The Role of Radiographic Phase-Contrast Imaging in the Development of Intracochlear Electrode Arrays

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Objective: This study describes the application of a new radiographic imaging modality, phase-contrast radiography, to in vitro human temporal bone imaging and investigates its use in the development of new electrode arrays for cochlear implants.

Background: The development of perimodiolar electrode arrays for cochlear implants requires detailed information from postoperative radiologic assessment on the position of the array in relation to the cochlear structures. Current standard radiographic techniques provide only limited details.

Materials and Methods: Nucleus standard electrode arrays and perimodiolar Contour electrode arrays were implanted into the scala tympani of 11 human temporal bones. Both conventional and phase-contrast radiographs were taken of each temporal bone for comparative purposes.

Results: Phase-contrast imaging provides better visualization

of anatomic details of the inner ear and of the structure of the intracochlear electrode array, and better definition of electrode location in relation to cochlear walls.

Conclusion: Phase-contrast radiography offers significant improvement over conventional radiography in images of in vitro human temporal bones. It seems to be a valuable tool in the development of intracochlear electrode arrays and cochlear implant research. However, this new radiographic technique still requires certain computational and physics challenges to be addressed before its clinical use can be established. **Key Words:** Cochlear implant—Electrode position—Imaging—Imaging plate—Microfocus—Perimodiolar electrode—Phase-contrast radiography—Temporal bone.

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In the development of advanced cochlear implants, improvements to the intracochlear electrode arrays are a key issue. To recognize a promising new design of intracochlear electrode array, it is imperative to know the exact anatomic position of the electrodes, the insertion depth, and any damage to cochlear structures that may occur. Currently, conventional radiography is the most common method for assessing the electrode position after cochlear implantation (1–3). However, conventional radiography cannot clearly demonstrate the exact anatomic position of the electrodes in relation to the fine bony structures of the cochlea and any possible insertion-induced damage to them. In the study described here, a new radiographic imaging modality, phase-contrast radiography (4), was applied to in vitro human temporal bone imaging.

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Conventional radiography (Fig. 1A) relies on the principles of absorption contrast derived from density differences and variations in composition and thickness of the object. In comparison to conventional radiography, phase-contrast radiography (4,5) uses a microfocus x-ray source to produce a coherent spherical wave. When the spherical wave passes through the object, the wave front becomes distorted by refraction. A relatively large object-image distance is used to allow further wave propagation and interference effects to occur, resulting in observable changes in intensity (phase contrast) in the image plane (Fig. 1B). The imaging geometry used also provides an inherent magnification and improved signal-to-noise ratio. This projection geometry also enables recording media such as imaging plates to be used, with their inherent advantages such as high sensitivity and large dynamic range, without the severe limitation imposed by their resolution (which is inferior to that of film, for example).

Studies by Wilkins et al. (4) and Gao et al. (5) demonstrated that phase-contrast imaging is able to improve the visibility of weakly absorbing features in small bio-

FIG. 1. **A.** Geometric optics representation of imaging of an absorptive object with an incoherent source. The resulting image is blurred when the object-image separation is large. **B.** Wave optics representation of imaging using a coherent source, demonstrating observable intensity variation caused by interference resulting from phase distortion of the wave front.

logic objects, for example, using goldfish, dragonfly, porcine liver, chicken knee, and human finger bone samples. In 1999, a preliminary study by Xu et al. (6) was conducted to investigate the possibility of using phase-contrast radiography for the imaging of human temporal bone: the bone with the most intricate anatomy and the highest bone density in the human body. The result was very encouraging. The study described here investigated the improvements that phase-contrast radiography can deliver for in vitro human temporal bone imaging and its potential role in the development of intracochlear electrode arrays for cochlear implants.

MATERIALS AND METHODS

Intracochlear electrode arrays

The Nucleus standard electrode array (Fig. 2A) and the newly developed perimodiolar Contour electrode array (Fig.

2B) were used in this study. The straight standard electrode array comprises 22 full-band Platinum (Pt) electrodes and 10 nonactive supporting bands, with the silicone carrier tapered from a tip diameter of 0.4 mm to 0.6 mm at the proximal end. The precurved Contour electrode array has 22 half-band Pt electrodes, oriented toward the modiolus, with the silicone carrier tapered from a tip diameter of 0.6 to 0.8 mm at the proximal end. The width of each electrode is 0.3 mm in both electrode designs. The diameter of the iridium-platinum wire connected to each electrode is 25 μ m.

