European Journal of Radiology, Vol. 40 (2) (2001) pp. 119 - 132

PII: S0720-048X(01)00380-1

Cochlear implant assessment: imaging issues

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Received 21 June 2001; accepted 25 June 2001

Abstract

Cochlear implants are electronic auditory prostheses used to rehabilitate deafened persons who have lost their hair cells. They are partly worn externally and partly implanted in the ear. They provide a direct stimulation of the spiral ganglion cells of the cochlear nerve by bypassing the destroyed hair cells. The objectives of this article are to summarise what head and neck surgeons need to know before cochlear implantation and to describe the imaging study protocol used and anomalies to look for. A few explanations are resumed about placement of a brainstem implant.

Keywords: Cochlear implant; Electronic auditory prostheses; Cochlea; Parthology

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1. Introduction

Cochlear implants were first developed in France in 1957 by Djourno and Eyries [1], who described how to stimulate the cochlear nerve by electric currents. In fact, auditory excitation was already demonstrated by Volta at the end of the XVIIIth century. At the beginning, development of cochlear devices was limited by the size of electronic components and by the weight of batteries. House developed the concept of a single-channel electrode stimulation [2]. Lately, Merzenich [3] developed cochlear stimulation by a multichannel electrode. In the last years, cochlear implantation has gained widespread acceptance in the profoundly deaf patients and more than 23,000 patients have been implanted in the worldwide. Cochlear implant is considered an effective procedure to treat patients with profound (>90 dB) and severe (between 70 and 90 dB) hearing loss. Improved speech processing strategy leads recently to improve auditory results. The cost of a cochlear implant procedure is approximately of 30,000-50,000 $. In 1997, 4300 patients have been implanted. As demands for cochlear implant increase, radiologists should be aware of what key points they have to check before implanting patients [4].

2. Cochlear implant device

Cochlear implant is an electronic device used to habilitate or rehabilitate patients with profound or severe hearing impairment. It provides a direct stimulation of the residual spiral ganglion cells of the cochlear nerve by bypassing the destroyed hair cells. In normal persons, the sound waves coming from the oval window pass to the scala vestibuli up to the helicotrema and then, go down towards the round window by the scala tympani. The hair cells are excited by the variations of pressure waves transmitted to the scala media (Fig. 1).

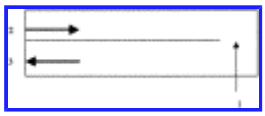

Fig. 1. Sound transmission to the inner ear: relation between the scala vestibuli by the oval fossa (2) and the scala tympani by the round window (3) via the helicotrema (1).

2.1. Cochlear implant device

The components of a cochlear implant device include (Fig. 2):

- The externally worn components: a speech processor placed in a pocket receiving speech stimuli, and *an ear-level microphone*, placed behind the ear and worn like a hearing aid. The microphone is connected to the transmitter.
- The internally implanted components: a transmitter or *receiver/stimulator coil*, firmly fixed beneath the retro auricular soft tissues within a well drilled-out area of the temporal squama. This transmitter has a transducer coil coupled across the skin by a magnet-disk with a receiver coil. And *an electrode array* inserted into the scala tympani of the basal turn via the round window for a distance of 20-24 mm (Fig. 3). In case of obliteration of the cochlea or of a round window stenosis, each electrode can be separately inserted by multiple antero-inferior transpromontory cochlear fenestrations.

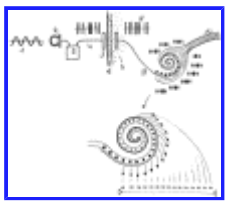

Fig. 2. Schematic diagram of a cochlear implant. (a) (1) acoustic waves; (2) external microphone; (3) speech processor; (4) encoded electric waves; (5) transducer coil; (6) squama; (7) receiver coil; (8) encoded electromagnetic waves; (9) electrode array with 15 slots; (10) cochlear nerve. (b) Differential excitation of the cochlear nerve by selective excitation of hair cells.

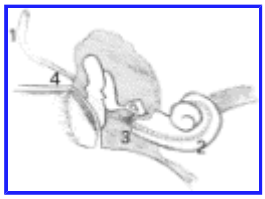

Fig. 3. Standard technique of insertion of an electrode array (1) into the scala tympani; (2) through the cochlear basal turn via the round window niche (3). Mastoid (4).

2.2. Function

The sound waves received by the external microphone are transduced into electric signals. These electric signals are then digitally encoded by an external speech processor, and then transmitted as electromagnetic waves across the skin by a transducer to the receiver which reconverts radiowaves into elementary electric signals to stimulate sequentially each slot of the implanted electrode array. Excited slot sequentially excites spiral ganglion cells or axons in the cochlea. Therefore, multichannel device provides a complex sound analysis similar to the physiological analysis of sound in normal patients.

