Cochlear implants (CIs) represent one of the most important achievements of modern medicine as, for the first time in history, an electronic device is able to restore a lost sense – hearing. More than 150,000 people worldwide have been implanted so far, and this number is increasing steadily despite the related cost [10].

The selection of candidates for cochlear implantation requires consideration of a variety of clinical and radiographic factors. The present article reviews the current knowledge regarding the preoperative imaging of CI candidates and explores emerging developments in different imaging modalities. Preoperative radiologic assessment should evaluate the status of the middle/inner ear, auditory nerve and central acoustic pathways. Preoperative computed tomography displays anatomic middle ear variations of surgical importance. MRI can demonstrate fluid/obliteration in the inner ear and depict the retrocochlear auditory pathways. Dual modality imaging with high-resolution computed tomography and MRI of the petrous bone and brain can provide the maximum information regarding surgical landmarks and detect deafness-related abnormalities. Cost–effectiveness issues also justify its use. New systems are now becoming available, offering improved soft-tissue delineation, sophisticated segmentation techniques, volumetric measurements, semitransparent views and superior surface resolution, thus significantly advancing our diagnostic acumen and making the preoperative evaluation of CI candidates more accurate and reliable.

**Keywords:** auditory • central • cochlear implant • CT • imaging • MRI • obliteration • tomography

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The selection of candidates for cochlear implantation requires consideration of a variety of clinical and radiographic factors [1]. Therefore, preoperative imaging of the temporal bone is accepted as standard of care [2], as it can demonstrate anatomic details relevant to surgical management, which may be essential in the presurgical evaluation of patients receiving CIs [3].

Preoperative recognition of anomalies gives the surgeon the opportunity to implant the most appropriate ear, plan a variation in surgical technique, select special electrode arrays and ensure that the expectations of the recipient and the family are appropriate [4]. In addition, the criteria for cochlear implantation have expanded and this procedure is now being performed in ears with residual hearing, severe congenital abnormalities, syndromes and other challenging pathologies [5,6].

The aim of the present article is to review the current knowledge regarding preoperative imaging of CI candidates, taking into account the related advantages and drawbacks of the various techniques employed. In addition, emerging developments involving different imaging modalities will also be explored.

**Materials & methods**

An extensive search of the literature was performed in Medline and other available database sources from 1982 to March 2009, having as a primary end point the critical assessment of the imaging techniques employed in the preoperative evaluation of CI candidates. Using an initial framework
of results, two secondary categories of outcomes were also analyzed: the current state-of-the-art imaging in cochlear implantation and the emerging imaging modalities that are becoming increasingly important with regard to preoperative CI assessment. During the search, the keywords 'cochlear implants', 'imaging', 'CT', 'MRI', 'new', 'surgery', 'pediatric' and 'adult' were utilized. The keywords 'cochlear implants' and 'imaging' were considered primary and were either combined with each of the other keywords individually or used in groups of three. In addition, reference lists from the retrieved articles were searched manually. Information from electronic links and related books was also included in the analysis of data. However, electronic links not relating to formally indexed journals were only cited in the text.

Results
One meta-analysis, seven prospective controlled studies, two retrospective controlled studies, 27 prospective studies, 23 retrospective studies, 12 ex vivo models, one theoretical model, nine systematic reviews, four case reports and two books met the defined criteria and were included in study selection.

Discussion
The consideration of cochlear implantation necessitates a wide selection process, for which imaging of the ear and the auditory pathway is very important [7]. This importance relies on the fact that any structural or functional disorder may hinder the signal from reaching the auditory cortex.

The first assessment involves the temporal bone and especially cochlear patency, which is considered crucial. Indeed, postoperative auditory perception is related to electrode insertion depth [8], whereas anatomic anomalies may represent issues of concern with regard to optimal postimplantation audiologic outcomes.

In pediatric candidates, the situation is even more complex, as up to 20% of congenitally deaf children have inner ear anomalies that impede the full insertion of the CI array [9,9]. Therefore, preoperative radiological assessment should be able to assess the status of the inner ear and the auditory pathways, as well as potential middle ear anomalies. Congenital aplasias of the cochlea or cochlear nerve are usually considered as absolute contraindications for implant surgery, whereas cochlear implantation is feasible in children with less serious inner ear malformations [10]. It is interesting to note that even the diagnosis of cochlear nerve aplasia per se (with the use of MRI techniques) might not reflect what actually happens in the single nerve that is located in the internal auditory canal. Although this nerve is always supposed to be the facial nerve, the possibility of this nerve containing fibers of the facial nerve, vestibular nerves and cochlear nerve cannot be excluded. Cochlear implantation in some of these cases has resulted in auditory sensation, although the functional outcomes are rather limited or at least inferior to other pediatric implantees [11,12].

Irrespective of the etiology of pediatric deafness, a thorough preoperative radiologic assessment should also reveal any disorders in the central auditory pathways (brainstem, cortex), either congenital or secondary to other diseases (e.g., hydrocephalus). Communication with the CI team can subsequently confirm whether or not cochlear implantation is still appropriate and help to obtain a more informed prognosis.