Insertion of electrode arrays into temporal bones

Eleven formalin-preserved human temporal bones were prepared as for cochlear implant surgery. A standard Nucleus electrode array was inserted into the cochlea of three temporal bones. The Nucleus Contour electrode array was inserted into the cochlea of seven temporal bones. A cochlear surface preparation was performed under a microscope on six of these seven temporal bones after insertion to assess electrode position and possible basilar membrane damage. No electrode array was inserted into the remaining temporal bone. A profile of those temporal bones is summarized in Table 1.

Radiographic techniques

Both a conventional radiograph and a phase-contrast radiograph were taken of each temporal bone for comparative pur-

FIG. 2. Photomicrographs of Nucleus standard electrode array (A) and perimodiolar Contour electrode array (B).

TABLE 1. Profile of 11 temporal bones

Temporal bone	Type of nucleus electrode array	Cochlear surface preparation (after insertion)
Temporal bone 1-3	Standard	No
Temporal bone 4	Contour	No
Temporal bone 5-10	Contour	Yes
Temporal bone 11	No electrode	No

TABLE 2. *Technical profile of conventional radiography and phase-contrast radiography for typical cases used in the present study*

	Conventional radiography	Phase-contrast radiography
Focal spot	0.3 × 1.0 mm	4 μm
Source-object distance	99 cm	30 cm
Object-image distance	35 cm	170 cm
Exposure	60 kV, 13 mAs	90 kV, 6 mAs
Recording medium	Agfa Curix Ortho Cassette with fine intensifying screen Kodak G/RA film	Fujifilm imaging plate BAS-SR (2025)
Scanner	PowerLook2000 (8.5 μm/pixel)	Fujifilm BAS-5000 (25 μm/pixel)

poses. An ultrafine focus skull radiographic unit (Ultracranio; Isotopan Snc, S. Angelo Romano (Roma), Italy) was used for taking conventional radiographs. The films were scanned at 8.5-μm pixel size with a PowerLook2000 scanner. An indus-

trial microfocus x-ray unit (Model FXE-225.20; Feinfocus Röntgen-Systeme GmbH, Garbsen, Germany) with stationary target, and Fuji photostimulable phosphor imaging plates, were used for taking the phase-contrast radiographs. The imaging

FIG. 3. Comparison of conventional radiograph (A,C) and phase-contrast radiograph (B,D) of the labyrinth part of temporal bone 1 implanted with an experimental Nucleus standard electrode array. (A,B, cochlear view) and the cochlear part of temporal bone 4 implanted with a prototype version of the Nucleus Contour electrode array (C,D, oblique view). SSC, superior semicircular canal; LSC, lateral semicircular canal; PSC, posterior semicircular canal; IAM, internal auditory meatus.

plates were typically scanned at 25 μm pixel size with a BAS-5000 scanner. Technical profiles of both conventional radiography and phase-contrast radiography are detailed in Table 2. The phase-contrast configuration described is the subject of an issued patent (7) and ongoing Patent Cooperation Treaty applications held by X-Ray Technologies Pty. Ltd., Melbourne, Australia.

RESULTS

Conventional versus phase-contrast radiographs

Conventional and phase-contrast radiographs were obtained for each temporal bone. The significant portions of the images were enlarged to an appropriate size for comparison. Figure 3 shows the cochlear view (1) of the labyrinth part of temporal bone 1 implanted with a Nucleus standard electrode array and an oblique view of the cochlear part of temporal bone 4 implanted with an early prototype version of the Nucleus Contour electrode array.

It is apparent that the imaging contrast was much enhanced at the edge of canal-type structures, such as the semicircular canals, the cochlea, and the internal auditory meatus, by the use of phase-contrast radiography (Fig. 3 B,D) in comparison with conventional radiography (Fig. 3 A,C). A good example of such a sharp contrast, between the otic capsule and the air- or fluid-filled cochlear scalae, is evident in Figure 3D.

Figure 4 shows part of a Nucleus standard electrode array in the cochlea of temporal bone 1 (Fig. 4 C,D) and part of the Contour electrode array in the cochlea of temporal bone 4 (Fig. 4 A,B) at a higher magnification. The phase-contrast radiographs (Fig. 4 B,D) contain more details of the microstructures of the electrode array. Single iridium-platinum wires, which are only 25 μm in diameter, can be clearly identified. By comparison, the platinum bands and wires are very blurry and indistinct in the conventional radiographs (Fig. 4 A,C).

It is obvious not only that the anatomic structures of the inner ear are shown in much greater detail by phase-contrast radiography, but also that the images of the electrode arrays are much more detailed. This advantage has not been observed with any of the other radiographic methods available to us previously.