2.3. Models

Different models with a variable number of electrodes exist for adult and children. All are now multichannel intracochlear array devices. Three main systems are in use world-wide—the Nucleus device (Nucleus 22/24 Cochlear Corp, USA), the Ineraid and the Clarion device (ad Bionic corp. USA, Wilson). Digisonic (MXM) is used in France.

3. Cochlear implant candidates

Cochlear implantation is only done on one ear. Criteria for selection of cochlear implant candidates are fixed by the 1995 NIH consensus conference. Cochlear implant candidates should usually be over two years of age, have bilateral profound or severe hearing loss, receive no enough benefit from external hearing aid with less than 30% of intelligibility, have a high motivation for rehabilitation [5].

A lot of factors are considered to select cochlear implant candidates: age, mental and physical health, audiologic testing, cause and duration of the deafness, capacity and ability to be reeducated, social status. Most of the implanted patients increase their speech reading. Some of them may communicate by phone after an extensive training. The rate of success of implantation is higher in acquired deafened patients than in prelingually deafened patients. In prelingually deafened patients, the best results are obtained in children operated as early as possible as the development and volume of the cochlear nerve depends on auditory stimulation. Implanted children improve their speech perception and their speech production. Experiences on normal, deaf non-implanted and deaf implanted mice suggested that development of cochlear nuclei depends on auditory stimulations. Sacrifice of animals at the end of the maturation of the cochlear nuclei, showed that the average volume of cochlear nuclei was similar in normal mice and in deaf-implanted mice meanwhile the average of cochlear nuclei of deaf mice dramatically decreased. Therefore, the earlier the children are implanted, the better the auditory results will be. Precoce cochlear implantation is possible as the cochlear capsule is ossified at birth.

Imaging study is a necessary although expansive part of evaluation. Therefore, it should only be performed in preselected candidates. Both CT and MR are mandatory to guide the choice of the cochlear device, the side to implant and the date of the surgery, looking for cochlear patency, round window niche access, degree of mastoid aeration. The main role of imaging study is to determine patients with contraindications for cochlear implantation.

4. Presurgical key points to consider

Imaging studies for evaluation of cochlear implant candidate should underline different key points. Several anatomical issues should be ruled out in imaging report:

- How is the aeration of the mastoid and of the middle ear? Well-aerated mastoid cavity indicates easier surgical intervention across the facial nerve recess. Inflammation of the

mastoid cells or presence of a middle ear cholesteatoma increases the risk of postoperative sepsis and failure.

- Is there any anomaly of the pathway of the VII cranial nerve or the carotid artery or of the sigmoid sinus? Facial nerve with an abnormal course through the mastoid cells is at significant risk during implantation. Hypoplastic mastoid bones and decreased of mastoid cell aeration increase the difficulty of performing a facial recess approach. Venous variants such mastoid emissary veins should be reported (Fig. 4).
- What is the size of the internal auditory meatus? An internal auditory meatus (IAM) less than 2 mm in diameter increases the risk of a congenital absence or of severe hypoplasia of the acoustic nerve. Similarly, patients with an absent or narrow modiolus (diameter less than 3 mm in CT, or a modiolar surface less than 4 mm^2 in MR) are at risk of absence of cochlear nerve [6] (Figs. 5 and 6). The modiolus is a bone area of low signal intensity in T2WI, located at the base of the cochlea. It represents the exit of the cochlear nerve.
- Is the cochlear nerve present and well developed? Exploration of the IAM by MR with CISS sequence and sagittal reconstructions allows the measurement of the diameter of the cochlear nerve in relation to the facial nerve taken as reference. Normally, the cochlear nerve lays on the inferior part of the internal auditory meatus and is larger than the facial nerve (Fig. 6). Its diameter is approximately of 0.4 mm.
- Is there any malformation of the membranous labyrinth? Both HRCT and heavely T2 thin sections are mandatory to determine the number of cochlear turns, symmetry of scala chambers, status of the modiolus and of the posterior membranous labyrinth (Fig. 6a and Fig. 7). Congenital anomalies discovered during preoperative imaging studies can be the cause of the sensorineural hearing loss and can increase the surgical risk to have a `Gusher-ear' during the electrode insertion within the round window (Fig. 8).
- What is the status of the endo- and perilymphatic fluid? Cochlear ossification or fibrosis may limit the full insertion of the electrode array or modify the choice of the cochlear implant and the way of insertion.
- How is the bony labyrinth? What is the status of the round window niche? In bone remodelling lesions such as Paget, otosclerosis, Lobstein disease and post-meningitis labyrinthitis, stenosis of the round window niche may occur (Fig. 9).
- Is there any variation of the pathway of the facial nerve? Facial nerve injury can occur during surgical placement of the cochlear implant device as surgical approach passes through the facial recess. Therefore, any variations of the pathway of the facial nerve should be searched for [7]. Facial nerve monitoring may be used in patients at risks.