With regard to acquired pediatric deafness, meningitis is undoubtedly recognized as the most common cause, associated not only with cochlear damage but also with additional disorders. The latter are not usually a contraindication to implant surgery, provided that the level of parental expectation is appropriate. However, the ensuing suppuration of the inner ear may cause a variable degree of fibrosis in the perilymphatic space, which in turn may progress to soft-tissue obliteration and ossification. This may have important implications for implant surgery, as optimal positioning of a multichannel implant includes insertion well into the second turn of the scala tympani. This task may prove extremely difficult (or even impossible) if the lumen is occluded. Various surgical techniques have been used to bypass the problem in cases of complete obliteration. However, the outcomes can vary and are often inferior. Therefore, if the degree of cochlear obliteration is assessed radiologically before the operation, the surgeon can choose the ear with less obliteration, and be prepared for the possibility of a difficult or suboptimal positioning. Moreover, repeated assessments to determine the rate of cochlear obliteration in postmeningitic children may indicate the need for intervening earlier, thus reducing the number of candidates with bilateral complete obliteration or ossification.

With regard to adult candidates, cochlear patency can decrease as a result of several middle ear disorders, including severe otosclerosis, disruptive temporal bone fractures and prior surgery [13]. The possibility of retrocochlear pathologies (i.e., acoustic neuroma) should also be investigated in adult patients.

The beginning: the era of polytomography
Historically, CI candidates were assessed radiologically with the use of polytomography [14,15]. Polytomographic techniques were initially able to assess, to a certain extent, cochlear patency or specific inner ear deformities [15–17]. However, the fact that the imaging plane usually included the orbital lenses, along with the advent of computed tomography (CT) imaging techniques that offered greater contrast resolution, gradually resulted in the disappearance of polytomography as a method of preoperative evaluation in cochlear implantation [18,19].

CT scans
CT scanning eventually replaced polytomography and became a very important part of the preoperative assessment for cochlear implantation, as its results may have a significant effect on the decision to implant, the side of implantation and potential procedure modifications [20–22], and can provide a preoperative picture of normal variants and avoidable surgical pitfalls (Figure 1) [1].

The current generation of scanners offers a resolution of approximately 0.5 × 0.5 mm in-plane and 0.5–1.0 mm in the direction of the z-axis [23]; the smallest discernible volume element in this resolution is called a voxel.

The addition of more and thinner sections to the detector subsystem, combined with the change from a parallel-beam to a cone-beam reconstruction, have decreased scanning time and
concomitantly increased spatial resolution [23,24]. Hence, the information provided by the CT scan may be used to inform surgeons and contribute to realistic expectations in cases where the possibility of a successful cochlear implantation is limited (e.g., total oblitative labyrinthine ossification, severe congenital cochlear malformations and extensive cochlear otosclerosis) [1].

With regard to cochlear ossification, a multicenter retrospective analysis revealed that the accuracy of high-resolution CT (HRCT) in predicting that specific condition was 94.6%, with 100% specificity and 71% sensitivity; meningitis proved to be the leading cause of cochlear ossification (44%) [25]. However, there seems to be a significant variation in the reported reliability of the CT scanning in various studies, which is partially attributed to the fact that there are fundamentally different categories of implant candidates. In addition, the CT scan techniques utilized may also be different, whereas CT scan results in the vast majority of studies are only expressed in terms of sensitivity and specificity, although predictive values may be more suitable for establishing the usefulness of diagnostic procedures.

Moreover, cochlear obliteration following meningitis may be fibrous in the outset or even very limited, and is most frequently misinterpreted as normal on the CT scan. Narrowing of the basal turn of the cochlea, which represents the most limited form of labyrinthine ossification, may prevent complete insertion of the electrode array into the scala tympani [26]. By selecting different scanning planes, clinicians can obtain more accurate information. Indeed, a study by Bettman et al. suggested that the predictability of cochlear obstruction using CT scans can improve significantly if the available information from axial and semilongitudinal planes is taken into account [13]. Theoretically, the semilongitudinal CT plane has the advantage of an excellent visualization of the basal and second turns of the cochlea. In addition, the analysis of coronal images may reduce the volume averaging effect at the top or bottom of the basal turn of the cochlea, which may erroneously suggest cochlear stenosis in axial images [26]. The condition of the lateral semicircular canal may also be a reliable predictor of the degree of cochlear ossification in postmeningitic patients [27]. Attention to subtle otological abnormalities, which may be demonstrated on the CT scan, can also prove helpful in the prediction of early success or failure of implantation in that category of patients. Such abnormalities may be associated with as high as 90% risk of incomplete or difficult insertions, and 70% risk of limited cochlear insertion [26]. In any case, otologists may find some degree of bony obstruction within the basal turn of the cochlea even when the CT scan is normal [28]. The pitfall in misinterpretations regarding cochlear patency is that the inexperienced surgeon may find him/herself unexpectedly drilling out a partially or totally obliterated cochlea [9].