Position of the electrode array within the cochlea

Figure 5 shows phase-contrast radiographs (cochlear view) of temporal bone 1 implanted with the Nucleus standard electrode array and temporal bone 6 implanted with the Nucleus Contour array. The enhanced imaging contrast at the edge of the cochlear wall using phase-contrast radiography enables better definition of the position of an electrode array in relation to the walls of the cochlea. The standard array in temporal bone 1 was located along the outer wall of the cochlea (Fig. 5A), far from the neural elements. In temporal bone 6, the Contour array (Fig. 5B) was inserted more deeply and positioned closer to the modiolus, compared with the standard array in temporal bone 1 (Fig. 5A).

A group of six temporal bones (temporal bones 5–10) was implanted with the Nucleus Contour electrode array. A surface preparation was performed on each temporal bone after electrode insertion. Figure 6 shows the phase-contrast radiographs of these six temporal bones (cochlear view orientation). The resultant images indicate that, in general, the Contour array lies close to the modiolus and achieves a greater insertion depth than does the standard Nucleus array. More details of two representative temporal bones are shown in Figures 7 and 8.

The phase-contrast radiograph of temporal bone 6 implanted with the Contour electrode array shows that the array is located close to the inner wall of the cochlea (Fig. 7A). Careful observation of the side view of the phase-contrast radiograph (Fig. 7B) shows that the osseous spiral lamina (OSL) is just visible, with the Contour array positioned under the OSL in the scala tympani. A cochlear surface preparation of this cochlea confirmed earlier that the insertion had been atraumatic: the electrode was visible through the intact basilar membrane and completely located in the scala tympani (Fig. 7C).

In temporal bone 8, the Contour array pierced the basilar membrane during insertion, and the apical part of the array was positioned in the scala vestibuli. This had been observed during the cochlear surface preparation after insertion (Fig. 8C). On the side view (Fig. 8B) of this temporal bone, the position of the apical electrodes in the scala vestibuli was indicated by the superiorly displaced array in the lower middle and upper basal turn.

FIG. 4. Enlargements of part of the Nucleus standard electrode array in the cochlea of temporal bone 1 (C,D) and the Contour electrode array in the cochlea of temporal bone 4 (A,B). Conventional radiographs (A,C) and phase-contrast radiographs (B,D). Diameter of microwires, 25 μm .

FIG. 5. Phase-contrast radiographs (cochlear view) of temporal bone 1 implanted with the standard array (**A**) and temporal bone 6 implanted with the Contour array (**B**) demonstrating that the Contour array was inserted deeper and closer to the modiolus. Arrowhead, outer wall of the cochlea; M, modiolus.

DISCUSSION

In conventional radiography, the quality of the radiograph is usually improved by reducing the focal spot size and object-image distance. Such an improvement is much more distinct in phase-contrast radiography, which uses a microfocus x-ray tube source and large projection distances (Fig. 1B). The microfocus source size ensures the sufficiently high level of spatial coherence of the x-rays on which the method relies. A very important aspect of this arrangement is the appropriate choice of source-object and object-image distances. Conventional radiography is based on absorption-contrast, whereas phase-contrast radiography is based on phase or refraction effects. Therefore, in conventional radiography, increasing object-image distance will usually degrade the clarity of the image (Fig. 1A). However, large object-image distances are used to advantage in the phase-contrast technique (Fig. 1B).

Improvements of phase-contrast radiography in temporal-bone imaging

The temporal bone contains a wide range of bone densities and variations in composition. Whereas the highest

FIG. 6. Phase-contrast radiographs (cochlear view) of cochlear part of temporal bones 5 through 10 showing that the Contour array was generally close to the modiolus.

FIG. 7. Example of atraumatic insertion of the Contour array in temporal bone 6. **A.** Cochlear view of phase-contrast radiograph. **B.** Side view of phase-contrast radiograph showing the Contour array located under the osseous spiral lamina (OSL). **C.** Photomicrograph of the surface prepared cochlea confirming that the electrode array is under the intact basilar membrane (BM). ST, scala tympani; arrowhead, margin of silicone carrier of electrode.

concentration of calcium can be found in the bone surrounding the labyrinth and inside the modiolus, weakly absorbing soft tissue, delicate structures (e.g. membranes, the organ of Corti, osseous spiral lamina) and fluid-filled canals (labyrinth) exist within the temporal bone. Moreover, the temporal bone also has a large range in the geometric dimensions of the various bony components. The maximum dimension of the bony labyrinth, from the posterior end of the lateral semicircular canal to the anterior end of the cochlea, is about 20 mm, whereas the thickness of the OSL is only about 0.1 mm (unpublished data from our laboratory). Conventional radiography is incapable of showing such fine details of the temporal bone. The results for phase-contrast radiography showed significant improvements in the detail of structures compared with conventional radiography in images of *in vitro* human temporal bones. These improvements include enhanced contrast at the edge of canal-type features, inherent image magnification, higher spatial resolution, improved signal to background (via the so-called air-gap effect) (5) and ability to use detectors such as imaging plates (cf. normal radiographic film without an intensifying screen).