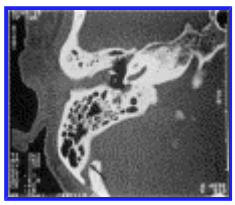

Fig. 4. Mastoid emissary vein (arrow), well-aerated mastoid cells. Filling of the external ear and of the round window recess due to a preoperative electric stimulation of the round window membrane.

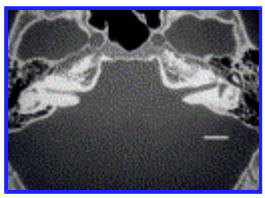

Fig. 5. Bilateral narrow internal auditory meatus. (a) HRCT; (b) T2W echo gradient image. Size of the IAM <2.5 m, cochlear nerve not depicted in T2WI images.

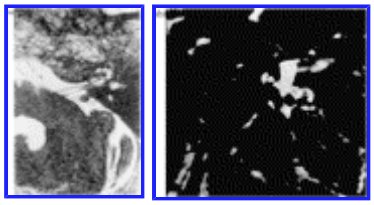

Fig. 6. Delineation of the cochlear nerve. T2WI (CISS). (a) Axial native section shows the cochlear nerve (arrow) and posteriorly the vestibular nerve. Low signal intensity area delineates the modiolus at the base of the cochlea (arrowhead). Linear low signal intensity delineates the scala intermedia. (b) Multiplanar sagittal reconstructed image: normal size of the cochlear nerve in reference to the facial nerve above (arrowhead).

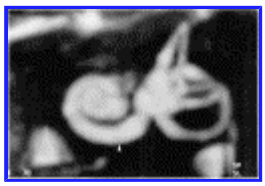

Fig. 7. Size and aspect of a normal cochlear tube (arrowhead) delineated by maximum intensity projection.

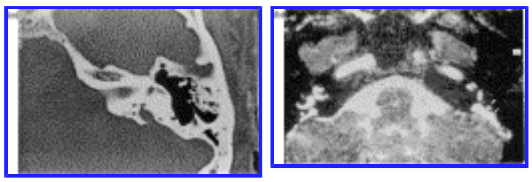

Fig. 8. Congenital anomaly. (a) CT; (b) T2-gradient echo MR. Asymmetric dilatation of the endolymphatic sac and duct (arrow). Associated dilatation of the right vestibule and of the common crus between the anterior and posterior semicircular canals.

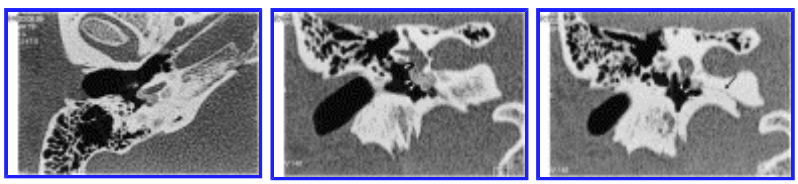

Fig. 9. The round window niche. Axial plane HRCT. (a) Reconstructed coronal plane passing through the oval fossa (arrowhead). (b) More posteriorly reconstructed coronal (c) plane passing through the round window niche fossa (arrow). Stenosis of the round window niche and of the basal turn by hypodense ostosclerotic foci extending towards the cochlear aqueduct (arrowhead).

5. Protocol imaging studies

5.1. CT

Recent development of submillimeter spiral HRCT is extremely useful in evaluation of cochlear candidates. It contributes to plan the surgical approach. It allows isotropic submillimeter resolution and reformatted images in the surgical plane parallel to the petrous bone passing through the facial recess.

HRCT is performed with contiguous native sections of 0.5-1-mm thickness in axial plane, with bone

windows setting, using the smallest pixel size. Edge bone enhancement increases the delineation of inner ear structures. Orientation of axial sections in a plane +30° allows to avoid the orbital lenses and to obtain good delineation of round window. No contrast injection is needed.

The following cochlear structures can be seen, from below: firstly, the sausage-shape of the basal turn with its parallel side walls and the osseous lamina; secondly, the air-filled round window niche under the subiculum; and then, the apical and the mesial cochlear turns communicating with the IAM by the modiolus. A careful attention will be focused on the status, size and development of the posterior labyrinth (Fig. 10).

