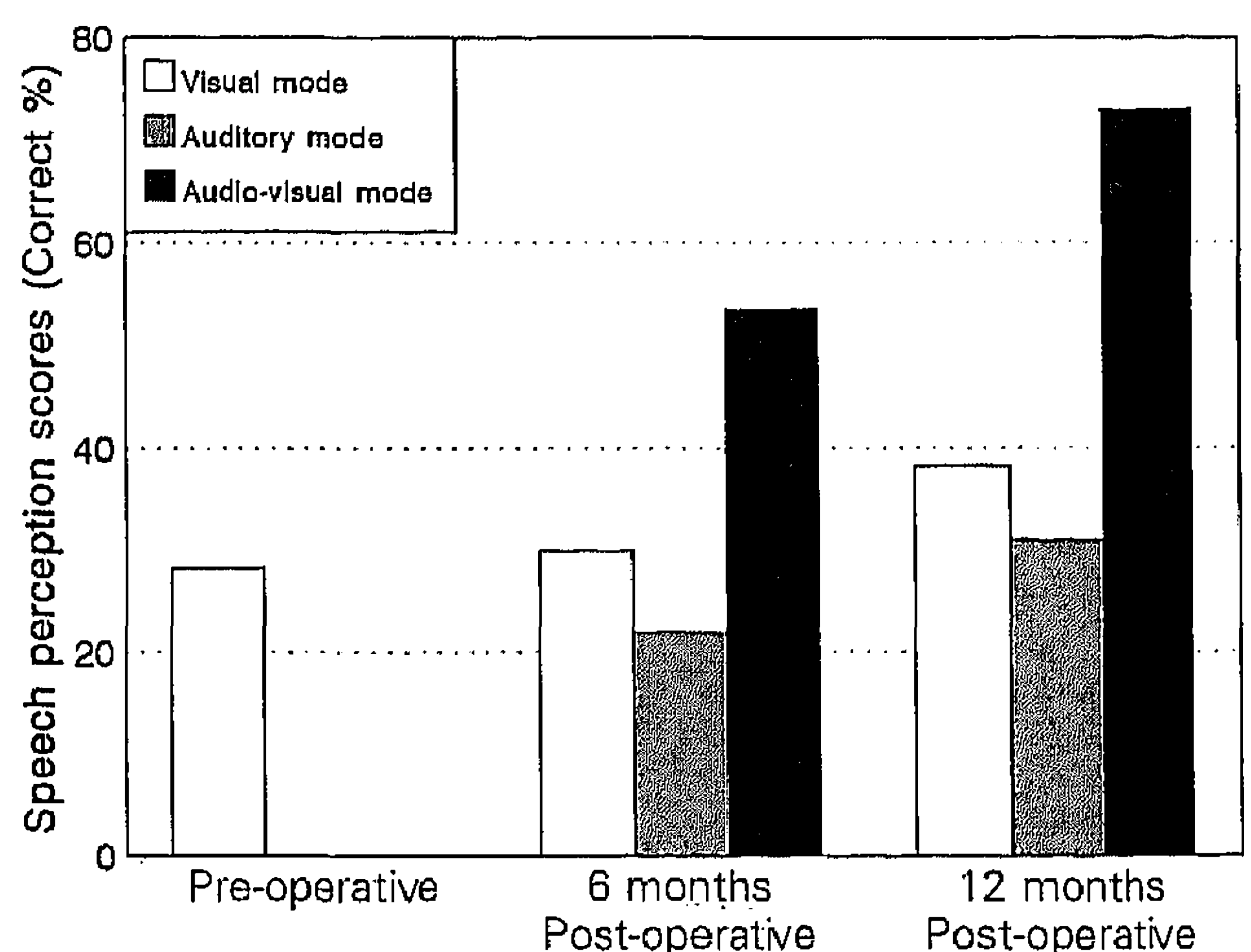


FIG. 4

The 6 and 12 month post-operative mean speech perception scores of 19 adult CI users implanted in Nijmegen. The white bar represents the speech recognition scores with lip reading (visual mode) only; the gray bar represents the scores with no lip reading (auditory mode) only; the black bar represents the auditory-visual mode scores. Scores in the visual condition only were also obtained before surgery.