The increase in contrast of the present radiographs of our temporal bone samples could be the result of two mechanisms: 1) Edge-enhanced contrast (8) of phase-contrast imaging increases the contrast at the edges of canal-type features. Because the petrous part of the temporal bone is characterized by such canal-type features

FIG. 8. Example of traumatic insertion of the Contour array in temporal bone 8. **A.** Cochlear view of phase-contrast radiograph. **B.** Side view of phase-contrast radiograph showing the superiorly displaced array in the upper basal turn and the lower middle turn. **C.** Photomicrograph of the surface prepared cochlea confirming that the Contour array had pierced the basilar membrane (arrowhead).

(cochlea, vestibule, semicircular canals, facial nerve canal, internal auditory meatus), the anatomic entities, especially in this section of the temporal bone, will be shown more clearly with the new imaging modality. 2) Absorption contrast, which is still present in phase-contrast radiographs, shows best the low spatial frequencies (large features) of an absorptive object and has improved signal to background in the present geometry. The contributions of phase contrast and absorption contrast to the total image contrast are largely complementary, relating to high and low spatial frequencies, respectively, and can therefore provide more information than a conventional radiograph.

In agreement with Wilkins et al. (4) and Gao et al. (5,8), who showed that phase-contrast radiography improves the contrast of weakly absorbing features in small biologic objects, we also noted that phase-contrast radiography improved the contrast of weakly absorbing features within the dense structures of human temporal bone. In particular, delicate structures, such as the OSL, were visible in the side view of temporal bone 6 (Fig. 7B), and nonmetallic materials, such as the silicone carrier of the electrode array, were observed in Figure 7 A,B.

The inherent image magnification is another improvement offered by phase-contrast radiography, especially when high spatial resolution is desired. Therefore, phase-contrast radiographs tend to retain sharpness better than do conventional radiographs when enlarged or zoomed (Fig. 4 B,D).

The ability to use imaging plates with higher detective quantum efficiency and a wider dynamic range than conventional radiographic film clearly has advantages of reducing the absorbed dose and increasing the level of information gained. This digital device is ideal for combining with the inherent image magnification of phase-contrast radiography.

Phase-contrast radiography in perimodiolar electrode development

It has already been demonstrated that the standard Nucleus multichannel electrode array is safe for use in profoundly deaf patients. However, the standard straight array is usually located along the outer wall of the cochlea (Figure 5A). A study by Shepherd et al. (9) has shown that moving the electrode array from the outer wall of the cochlea toward the modiolus, which contains the spiral ganglion cells in the Rosenthal canal, can reduce stimulus thresholds and increase the dynamic range. From a very early stage of our perimodiolar electrode development (10,11), the aim has always been to achieve a perimodiolar placement of the electrode with as little insertion-induced damage as possible (10-12). Cohen et al. (3) developed a method to estimate the position of the electrode within the cochlea using the postoperative radiographs (a cochlear view (1) orientation). The accuracy of this method relies on the visibility of anatomic landmarks on the radiograph. The study described here demonstrates that phase-contrast imaging can have important

advantages in the visualization of those anatomic details of both the inner ear structures and the intracochlear electrode array. It therefore can provide a better definition of electrode location in relation to the outer cochlear wall and the modiolus. The method is capable of spatial resolutions on the order of about 1 μm , because spatial resolution can be comparable to the source size (13). Therefore, phase-contrast radiography is well suited to the investigation of any microelectronic devices.

Clinical application of phase-contrast radiography

Phase-contrast radiography relies on having high spatial coherence of the x-rays and a very uniform wavefront incident on the feature of interest. The technique is very sensitive to extraneous mechanisms of scattering that either complicates the wavefront or adds background. In practice, this will mean strict quality controls on in-line components such as windows and filters as well as a limit on the thickness of objects to be imaged. Nonetheless, previous studies (4,5) have reported experiments demonstrating detectable phase-contrast on soft-tissue samples ≤ 50 mm in thickness. Moreover, this study provides support for the feasibility of applying phase-contrast radiography to in vitro human temporal bone. However, its usefulness in large objects or even cochlear implant patients in a clinical setting is still an ongoing computational and physics challenge.

CONCLUSIONS

This study demonstrates that phase-contrast radiography offers significant improvement over conventional radiography in images of in vitro temporal bones. The phase-contrast imaging provides better visualization of anatomic details of the inner ear and of the structure of the intracochlear electrode array, and better definition of the electrode position in relation to the cochlear wall. It is a potentially valuable tool in the development of new electrode arrays for advanced cochlear implant systems.

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