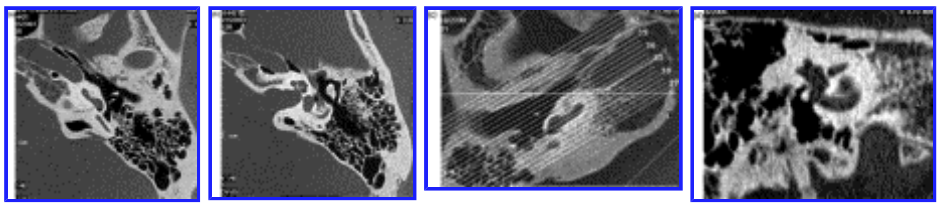

Fig. 10. Unenhanced HR spiral CT, contiguous native sections of 0.5-mm thickness, axial plane, bone windows settings evaluate cochlear structures: (a) below, sausage-shape of the basal turn with parallel side walls and osseous lamina inside. Air filling the round window niche under the subiculum. (b) Apical and mesial cochlear turns communicating with the IAM by the modiolus. Well-pneumatised mastoid cells. (c) Reconstructed section, `Stenvers plane', parallel sections to the petrous bone. (d) Cochlea and basal turn.

HRCT evaluates the status of mastoid pneumatisation, thickness of the cortical bone, middle ear aeration, the round window niche. It may display anatomic middle ear variations of surgical importance such as: dehiscent facial nerve, low lying roof, high jugular bulb and aberrant carotid artery. Furthermore, CT may demonstrate anomalies of the bony labyrinth such as Paget, otosclerosis, postmeningitis stenosis of the round window niche.

5.2. MRI

MR protocol includes brain T2WI and focused inner ear T2W gradient echo images [8]. Brain T2 sequences are mandatory to look for abnormalities and should be centred on the central acoustic pathway, displaying the anatomy from the cochlear nuclei to the temporal acoustic area. Focused inner ear T2W and pre- and post-gadolinium T1W sequences are performed to display the cochlear anatomy and its anomalies. Heavily T2 weighted-images delineate the endolymphatic and peri-lymphatic fluid and each part of the membranous labyrinth from the basal turn to the apical turn. Each nerve in the IAM may be delineated by axial or sagittal T2 sequences (Fig. 6). Identification of the cochlear nerve and delineation of its size are of great importance. In the future, functional MRI may have a place in the selection of cochlear implant candidates.

Advantages of MRI over CT are without discussion to distinguish between cochlear fibrosis and ossification and to diagnose cochlear nerve agenesis. Moreover, MRI may depict unsuspected acoustic nerve or central acoustic pathway anomalies including acoustic nerve tumours (Tables 1-3). The main disadvantages of MRI are its additive cost as MRI does not replace CT. Good quality MR images in deaf patients are more difficult to obtain, as difficulties of communication may lead to movement artefacts. Moreover, sedation is needed in children.

Table 1. Key points for preoperative imaging studies for cochlear implantation

Contraindications for cochlear implantation	Absent cochlear nerve: diameter of IAM (mid-part) <3 mm
	Absent cochlea

	Absent modiolus
Modifying surgical strategies or implant device	Cochlear ossification (partial or total; length in basal turn)
	Hyperostosis of the round window niche
	Persistent membranous labyrinth inflammation
	Inner ear at risk of `Gusher': endolymphatic sac dilatation; abnormal cochlear segmentation, deficient modiolus, semi-circular canal or vestibular dilatation
	Stenosis of the basal turn: otosclerosis foci; Paget...
Increasing surgical risk	Hypoplastic mastoid process
	Inflammed middle ear
	Dehiscent or aberrant facial nerve
	Mastoid emissary vein
	Deep sigmoid sinus
	Exposed jugular bulb
	Aberrant carotid artery
	Persistent stapedial artery

Table 2. Role of preoperative MRI

To identify cochlear fluid fibrosis
To identify active fibrosis
To depict cochlear nerve agenesis and cochlear anomalies
To detect occult an acoustic nerve tumour
To detect brainstem anomalies (trauma, congenital)

Table 3. Key points for evaluation of brainstem cochlear implant candidates

Status of cochlear nuclei: do axial spin echo T2 sequence
Status of the lateral recess: do axial spin echo T2 sequence
Status of meningeal inflammation: do native and enhanced axial T1 sequences
Status of brain stem: do axial and coronal planes
Size and status of the jugular vein: do post Gd T1WI
Presence of mastoid emissary vein: do CT and post Gd T1WI

5.3. Functional MRI

Recently developed, FMRI is a new non-invasive technique testing imaging cerebral function. It is based on the concept that blood has oxygenation-sensitive paramagnetic characteristics. It can test cerebral auditory pathway and, therefore, may add criteria in predicting who are good candidates for cochlear implantation. The response to auditory stimuli is obtained on the superior temporal gyrus and predominates on the left side in a right handed group (10).

6. Pathologies

A large range of labyrinthine anomalies have to be looked for.

6.1. Labyrinthine ossification

New bone formation within the cochlea may occur after meningitis (meningogenic labyrinthitis, septicemia), middle ear infection (tympanogenic infection), mumps and measles, Cogan syndrome, labyrinthectomy or trauma [9,11].