The conversion of CT images into a rotating CT movie may prove useful for the intuitive understanding of the position and degree of ossification in the cochlea, and for reducing any associated human error [29]. This innovative imaging technique employs multiplanar reformation of 0.5-mm thin CT slices, and processing of the images using QuickTime Pro™ software. The perceived advantage of the CT movie over sequential CT films is the ability to comprehend the 3D spaces in the cochlea. Indeed, it seems reasonable that the human brain can reconstruct 3D images more efficiently by watching a rotating movie, rather than viewing a large number of sequential static films. A preliminary report suggested that the extent of the ossified region on the CT movie corresponded to the intraoperative findings in all tested patients, thus facilitating the clinician to plan a full insertion of the electrode array into the ossified cochlea [29].

Various temporal bone abnormalities are not uncommon in the population undergoing cochlear implantation and high-resolution temporal bone CT scanning is essential in their preoperative evaluation. In cases of congenital bony malformations, temporal bone fractures or suspected middle ear disease, detailed imaging of the bony structures is usually required (Figure 2) [14]. In a study by Mueller et al., abnormalities had been identified in 12 of the 24 ears examined. The additional information had strongly influenced the selection of the ear to be implanted in two patients, whereas information that was considered useful for preoperative planning had been provided in four additional cases [30]. This very high percentage (50% of the examined ears) confirms the substantial contribution of a preoperative CT scan in cochlear implantation.
Results from different studies indicate that the concordance of CT scan interpretations with surgical findings is partially related to the etiology of hearing loss, and the experience of the surgeon and the neuroradiologist [3,31]. Hence, the CT scan should be interpreted with adequate knowledge of the operative procedure in order to evaluate any possible barriers to the insertion of the internal components of the system [30].

In addition, limitations inherent to this imaging technique should be taken into account. A customary slice thickness of 1–1.5 mm is wider than the intracochlear structures. Hence, despite the advances in CT scanning technology, a number of important anatomic structures are still below the resolution limit. Consequently, the resolution obtained is relatively poor and the structures appear either blurred (due to the partial volume effect) or are not seen at all [32]. Occasionally, it may also be hard to assess the intracochlear fluid on printed film owing to slight differences in the attenuation coefficient between fluid and soft tissue. With regard to congenital anomalies, the CT scan is unable to identify congenital aplasia of the cochlear nerve as it can only image the internal auditory canal (IAC) and not the nerve bundles. Therefore, if the IAC has normal size but no nerves, the CT scan will be normal [14]. However, if the dimensions of the IAC, as measured by CT, are less than 1.4 mm in diameter, the possibility of cochlear nerve abnormality is considerable. By contrast, if the IAC is wider than 3.0 mm, other anomalies may coexist and the risk of cerebrospinal fluid gusher during implantation should be carefully considered [33,34].

It is interesting to note that during preoperative planning, the surgeon should be aware that the anatomic structures that are measured in the CT scan are magnified by approximately 5% compared with their original dimensions. This feature seems to be an inherent characteristic of CT imaging, presumably attributable to the computing of connective tissue adjacent to the bone and the inability of CT to demonstrate structures of different density in the same voxel. However, this difference, does not seem to have any operative consequences when performing a cochleostomy, as the respective deviation is less than a tenth of a millimeter [35].

Although conventional 2D imaging has been used extensively to depict the individual structures of the temporal bone, the complex multispacial orientation of these structures often makes it difficult to appreciate their 3D orientation and complicated inter-relationships [36]. In addition, because of the anisometric voxels, which are inherent to the multislice CT technique, the appearance of the structures depends very much on the scan plane. The use of digital flat-panel detectors may provide isometric voxel imaging that can render image quality essentially independent of the cut plane.
In order for 3D rendering of the middle and inner ear to be accurate, thin 2D sections should be scanned using special reconstruction software, which can allow enhancement of the bony details and improved spatial resolution. The temporal bone microanatomy, potential subtle bone fractures or erosions, ossifications and intraosseous pathology can, therefore, be identified [44].

Postprocessing of the 2D images can be performed using either surface or volume rendering. Surface rendering was used initially in radiologic studies in order to reconstruct the external anatomy of the temporal bone, and enable visualization of its relevant landmarks and adjacent structures from different angles [42]. Volume-rendered 3D views, on the other hand, have the advantage over the previously described surface techniques of demonstrating internal structures, such as the labyrinth [42,45–47]. These images can be rotated in space and dissected in any plane, thus permitting a multiprojectional display of the various temporal bone structures. The ability to reformat these images rapidly and manipulate their spatial orientation, enables a more thorough evaluation of congenital anomalies, such as the classic funnel-shaped deformity of the dilated vestibular aqueduct. The course of the facial nerve within the temporal bone can also be depicted. In addition, volume rendering can be combined with special surface-shaded displaying techniques and the resulting hybrid-rendered imaging method can allow a virtual endoscopic depiction of inner ear architecture [43].