Outcome of cochlear implantation in children

Several studies have focused on speech perception skills in children with a CI. Gantz *et al.* (1994) studied the benefit of the Nucleus multichannel CI in 54 children. They found that the speech perception skills of postlingually deaf children improved significantly in the first year after implantation. The prelingually deaf children progressed at a slower rate than their postlingual counterparts. However, some of the prelingually deaf children attained comparable and in some instances even better speech understanding than some of the postlingually deaf children. These authors also observed that speech perception and production continued to improve over the five-year follow-up period. Waltzman *et al.* (1994) analyzed the post-operative speech performance of 14 congenitally and prelingually hearing impaired children whose age at the time of cochlear implantation was younger than three years. The results indicated that all the children developed good auditory skills. In addition, they concluded that congenitally and prelingually deaf children should receive a CI at an early age, because it will be more beneficial for the development of speech perception and because there was no difference in performance between the congenital and prelingual groups. It has become firmly established that the perceptual abilities of children with a CI continue to improve significantly over time. This is in contrast with profoundly deaf children who use conventional hearing aids, as they show plateau scores (Miyamoto *et al.*, 1995; Snik *et al.*, 1997a).

With regard to speech production, the earlier cochlear implantation is performed in children, the better their speech intelligibility. Osberger *et al.* (1993) reported that children with early onset of deafness who were implanted before the age of 10 years demonstrated good intelligibility, whereas similar group of children who received a cochlear implant after the age of 10 years had the poorest speech intelligibility.

To achieve the best results, the electrode array should be inserted into the cochlea over its full length. However, this cannot always be achieved in the case of severe ossification of the cochlea. Nevertheless, Kemink *et al.* (1992) reported that the performance of children with partial insertion was comparable to that of children with full insertion. However, other groups reported that partial insertion children had inferior results and required higher stimulation levels (Van den Broek *et al.*, 1995). Cohen and Waltzman (1993) also found poor performance in most of their partial insertion subjects. Nevertheless, in some of them, they found significant scores on the open-set speech recognition test.

Auditory skills of 20 children with acquired profound deafness caused by meningitis, implanted in Nijmegen with a Nucleus multichannel system were evaluated. Four out of the 20 children had a partial insertion. The other 16 children were divided into three groups according to age at the onset of deafness. The first group comprised children who

became deaf between 0.3–1.9 years, the second group children who became deaf between two to 2.9 years and the third group comprised children who were three years or older at the onset of deafness. The scores obtained on a speech perception test battery were reduced to a single measure, called the 'equivalent hearing loss' as described by Snik *et al.* (1997a). For this purpose, a large group of age-matched severely and profoundly deaf children using conventional hearing aids were tested with the same speech tests. Statistical methods were used to establish the relationship between the scores of the children using hearing aids and the degree of their hearing loss. Then, this mathematical relationship was applied in reverse to convert the scores of a child with a CI into an 'equivalent hearing loss' value (Snik *et al.*, 1997a). Figure 5 shows the mean value of the 'equivalent hearing loss' for the four groups of children with the CI. Pre-operatively, the 'equivalent hearing loss' values were above 125 dB HL for all four groups, as is shown in the figure. This indicated that on average, the children from all four groups were performing as poorly as the children in the reference group with hearing loss of above 125 dB HL. During follow-up, remarkable improvements were observed in all four groups.

The greatest improvement was observed in the group of children who became deaf after the age of three years. At three years follow-up, their scores were as good as those of children from the reference group with a hearing loss of 72 dB HL. Broadly speaking, the children who became deaf between two and 2.9 years of age showed a similar curve, however, with a delay of one year. In the groups with full insertion, the children who became deaf between birth and two years of age showed the poorest performance. Nevertheless, there was constant