Bacterial meningitis is the most common cause of bilateral labyrinthine ossification. Ossification

predominates within the scala tympani at the level of the basal turn. In fact, in postmeningitic labyrinthitis, infected cerebrospinal fluid enters the scala tympani passing through the cochlear aqueduct. Fibrosis may precede ossification and areas of fibrosis and ossification may coexist. However, because of a significant number of spiral ganglion cells survive despite severe ossification, cochlear ossification is not a contraindication to implantation but renders electrode insertion difficult. In such cases, the surgeon needs to know:

- status of the round window niche (RWN). The RWN may be completely obliterated by postmeningitic scar tissue as infection spreads through the cochlear aqueduct;
- patency of each scala (MRI). Introduction of the electrode array in the scala vestibuli through the oval fossa may be used in case of complete ossification of the scala tympani;
- extension of the ossification within the cochlea which may change the technique of implantation. Remaining patency of the cochlear apex may change the way to insert the device;
- amount of fibrosis in patients without completely ossified cochlea (Fig. 11). Both fibrosis and mild ossification are difficult to identify in CT and are better depicted by MR because heavily thin T2 images may detect any subtle alteration of the membranous labyrinthine fluid;
- nature of the fibrotic area. Enhancement of fibrosis post bacterial infection or post autoimmune disease (Cogan syndrome) suggests that fibrosis is still proliferative. It is probably a factor to consider in decision-making in order to proceed rapidly to a cochlear implantation (Fig. 12).

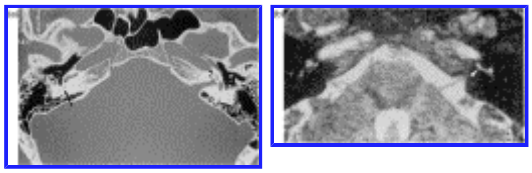

Fig. 11. Fibrosis versus calcification. Bilateral post-meningitis labyrinthitis. (a) HRCT shows a left calcified apical and mesial turns (arrowhead) and obliteration of the posterior semicircular canal (arrow). (b) T2WI shows a bilateral decrease of the high signal of the posterior membranous labyrinths. Remaining patency of the left stenotic basal turn (arrowhead).

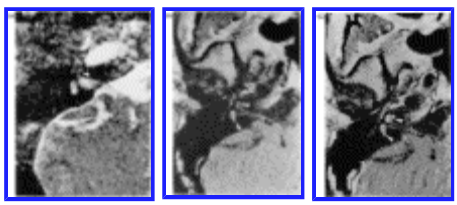

Fig. 12. Active fibrosis. Patient referred 6 months after a bacterial meningitis. Incomplete bilateral cochlear ossification depicted by HRCT. Comparison of pre- (a) and post (b) Gd T1WI displays a labyrinthine enhancement. Abnormal spontaneous high signal intensity on T1WI of the membranous labyrinthine fluid (arrowheads). (c) T2WI a complete loss of the normal high signal intensity of the membranous fluid of the cochlea (arrowhead).

Since a significant number of spiral ganglion cells survive even in case of severe ossification, cochlear ossification is not a real contraindication to implantation but complicates the insertion of the electrode-array. Therefore, preoperative delineation of the extent of fibrosis/and ossification is of great importance as it may change the technique of implantation according to the degree of involvement of each cochlear ramp and to the extension of the ossification along the cochlear tube:

- if ossification occludes the round window or extends 8-10 mm into the inferior segment of the

basal turn, the ossification can be successfully drilled out and the electrode array inserted by an antero-inferior basal turn fenestration;

- if ossification extends more than 10 mm into the inferior segment of the basal turn, the electrode array may be inserted in the scala vestibuli through the oval window niche if still patent (Fig. 13);
- if the labyrinth is completely ossified, other techniques such as multiple cochleostomies may be performed. A special cochlear implant receiver designed for complete cochlear obstruction with eight-separated electrodes wires may be used, each electrode being inserted by separated drilled holes thanks to a *trans*-promontory approach around the modiolus. If the scala vestibuli is still patent, the electrode array may be inserted within.

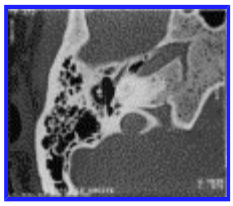

Fig. 13. Post-bacterial labyrinthine calcification. HRCT passing through the basal turn show large ossification of the round window niche. Well-aerated round window niche.

6.2. Cochlear otosclerosis

Diagnosis of cochlear otosclerosis may be overlooked and only diagnosed at the time of evaluation of a cochlear implant candidate. Otospongiotic foci compromise insertion of a cochlear implant if they occlude the round window niche. When the occlusion is limited to the round window and if the basal turn is still patent, the electrode array may be successfully implanted after drilling of the round window (Fig. 9) [11].