However, it should be mentioned that an ideal 2D data acquisition plane for obtaining 3D and virtual reconstructions does not exist. The axial planigraphic plane is usually preferred, although structures such as the superior and posterior semicircular canals, or the mastoid segment of the facial nerve and the vestibular aqueduct, would probably be shown more easily with sagittal or coronal projection data. The routine low-dosage protocol, which is used in the acquisition of 2D data, ensures that the patient is not exposed to any additional irradiation and that the datasets meet the current radiologic status in a clinical environment.

Even though the ultimate aim of 3D reconstructions of the middle and inner ear structures from CT data is to enable detailed analysis of an individual patient’s anatomy in routine clinical work, they are still used as a complementary investigation to conventional 2D temporal bone imaging. The reasons for this are the well-recognized limitations of 3D reformations, which include bone depletion artifacts (pseudoforamina) and misregistration (motion). Furthermore, their value in further defining temporal bone morphology should be weighed against the additional cost entailed by their use [47], as the reconstruction procedure is considered time-consuming and the related computational means may not be always widely available [42].

In conjunction with advanced rendering algorithms and powerful workstations, the rapid manipulation of imaging data sets, along with improvement in the postprocessing quality of 3D visualization methods, can provide a more detailed morphometric analysis of the middle and inner ear, which in turn may prove invaluable during individual preoperative planning in CI surgery [42,43].

**Magnetic resonance imaging protocols**

MRI is the study of choice for imaging evaluation of the membranous labyrinth [48]. Unlike CT scans, it is able to demonstrate the fluid in the inner ear [48,49], a property that is very important in postmeningitic implant candidates (as discussed earlier). Moreover, MRI is, by definition, better in the imaging of retrocochlear auditory pathways and the cortex [14]. It produces images of the cochleovestibular nerves and can identify central brain lesions and potential congenital abnormalities (Figure 3) [2,14].

The depiction of inner ear structures in MRI scans depends very much on certain technical characteristics of the examination, such as the T1 (longitudinal) and T2 (transverse) relaxation times of the magnetic field, the repetition (TR) and echoing (TE) times of the administered radiofrequency (RF) pulses, and the type of coil that is used to obtain the magnetic images. The TE represents the time between the application of the RF pulse and the peak of the obtained echo signal, whereas the TR is delineated by the initiation of the first RF pulse, which is then repeated at a given time. Variations of the TR value may significantly influence image contrast. Hence, short TR and TE times can produce T1-weighted images, which have the advantages of enhanced image brightness and contrast that are essential for depicting detailed

![Figure 3. Coronal MRI projection depicting agenesis/hypoplasia of the left cochlear nerve (arrow).](image-url)
anatomical structures [48], while decreasing the overall scanning time. Gadolinium- (Gd-) contrast enhancement can make these sequences quite valuable in revealing pathology within the IAC, as well as in the labyrinth. T2-weighted images, on the other hand, are very useful in demonstrating inner ear pathologies, as they are considered less susceptible to magnetic field inhomogeneities owing to their long TR and TE times, at the expense of the overall scanning time and potential motion artifacts. Sagittal or oblique-sagittal T2 sequences are especially helpful in delineating the cochlear nerve in the IAC and comparing its dimensions with the contralateral cochlear or the facial nerve [50]. Congenital absence of the cochlear nerve should be suspected when the diameter of the IAC is less than 2.5 mm [51], whereas a nerve that is smaller in diameter than that of the facial nerve should be considered deficient (Figure 4) [4].

Standard MRI protocols also include brain sequences in addition to focused inner ear images. Brain anomalies can be discovered on magnetic resonance (MR) evaluation of CI candidates, and may explain, to a certain extent, the wide variation of performance across individual CI recipients. Brain T2 spin-echo sequences can reveal congenital, post-traumatic or post ischemic brain abnormalities, which may affect the acoustic pathways. Although routine 2D techniques provide sections not less than 2 mm thick, they are considered quite practical as they are less time consuming. Volume visualization techniques, such as the maximum intensity projection (MIP) algorithm, as well as surface and volume rendering reconstruction, may provide additional imaging data that can be used for better interpretation of traditional 2D MR images [48].

Although imaging methods to visualize inner ear structures have been in continuous development over the past decade, several malformations are difficult to assess on CT or planar MRI images, thus limiting the overall reliability of the planar source images [52]. The major advantage of 3D imaging is the ability to acquire data with approximately isotropic resolution. This allows multiplanar reformatting, which simplifies imaging protocols and reduces measurement time when imaging in multiple planes is required [53]. Although, in principle, isotropic resolution can be achieved with 2D sequences, this requires long RF pulse lengths that increase imaging time [54].