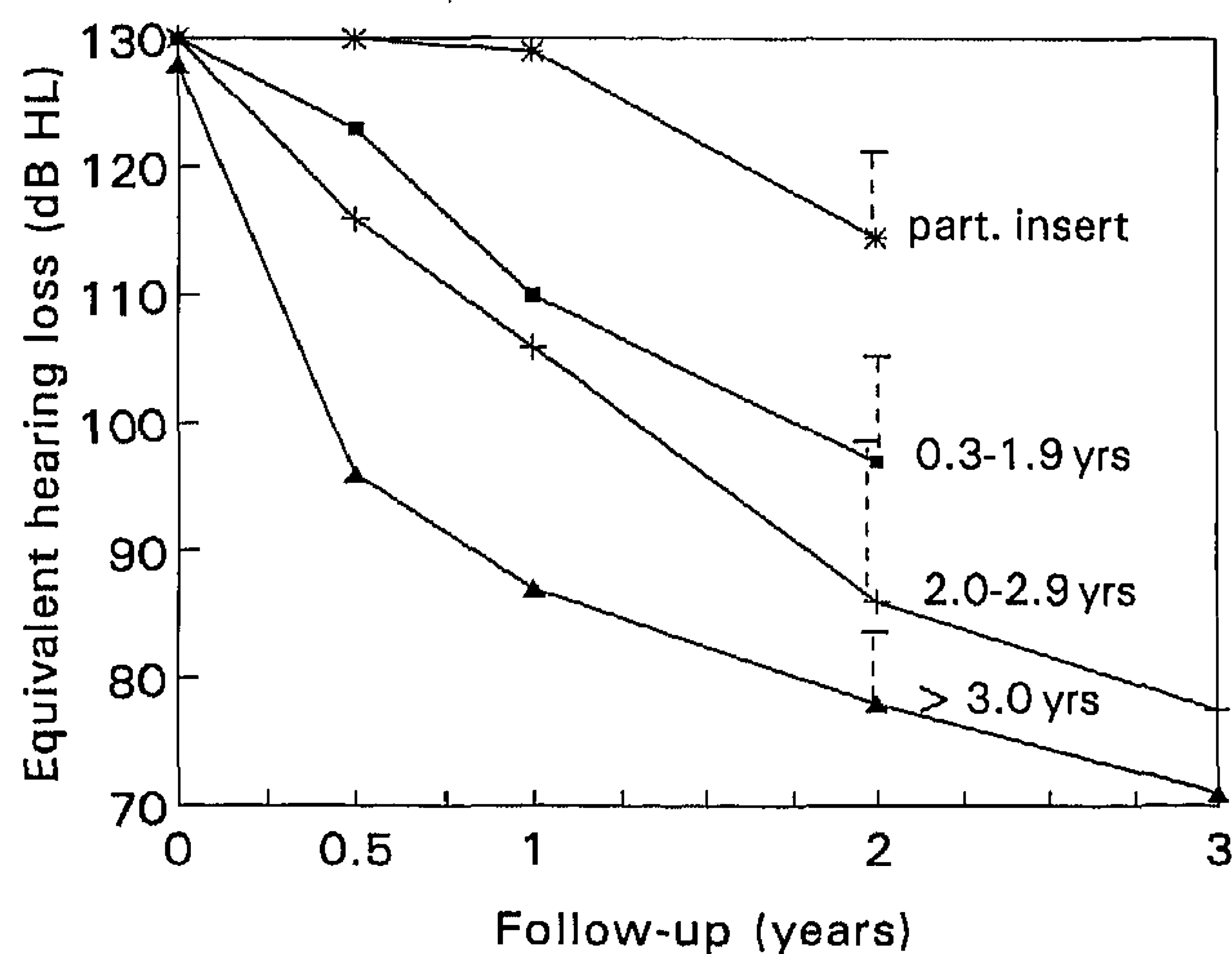


FIG. 5

The mean 'equivalent hearing loss' of four groups of children with a CI as a function of follow-up. * indicates the mean scores of the children with partial insertion ($n = 4$); ■ indicates the mean scores of the children with acquired deafness between 0.3 and 1.9 years of age ($n = 5$); + indicates the mean scores of the children with acquired deafness between 2.0 and 2.9 years of age ($n = 6$); ▲ indicates the mean scores of the children whose age at the onset of deafness was above 3 years ($n = 5$). At a follow-up of two years, standard deviations are indicated.

improvement during the whole evaluation period, with no signs of plateau scores in any of the three groups.