6.3. Post-traumatic hearing loss

Trauma is a rare cause of cochlear ossification. The labyrinthine abnormalities are maximum adjacent to the temporal bone fracture pathway. For certain institutions, severe disruptive fracture in both cochlear regions are absolute contraindications [10] but our experience is different. Remaining membranous fluid patency allows cochlear implantation after drilling of the stenotic area (Fig. 14). Brain MR imaging should rule out patients with sequelae of traumatic injuries to the brainstem who probably are of bad prognosis for implantation.

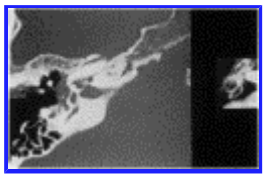

Fig. 14. Labyrinthine trauma. HRCT shows a fracture line passing through the cochlear apex and the mesial cochlear turn.

6.4. Cochlear malformations

6.4.1. Enlarged vestibular aqueduct

The most frequent malformation discovered in adult cochlear implant candidates is an enlarged vestibular aqueduct (EVA). EVA is not a contraindication for implantation even if the risk to gush is increased. EVA is a genetic disease, presenting an autosomic recessive inheritance. MR may guide

the choice on which side to implant in delineating the extra-osseous part of the sac and its degree of dilatation (Fig. 8). This malformation, bilateral in 90% of cases, is associated in almost 50-70% with cochlear anomalies. This congenital anomaly may be uni- or bilateral. Hearing loss may progressively appear. Even if enlarged vestibular aqueducts are thought to be associated with an increase chance of an intraoperative `Gusher', this is not a contraindication to implantation. Imaging studies may determine the choice of the side to operate if the dilatation of the vestibular aqueduct is unilateral or asymmetric [12].

6.4.2. Cochlear dysplasia

Cochlear development arrests induce morphologic anomalies of the cochlea, displayed by both CT and MR:

- Cystic cochlea (interruption of normal cochlear development during the 5th/6th weeks of fetal life) and incomplete cochlear partition (non-separated scala chambers, 7th week of life). Cystic cochlea is defined by coexistence of a normal basal turn with dilated middle and apical turns forming a common cavity structure. Incomplete partition may coexist with asymmetric scalar chamber and with a deficient or absent modiolus (Fig. 15). These cochleas will certainly gush when implanted, but do not contraindicate implantation as some of these patients have been implanted successfully.
- Single cavity (5th-6th week of life). True Mondini malformation (dilatation of the basal turn) may benefit of implantation.
- Inner ear aplasia (before the 4th week of gestation) (Michel's anomaly) is a contraindication to cochlear implantation (Fig. 16).
- Others: slight cochlear dysplasia may be difficult to diagnose such as a focal absence of scala intermedia or a decrease of height of the cochlea.

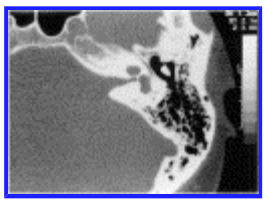

Fig. 15. Cochlear dysplasia. CT shows an incomplete cochlear partition between apical and middle turns. The apex of the cochlea forms a common cavity. Narrow modiolus (arrowhead).

Fig. 16. Inner ear aplasia. HRCT shows the absence of the petrous apex, of the cochlea and of the IAM. Well-developed middle ear. No oval fossa and no stapes. Direct connection between the long process of the incus (arrow) and the promontory. Below the incus, presence of a short tubular canal probably due to the course of the facial nerve.

6.4.3. Anomalies of cochlear nerve

Cochlear nerve is well displayed by sagittal or oblique sagittal HR MR T2 gradient-echo sequence of the IAM. Its dimension should always be determined in reference to the controlateral cochlear nerve and to the facial nerve. Congenital absence of cochlear nerve should be suspected when diameter of

the IAM is smaller than 2.5 mm (Fig. 17) [6]. Presence of a cochlea does not guarantee presence of a cochlear nerve as the development of these elements are independent. The absence of the cochlear nerve is an absolute contraindication of implantation. A wide range of abnormal inner ear are reported associated with narrow IAM: absence of modiolus, deformed cochlea or anomalies of the vestibular system, absent cochlea [12,13].

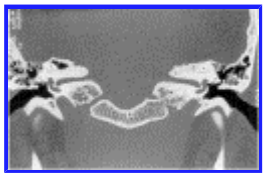

Fig. 17. HRCT shows a bilateral narrowing of the IAM.

Absence of the cochlear nerve occurs at the 5th week of gestation. It is due to a failure of development of the cochleo-vestibular nerve and connection with the inner ear meanwhile the facial nerve is normally developed [14]. A normally developed facial nerve explains that such patients if implanted have a facial response in answers to auditory stimuli.

Long-standing deafness may favour acquired cochlear nerve hypoplasia which coexists with normal size of the IAM.