Maximum intensity projection had been the method of choice for 3D reconstruction until recently, as the images obtained provided more detail, compared with conventional HRCT of the temporal bone or 2D MR images [55–69]. However, MIP has demonstrated partial volume artifacts, some restraint in the rotation of the voxel of interest and relatively poor spatial resolution.

Surface rendering, despite its ability for detailed 3D reconstruction, may not be very helpful in cochlear implantation, as the interior structure of each element in the inner ear is not visible following its mode of operation.

By contrast, volume rendering (VR) can provide comprehensive spatial information, especially on small and complex structures, such as the inner ear. When compared with MIP, the ability of rotating each voxel without restriction may allow fast and direct 3D visualization of the area of interest, which has become increasingly important as we move towards higher resolution at a smaller field-of-view [70].

3D T2-weighted turbo spin-echo and contrast-enhanced 3D T1-weighted gradient-echo sequences enable significantly better visualization of the anatomic structures in the cerebellopontine angle, and provide more detailed information about the inner ear than 2D sequences [58]. Indeed, MIP images of the 3D T2-weighted turbo spin-echo sequence are very useful in evaluating the membranous labyrinth [58]. They can also enable excellent anatomic depiction of the IAC, even though they often demonstrate difficulties in differentiating vessel loops from nerves in the cerebellopontine angle because of their similar low signal intensity. 3D T1-weighted gradient-echo sequences, on the other hand, enable flow-related enhancement of these vessels, providing higher signal intensity compared with nerve structures. They can also achieve more accurate identification of the four nerves in the IAC compared with 2D sequences owing to the better spatial resolution provided by their thinner sections [58].

Numerous studies have also demonstrated the excellent performance of 3D VR images of the constructive interference

Figure 4. Single nerve (arrow) in the internal auditory meatus (circle). Please note the appearance of the normal internal auditory meatus in the upper right quadrant.
in steady state (CISS) sequence in depicting subtle pathologic changes of the inner ear, including those of the posterior labyrinth, internal auditory meatus and cerebellopontine angle (Figure 5) [12,60,61,64,65,71]. This is because 3D CISS results in a better contrast-to-noise ratio compared with other 3D sequences (i.e., fast spin-echo employing techniques) [70]. Hence, it can provide better nerve definition, particularly in patients with small IACs and potentially deficient cochlear nerves. Cochlear nerve deficiency, as discussed earlier, is not an absolute contraindication for cochlear implantation; however, its preoperative recognition may significantly influence the choice of the ear to be implanted and/or alter patient (or parental) expectations regarding the outcome of the operation. The increased contrast-to-noise ratio in 3D VR CISS images can avoid potential misinterpretations of the anatomy of the posterior labyrinth, which may occur owing to a loss in signal intensity and enable a more reliable depiction of the facial nerve canal [70].

When 3D CISS is applied in MR cisternography imaging, caution in assessing the cochlear patency in CI candidates is warranted, as susceptibility artefacts may be seen in the semicircular canals, and the area of the round and oval windows. Such artefacts may be misinterpreted as deformities of the vestibule, especially near the oval window [72]. The application of multidirectional phase cycling techniques, such as the segment-interleaved motion-compensated acquisition in steady state (SIMCAST), may help to reduce these artefacts, although it may significantly lengthen scan time [73].

Magnetic resonance cisternography has been used in the presurgical assessment of the perilymphatic space patency in CI candidates and the evaluation of potential inner ear malformations [72]. The clinical utility of MR cisternography in visualizing the IAC structure is also well established. The technique ensures excellent (or at least good) visualization of the vestibulocochlear nerve, using heavily T2-weighted images acquired by 3D fast spin-echo sequences [74]. Another advantage of this method is the ability to obtain MIP, which may prove additionally useful in the evaluation of the complex structure of the inner ear. With the use of a long echo train length and a half Fourier transformation technique, 3D fast spin echo cisternography allows significant time reduction and high spatial resolution in MR inner ear studies at an acceptably lower signal-to-noise ratio (SNR) [74].

While MR cisternography visualizes mainly the morphological anatomy of fluid-filled organs, 3D fluid attenuated inversion recovery allows the assessment of subtle alterations in the inner ear fluid composition, and is able to detect perilymph enhancement while suppressing the signal from the endolymph. With the relatively recent development of 3-T scanners and fast imaging protocols, such as Sampling Perfection with Application Optimized Contrasts Using Different Flip Angle Evolutions (SPACE), 3D fluid attenuated inversion recovery (of a thickness of <1 mm) has not only become clinically feasible [72,75], but also more sensitive than T1-weighted images (such as the T1 Volume Interpolated Breath-Hold Examination [VIBE]) in detecting subtle compositional changes of the lymph fluids [76].