The children with partial electrode insertion were the poorest performers. Three-year follow-up results were available for two out of the four children (not presented in the figure); these two children did not show any further improvement by this stage. These results and those of other studies (Waltzman *et al.*, 1994; Miyamoto *et al.*, 1995; Summerfield and Marshall, 1995) showed that significant but variable cochlear implantation outcomes can be achieved in children. Age at the onset of deafness and whether the electrode array is fully or partially inserted, play a role.

Cost-effectiveness considerations

It is known that cochlear implantation is a very costly procedure. The cost of cochlear implantation includes the cost of pre-operative assessment, device, surgery, rehabilitation and maintenance of the device. The cost-effectiveness analysis is based on the relation between the resources consumed (cost) and the quality of life outcome (effect). The outcome is expressed as Quality-adjusted life years (QALYs). Mostly, the QALY is a numerical health-utility factor ranging in value from 0 (representing death) to 1 (representing perfect health). The value of the QALY incorporates change in quality of life that occurs from the treatment and life-expectancy. This means that if a medical intervention prevents death and provides a patient with one year of perfectly healthy life, 1 QALY has been gained. In contrast, treatment that improves the patient's general health and resume normal life is expressed as a proportional increase in QALY (Cowan, 1997). The lower the cost per QALY, the better is the cost-effectiveness. Wyatt *et al.* (1995) analysed the cost-effectiveness of 301 postlingually deaf adults Nucleus 22-channel CI users, who had been using their device for at least two years. They calculated the cost per QALY offered by multichannel CI and the result was approximately 9.325 US\$. The two major cost factors were the device and the surgery. They concluded that cochlear implantation provides significant improvements in the quality of life and is quite cost-effective when compared to other accepted medical interventions in US. In the United Kingdom, cochlear implantation cost-effectiveness was studied by Summerfield and Marshall (1995). Their calculation revealed approximately 50 per cent higher costs per QALY compared to that reported by Wyatt *et al.* (1995) study. They conclude that cochlear implantation in United Kingdom is cost-effective and it is likely the costs may decrease as the implanting teams became more experienced and procedures more standardized (Summerfield and Marshall, 1995).

Conclusion

Nowadays, cochlear implantation is generally considered to be of significant value for postlingually profoundly deaf adults and children and also for prelingually deaf children. Adequate rehabilitation is important for postlingually deaf subjects, but it is most crucial for prelingually deaf children to maximize the benefits of cochlear implantation.

The application of cochlear implantation to prelingually deaf adults has often been debated. Although they may make very slow progress in speech recognition skills, they nearly always experience other basic benefits, such as improved sound awareness that assist their psychological satisfaction and help to meet safety needs. This is important for profoundly deaf subjects who suffer from a progressive visual impairment such as subjects with Usher's Syndrome.

Many studies reported that auditory performance with a CI varies among individuals. Until now, there has not been a completely satisfactory explanation for this observation. However, performance seems to be best in individuals with a short duration of deafness, who acquired speech and language before their deafness occurred.

The outcome of partial insertion of multichannel electrode arrays is generally poorer than that of full insertion. This will depend on the position and number of active electrodes. It is still questionable whether cochlear implantation in a severely obliterated cochlea is worthwhile. New development in implant design and coding strategies can be important to improve these results.

Over the years, inclusion and exclusion criteria have gradually changed with growing knowledge. Generally, aetiology and age at implantation as such do not seem to affect the post-implantation auditory performance. However, the earlier the implantation the better the result, especially in prelingually deaf patients. Nowadays, most groups only use a limited number of exclusion criteria. The most important exclusion criteria is the ability to utilize any residual hearing with well-fitted conventional hearing aids.

Audiological results are the primary basis for patient selection. Pre-operative HRCT scanning is valuable to detect any bony ossification and anatomical abnormalities. However, if the result is ambiguous, MRI may supplement HRCT scanning. Generally, the surgical procedure to place a CI is uneventful. Re-implantation has proved to be possible with good results.

Owing to technological evolution and an increase in experience, the era of cochlear implantation is advancing rapidly. New techniques may enable wider groups of pre- and postlingually hearing impaired individuals to benefit from cochlear implantation.

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