6.4.4. Brain

Brain anomalies can be discovered on MR evaluation of cochlear implant candidates and can explain the wide variation of performance across individual cochlear implant users. Therefore, brain T2 SE sequences should always be included in the protocol study. Functional imaging of the brain might probably be applied to investigate the ability of the implant to activate the central auditory system. Congenital, post-traumatic or post-ischemic brain abnormalities located on the acoustic pathways are signs of bad prognosis. In children and young adults, mitochondrial disorders should be suspected in presence of severe brain atrophy and hyperintensities on T2WI in the globus pallidi (Fig. 18) [15].

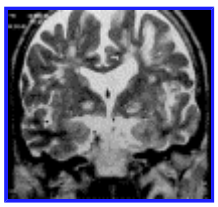

Fig. 18. Mitochondrial brain disorders. Coronal T2WI shows bilateral hyperintensities of the globus pallidi and cystic dilatation of the Wirshow-Robin spaces.

6.4.5. Incidental anomalies

Some abnormalities may complicate the surgical approach of a cochlear implantation such as exposed jugular bulb, aberrant or lateral carotid artery, persistent stapedial artery, dehiscent facial nerve, hypoplastic mastoid cells and chronic otitis media [4]. Facial nerve injury is a rare event in cochlear implant surgery [7]. Exposed or aberrant curse of the facial nerve explain postoperative facial injury reported by House as the heat produced by drilling the round window may be transferred to the facial nerve. Exposed facial nerve is encountered approximately in 50% patients with dehiscent tympanic portion not covered by bone or with dehiscent geniculate ganglion. Too anteriorly positioned mastoid portion of the facial nerve can complicate the transfacial recess approach procedure facilitating the transmission of heat of drilling. Facial monitoring during surgery avoid this complication.

Furthermore, CT may demonstrate labyrinthine bone abnormalities: such as Paget (Fig. 19), otosclerosis (Fig. 9), postmeningitic stenosis of the round window niche. All these bone anomalies may cause difficulties for drilling the round window niche and for introducing the electrode array. Both CT and MR have a role for delineating extension of the bone anomaly and the patency of the membranous labyrinth behind.

Fig. 19. Paget disease. HRCT shows an extreme bone demineralisation of the petrous apex, of the IAM and of the otic capsule.

7. Post surgical follow-up

7.1. Electrode position

Postoperative radiographic documentation may be necessary to underline the position of the implanted electrode and to assess the implant's function. Position of the electrodes can be helpful in setting work parameters. Some teams are working for a better adjusting of the frequency bands of electrodes to increase speech recognition. However, audiometric testings detect better than radiographic evaluation failure of a cochlear implant. Radiographic evaluation ensure intracochlear position, detect electrode kinking and may serve as a reference. Plain X-ray films (profile and modified Stenvers's views) suffice to depict the pathway of the whole electrode array (Fig. 20) [16]. To appreciate surgical insertion depth, a vertical line called VL1 parallel to the superior semi-circular canal is drawn. A second horizontal line passing by the basal turn and perpendicular to VL1 is drawn. Section of these two lines point to the level of the round window niche, the slots of the electrode array should not be lateral to this point. Spiral HRCT may help to depict the location of electrode array due to its capacity of multiplanar reconstructions (Fig. 21).

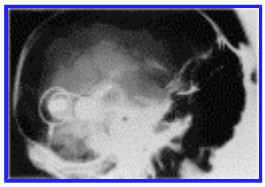

Fig. 20. Post cochlear implantation. Plain X-rays follow-up (profile) shows the implanted transmitter and receiver with their electrode array. Introduction of the electrode array within the basal turn by the round window niche. MP reconstructed plane sternvers showing the pathway of the electrode array and the length of cochlear penetration.

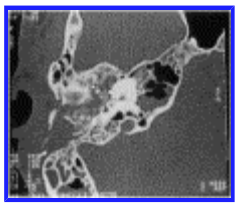

Fig. 21. Cochlear implant failure. HRCT shows kinking of the electrode array in an obliterated middle ear.

7.2. Complications

The rate of complications of cochlear implants procedure is less than 5%. Rarely, the labyrinthine portion of the facial nerve may be stimulated by the electrode inducing facial twitching. The most frequent complications are: device failure, extrusion of the electrode and middle ear inflammation (Figs. 21 and 22). If, from auditory responses, a misplacement or extrusion of an electrode is suspected, both plain X-rays and CT are performed.

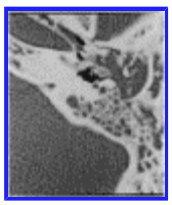

Fig. 22. Failure of cochlear implantation. HRCT shows calcification of the basal turn after removal of the cochlear implant. Large calcifications into the middle ear and the obliteration of the middle ear.