Disadvantages of 3D reconstruction include a degree of image blurring, in order to achieve heavily T2-weighted images in a relatively short period of time, along with banding and motion artifacts [70]. Another important technical note is the use of a head versus a surface coil for evaluation of the inner ear structures. Although surface coils can produce high-resolution images of the labyrinth, they demonstrate a significant drop in the signal from the deeper regions compared with ones closer to the coil. This can result in loss of contrast between various structures. Conversely, not only can the use of a head coil provide uniform inherent contrast between various tissues, it can also demonstrate identical structures in the contralateral ear for comparison [48]. The addition of more channels to the coil can also improve the SNR, provided that the other scan parameters remain the same. Indeed, a 32-channel head coil can obtain as much as 50% higher SNR in the vicinity of the inner ear, compared with a conventional 12-channel one. That means, in effect, that we can obtain either similar quality images in less than half the scan time, or increased spatial resolution, which can allow 3D VR of the perilymphatic space [72].

Figure 5. 3D MRI of the constructive interference in steady state sequence (right cochlea).
Expert commentary: the dual modality approach

High-resolution CT and MRI scans have been employed separately as primary preoperative imaging modalities in cochlear implantation in order to reduce the bulk of preoperative examinations, as well as associated costs in money and resources, and discomfort for CI candidates [31,77]. The perceived advantage of using CT scanning as the preoperative investigation of choice is that it may display anatomic middle ear variations of surgical importance, such as the bony borders of a malformed labyrinth, a low lying roof, a high jugular bulb or an aberrant carotid artery (Figure 6) [50,55]. This information can be important for the surgeon in order to analyze the direction of insertion of the cochlear array preoperatively, thus minimizing the risk of misplacement or intraoperative injuries [55]. Other aspects related to cochlear implantation in patients with cochlear anomalies are the site of cochleostomy, the electrode selection, placement and stability, and the increased likelihood of perilymph/cerebrospinal fluid leak [78]. The presence of an enlarged vestibular aqueduct, which may predispose to intraoperative gusher, can also be diagnosed with the use of HRCT [2]. Furthermore, the CT scan evaluates the status of mastoid pneumatization and identifies the potential presence of hypotympanic air cells, which might be mistaken for the round window niche and lead to surgical difficulties [55]. Implantation of the receiver also requires information about the thickness of the parietal bone [50,55]. The tympanic and descending portions of the facial nerve can also be visualized in the CT scan, and any related anomalies in the course of the facial canal can be identified (especially where significant abnormalities of the semicircular canals coexist) [2,4,50].

Figure 6. Aberrant carotid artery in the right middle ear (arrow).

However, HRCT cannot identify early labyrinthine obliteration or cochlear nerve anomalies in the IAC [2]. MRI is more sensitive and specific in detecting these abnormalities, and its findings are considered more likely to influence the implantation process [2,4]. Indeed, in the study of Parry et al. [4], 43% of pediatric implant candidates had at least one inner ear anomaly and 29% of them had asymmetric findings only identifiable on MRI scans, which had directed the surgeon towards the most normal ear. These anomalies included 12% of imaged cochlear nerves, with as many as 50% of patients with an abnormal cochlear nerve demonstrating asymmetric nerve findings [4].

MRI can additionally detect unsuspected acoustic nerve tumors, as well as central brain anomalies; the latter may coexist in up to 40% of pediatric CI candidates [2,4,50]. Modiolar or other deficiencies can also be more easily identified on MRI, thereby warning the surgeon of the possibility of a perilymph gusher [4].

Admittedly, MRI scan is not without its disadvantages; it often requires sedation or anesthesia, especially in pediatric implantees, with their attendant risks and costs. Good quality images may also be difficult to obtain in deaf adults, as communication difficulties may lead to motion artifacts [50]. The bony structures of the ear – a very important element in planning surgery – cannot be demonstrated in MRI images. MRI cannot evaluate conditions such as fibrous dysplasia or enlarged vestibular aqueduct syndrome (although the endolymphatic duct and sac are only imaged by MRI techniques), and is less successful in localizing the mastoid segment of the facial nerve [2,4] (even though the use of surface coils may significantly improve the anatomic depiction of the latter [48]).

It is, therefore, evident that dual modality imaging with HRCT and MRI of the petrous bone and brain can provide the maximum information to the operating surgeon with regard to surgical landmarks, and also detect abnormalities related to deafness, which would otherwise not be found using either modality alone [2]. However, cost–effectiveness issues should also be considered [4,55]. The overall cost of cochlear implantation in adults amounts to approximately £28,000 over a 12-year period (including follow-up and maintenance of the system) [14], and it reaches £49,000 in pediatric implantees [79]. Taking into account the high expenses of CIIs, the vulnerability of pediatric implant candidates, related parental expectations and individual circumstances in adult candidates, dual modality preoperative imaging may not only distinguish patients who will benefit most from implant surgery but will also help identifying surgically challenging cases or avoid unnecessary operations [55]. Hence, the related earnings in resources may prove substantial.