7.3. Life-duration of the electrode

This is not previsible. About 95% of cochlear implants are still functioning after 9 years.

7.4. MR

Cochlear implants are a contraindication for MRI because they are electronically activated and have a magnet [17,18]. However, recent works [19] tended to demonstrate that MR exam did not alter function of certain cochlear implant or displace a well-positioned cochlear implant when performed at IT Unit. However, this contraindication persists due to the danger of heating or of exciting currents with adverse nerve-effects. In any case, susceptibility artefacts induced by the implant are so important that it completely blurs the posterior fossa. Therefore, MR cannot be used in case of failure of the implanted device. This should encourage manufacturers to develop cochlear implant devices with an external part that can be easily removed and with an electrode-array without ferromagnetic components (i.e. tantalum, titanium, platinum, etc.) and performed with a nonmagnetic-effect shape [20].

8. Brainstem cochlear implants

Work on Auditory brainstem implants (ABI) began in 1979 and is still under investigation. Brainstem cochlear implants are intended for patients who have lost the function of cochlear nerves bilaterally. Its use is limited to patients with bilateral acoustic tumours. Its indications mostly concern NF2 patients. More than 160 ABI have been inserted worldwide. The electrode array is inserted deep in the lateral recess of the fourth ventricle in the area of the cochlear nuclei by a *trans*-labyrinthine approach (Fig. 23). The components of the ABI electrode are similar to those of cochlear implant electrodes [21]. They consist of eight-electrodes disks placed on a silastic base. Known contraindications of ABI are:

- widened lateral recess, which can be at the origin of an unstable position of the electrode;
- sequelae of infarction of the cochlear nuclei (Fig. 24);
- radiation injury to the brain stem after gammaknife or stereotactic irradiation of acoustic neuroma.

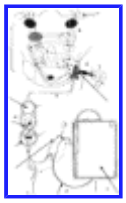

Fig. 23. Diagram of an ABI: (1) microphone; (2) connections between microphone and external speech processor; (3) external speech processor; (4) transmitter (receiver/stimulator coupled across the skin), (5) electrode array; (6) acoustico-vestibular nerve; (7) cochlea; (8) cochlear nuclei; (9) bilateral transmission of the excitation to auditory cortex by the lemnicus lateral.

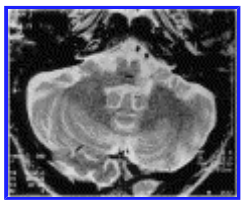

Fig. 24. Brain T2WI left lateropontine ischemia (arrowhead) with large lateral recessus.

Sequelae of meningitis lead to excessive bleeding and increase surgical difficulties. Brainstem cochlear implants may induce side effects such as facial twitching (excitation of the facial nuclei). Postoperatively, position of the electrode may be detected by MR. Patients with nonmagnetic integrated cochlear implant are able to undergo MR studies if the superficial magnet is surgically removed. Gradient echo better than spin echo images depict the location of the electrode due to their magnetic susceptibility [21,22].

Models of brainstem cochlear implant's implanted before 1993 are not MRI compatible and should be controlled by CT. Thin sections, reversed image, edge enhancement algorithm may diminish artefacts on CT.

9. Totally integrated cochlear amplifier

It is a new hearing system implanted into the temporal bone to rehabilitate patients with severe hearing loss, It was developed to improve a better auditory rehabilitation. Complete removal of the mastoid cells is necessary to create a cavity for the implant [23]. Axial high resolution computed tomography (CT) with multiplanar reformatting should be performed to appreciate difficulties in creating a mastoid neocavity and in order to rule out anatomic variations of the temporal bone leading to complications. A 3-D virtual reality may contribute to a proper presurgical evaluation. TICA has three components—the first one implanted subcutaneously behind the auricle, including a digitally programmed three channels audio processors and a rechargeable battery; the second one, a microphone implanted into the posterior part of the auditory canal; and the third one or transducer implanted into the mastoid cavity. Its tip is connected to the incus. Imaging studies should appreciate the incus, the aeration of the middle ear and the variations of size and aeration of the mastoid cells. A 3-D reformatted images may be of contributive help. A particular attention should be underlined on presence of a mastoid emissary vein.

10. Conclusion

In conclusion, cochlear implants are now a well-accepted treatment of profound and severe deafness. Imaging studies are a part of the candidate evaluation. Both CT and MR should be used as they delineate in different manners cochlear and middle ear anatomy, look for labyrinthine ossification

and malformations. Imaging studies may orient and modify surgical strategy. Brainstem cochlear implant is a new procedure at present still reserved for NeuroFibromatosis type 2 patients. If the rate of surgical complications does not increase with this procedure, it probably will be considered for other indications such as sensorineural hearing loss due to bilateral labyrinthine ossification or to severe cochlear malformations. Functional MRI is a new way for testing candidates of cochlear implantation.

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