However, it should be noted that the dual modality approach does not represent the standard of care in all CI centers. As mentioned earlier, fiscal limitations, along with efforts to avoid the exposure of implant candidates (especially pediatric ones) to a significant dose of radiation, have resulted in the use of MRI scans for their initial evaluation. The rationale behind the single modality approach is that there is a reported concordance between the two imaging modalities regarding the abnormalities detected; therefore, the selective use of MRI within a diagnostic algorithm can be considered. The crux of such algorithms lies in filtering patients with risk factors for intraoperative complications into the dual imaging pathway [2].
Hence, HRCT is performed in cases of suspected anomalous course of the facial nerve, indications of significant bony abnormalities (i.e., craniofacial syndromes), CHARGE association, cochlear dysplasia or history of meningitis [2,4]. The ultimate aim of the single modality approach is to apply principles of cost–effectiveness successfully, without lowering the diagnostic yield afforded by the dual modality approach (gold standard).

Five-year view
Cochlear implantation represents the first successful attempt to restore, at least to some extent, a lost or absent human sense. Hence, it may be considered among the greatest clinical accomplishments of the 20th Century. The new millennium has witnessed medicine achieving even greater advances in cochlear implantation. However, related advances in imaging are necessary to transform this progress into everyday clinical practice. Nevertheless, the future looks more promising than ever, as new imaging techniques are continuously evolving.

Optical coherence tomography (OCT) is an imaging technique that provides optical cross-sections of tissue structures, which can be read analogous to B-scan sonography [80]. It is an interferometric method that uses the position of a reference mirror to determine the depth in the sample at which the magnitude of the probe light reflection is registered within the coherence length of the original light source. This generates an OCT A-scan. Scanning the sample beam along a transverse axis can be used to create a B-scan image, where the measured amplitude is converted into a logarithmic grayscale.

Two different systems are available; time-domain OCT and spectral-domain OCT. Spectral-domain OCT can be used more appropriately in otology, as it can reveal parts of the cochlear morphology without opening its enveloping membranes. This can be achieved with a specially adapted operating microscope, which exercises OCT scanning on any object in the center of the field of vision on which the microscope is focused. Hence, it is possible for the operating surgeon to know the anatomic site of the scalae/projection of the basilar membrane for the ‘correct’ insertion, prior to opening the membranous cochlear walls (Figure 7) [81].

In addition, implant recipients may benefit from the improved pitch resolution that can be provided by both electrical and acoustic hearing, in cases of residual hearing if a very flat electrode array (endosteal electrode) is inserted into the crevice between the bony cochlear capsule and the spiral ligament, without opening the fluid-filled inner ear [82]. However, it is essential to know which part of the exposed soft tissue membrane is sufficiently thick (spiral ligament) to offer enough resistance to the electrode, and prevent it from penetrating the lumen [6]. OCT can make localizing specific structures within the cochlea much easier, and may be useful as an adjunct to cochlear implantation [5].

Further improvements of OCT imaging may include adding a reference laser, the beam of which will be a precise indicator of the scanned area, as well as increasing the optical strength of OCT [81].

The development of perimodiolar electrode arrays for CIs may also require detailed information on the expected position of the array in relation to the cochlear structures. The development of phase-contrast imaging represents an additional option that can provide better visualization of the anatomic details in the inner ear and help pinpoint the expected electrode location in relation to the cochlear walls [83].

At a more practical level, the localization and form of the drilling canal have so far been defined solely by the surgeon during the operation, and an enlargement of the drilling canal is often necessary. Navigated computer-assisted surgery with titanium screws as referencing markers may allow an exactly defined optimal point for the cochleostomy. A target assessed by navigation has proven better than one reached without navigation in terms of reproducibility and accuracy [84,85], although deviations larger than the intended target size continue to exist. The aim of totally navigated cochleostomy may be reached with further technical progress. Indeed, intraoperative 3D volume tomography-based navigation can enhance the precision of navigation and reduce the risk of improper electrode placement and additional surgery, especially in cases of complex malformations [86].

Hence, it is important that 3D CT imaging is incorporated in clinical practice in order to assess the middle and inner ears more precisely. Admittedly, the problem until now has been that different structures within the ear have similar threshold densities, making their separation by simply adjusting volume-rendering parameters impossible. A solution to this problem is called segmentation, and involves the manual removal of unwanted structures from the image. As this is a time-consuming process, automated segmentation algorithms based on elastic registration are being developed and their clinical use may reduce post-processing time significantly, while still allowing precise segmentation [42]. The ability to also produce high quality hybrid rendering and virtual endoscopic images of sub-millimeter structures from spiral CT datasets, opens new possibilities for the morphologic analysis of the middle and inner ears [43].

Figure 7. Optical coherence tomography scan of the cochlea in a cadaveric specimen. The borders of the membranous scalae and the BM (arrow) can be identified within the bony otic capsule.

BM: Basilar membrane; ST: Scala tympani; SV: Scala vestibuli. Reproduced with permission from [81].
Recent clinical studies in patients involving intratympanic Gd–diethylenetriamine penta-acetic acid (DTPA) injection for 3D MR imaging demonstrated excellent separation between the perilymph and the endolymph. Vestibular enhancement is observed first, followed by advance of the enhancement to the basal cochlear turn and semicircular canals and finally the apical turn of the cochlea. The optimum time interval between Gd administration and MRI has been determined to be 24 h [72]. However, despite the promising results in depicting the inner ear, intratympanic Gd–DTPA administration is still an off-label use. Hence, more sensitive methods for detecting very low concentrations of Gd–DTPA are being developed in order to achieve separate visualization of the perilymph and endolymph.

In addition, recently developed functional MRI (fMRI) is a noninvasive technique for imaging cerebral function. Being different from static imaging per se, it is based on the concept that blood has oxygenation-sensitive paramagnetic characteristics. fMRI measures signal changes in the brain that are due to changing neural activity. Increases in neural activity cause changes in the MR signal via T2-weighted changes [87]; this mechanism is referred to as the blood oxygen-level dependent (BOLD) effect. The precise nature of the relationship between neural activity and the BOLD signal is a subject of current research.

While the BOLD signal is the most common method employed for neuroscience studies in human subjects, the flexible nature of MRI provides means to sensitize the signal to other aspects of the blood supply. The cerebral blood volume method requires injection of a class of MRI contrast agents that are now in human clinical trials. As this method has been shown to be far more sensitive than the BOLD technique in preclinical studies, it may expand the role of fMRI in clinical applications. Hence, fMRI can test the cerebral auditory pathway and add criteria for CI candidacy [50,88].

Financial & competing interests disclosure
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Key issues

- The consideration of cochlear implantation necessitates a wide selection process, of which imaging of the temporal bone is an important part. Preoperative radiologic assessment should be able to assess the status of the middle ear and inner ears, the auditory nerve and the central acoustic pathways.

- The perceived advantage of using computed tomography (CT) as the preoperative investigation of choice is that it may display anatomic middle ear variations of surgical importance and, hence, be very helpful to the surgeon in preoperative planning. However, CT cannot identify early or soft-tissue labyrinthine obliteration, cochlear nerve anomalies in the internal auditory canal or certain retrocochlear abnormalities in the auditory pathway. Otologists should also expect to encounter some degree of obstruction within the basal turn of the cochlea, even when the CT scan is normal.

- MRI is the imaging study of choice for imaging evaluation of the membranous labyrinth. Its main contribution in preoperative cochlear implant imaging is the clear demonstration of fluid in the inner ear and the more superior imaging of the retrocochlear auditory pathways. However, MRI scan is not without disadvantages; it often requires sedation, especially in pediatric implantees, and cannot evaluate bony structures and certain middle ear pathologies. It is also less successful in localizing the mastoid segment of the facial nerve.

- A dual modality imaging method with high-resolution CT and MRI of the petrous bone and brain can provide maximum information to the operating surgeon with regard to surgical landmarks, and also detect abnormalities related to deafness, which would not otherwise be found using either modality alone. In addition, if cost–effectiveness issues are to be considered, dual modality preoperative imaging may not only distinguish patients who will benefit from implant surgery, but will also help identifying surgically challenging cases or avoid unnecessary operations. Moreover, the high cost of the procedure itself suggests that any extra cost that the dual modality approach may incur is not significant.

- The future is very promising and new systems are now becoming available, offering improved soft-tissue delineation, sophisticated segmentation techniques, volumetric measurements, semitransparent views and superior surface resolution, thus significantly advancing our diagnostic acumen.

- These advances should further serve to solidify the role of radiographic imaging in the preoperative evaluation of cochlear implant candidates and provide a detailed and reliable assessment of normal variants and various pathologies, in order to avoid surgical pitfalls and improve the cost–effectiveness of cochlear implantation.

References

Papers of special note have been highlighted as:
- of interest
- of considerable interest

Abnormalities detected on MRI are more likely to influence the implantation process than the ones detected on CT.


Review

Vlastarakos, Nikolopoulos, Pappas, Buchanan, Bewick & Kandiloros

By correlating 3D images and virtual endoscopy to 2D cross-sectional images the authors confirmed an added diagnostic benefit of 3D visualization in understanding temporal bone anatomy.

3D hybrid rendering and virtual endoscopy can improve the value of 2D imaging in the diagnosis and management of patients with middle or inner ear diseases.


Excellent summary of imaging issues in cochlear implantation, including presurgical key points and various inner ear pathologies.


Cochlear implantation update: the dual modality approach as a standard of care


Up-to-date review of recent advances in clinical MRI.


Optical coherence tomography may provide further information about cochlear structures during cochlear implant surgery before opening the fluid-filled inner ear.


Aschendorff A, Maier W, Jaekel K et al. Radiologically assisted navigation in cochlear implantation for X-linked deafness malformation. Cochlear Implants Int. 10(Suppl. 1), 14–18 (2009).

3D radiologically assisted navigation reduces the risk of improper electrode placement and additional cochlear implant surgery in complex inner ear malformations.


Website