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Measurement of Cochlear Implant Electrode Position from Intraoperative Post-insertion Skull Radiographs: A Validation Study

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INTRODUCTION

Several methods of determining the depth of cochlear implant electrode insertion as well as the position of each of the electrode contacts within the cochlea have been described [1-5]. While simple to understand, these methods require either a post-insertion computed tomography (CT) scan, which adds radiation, cost and time to the procedure [1-3, 6], or a precisely protocolled skull radiograph that requires expertise of the technician and usually adds an extra postoperative visit for the patient [4, 7, 8]. Additionally, image processing software is needed to calculate angles and distances of the electrode contacts.

Many cochlear implant centers obtain an intraoperative post-insertion skull radiograph to confirm that the electrode assumes a typical coil position within the cochlea. This allows for assessment of kinks or tip rollover of the electrode array, which can be difficult to determine with standard telemetry [9]. The skull radiograph is typically obtained easily and rapidly within the operating room and stored on a picture archiving and communication system (PACS). Potentially, this X-ray could also be used to determine the angular depth of insertion (aDOI) of the electrode and each of the contacts relative to the intracochlear structures [4, 10], obviating the need for additional radiologic studies. The depth of cochlear implant electrode array has been correlated with preservation of residual hearing and word identification scores [5, 11-14]. Further, pitch perception for implanted patients may depend on the actual depth of placement of each of the individual electrode contacts [5, 11, 15, 24]. One concern with intraoperative skull radiographs is that the angle at which the patient's head is rotated or tilted is not standardized. The method described by Cohen, et al. [4, 10] for determining electrode position relies on a radiograph taken at exactly a 50° angle of head rotation relative to the X-ray tube (“cochlear view”), with the implant side towards the film. In clinical practice, however, the usual intraoperative post-insertion film is taken with the

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patient's head rotated obliquely to a variable (non-standardized) angle of X-ray acquisition (aX; **Figure 1**). Further, for bilateral simultaneous or sequential implants, in order to avoid additional radiation or risk overlap of electrode leads which can impede accurate assessment of their placement, the film is usually taken with the head aligned anteroposterior to the direction of the tube (0°). While these radiographs are adequate to acquire immediate clinical information, there may be reluctance to use them for calculating angular depth of insertion (aDOI) and position of individual contacts because of the non-standardized acquisition of the skull radiograph (aX). Indeed, several published studies have expressed concern over the error that might be introduced by estimating electrode position based on a radiograph, particularly if it was obtained without the nuances recommended by Cohen, et al [2, 18, 19]. As far as we are aware, there are no published studies addressing the non-standardized aX as a potential source of error when measuring depth of intracochlear electrodes, or other sources of error such as intra- and inter-rater discrepancies.

Here we describe and validate a simplified method of determining the aDOI as well as the position of each of the electrode contacts by reviewing eighteen intraoperative post-insertion skull radiographs. Additionally, with the assistance of three-dimensional modelling software and a cadaveric temporal bone model, we investigate the variability of the aDOI in the face of non-standardized aX between the X-ray tube and the patient's head.

METHODS

Acquisition of skull radiographs

We conducted a retrospective patient chart and plain radiograph image review from our tertiary care center's picture archiving and communication system (PACS). The retrospective review of the previously acquired radiographs was approved by the New York Langone Medical Center Institutional Review Board. Eighteen postoperative cochlear implant X-rays from randomly chosen subjects, distributed evenly among adult and pediatric groups (8 vs. 10, respectively), male and female (9 in each group) and 22-electrode and 16-electrode arrays (8 vs. 10, respectively) acquired at variable X-ray angles (aX) over the last 5 years were analyzed for electrode angular depth of insertion (aDOI). Films of seven electrodes were acquired with the patient's head positioned implant side up at a variable oblique angle aX, $0° < aX < 90°$, performed for unilateral implants (**Figure 1)**. The remaining 11 electrode films were acquired with the patient's head facing the tube, $aX \approx 0°$, performed for bilateral or simultaneous implants. All patients had intraoperative radiographs taken at a distance of 40″. For adults, 60-65 mA tube current was used at 70-80kV and for infants and pediatric patients 16-20 mA were used at 70-73kV. The protocol included covering adults and children with lead aprons to minimize radiation exposure. These radiographs were taken as part of the usual standard of care. No additional radiographs were taken for the present study.

Measurement of angular depth of electrode contacts and angular depth of insertion (aDOI)

aDOI was measured based on earlier described methods by Cohen, et al. [4, 7, 10]. A line was drawn through the apex of the superior semicircular canal (SSCC) and the center of the vestibule as determined by visual inspection of the plain skull intraoperative radiograph; the point where this line intersected the electrode lead was taken as an estimate of the round window location (RW). The modiolus was determined by visual inspection at the center of the electrode spiral. The line connecting the modiolus with the RW defined the 0° reference line; the aDOI was the angle of rotation the most distal electrode assumed with respect to the 0° reference line (**Figure 2**). This angle may exceed 360° if the electrode array was inserted more than one full turn of the cochlear spiral. The position of all of the remaining electrode contacts was similarly determined by the angle they each assumed from the 0° reference line. All of the intraoperative radiographs were uploaded onto a web-based image reader; the DICOM files were then individually converted to a JPEG format. Markers and lines for the above mentioned structures were drawn utilizing Microsoft PowerPoint 2013 software (Microsoft Corporation, Redmond, WA). Each new JPEG image, which contained the radiograph and the markers, was then individually analyzed with public domain “ImageJ” software (http://rsbweb.nih.gov/ij/download.html) for angle measurements.

Calculation of intra-rater and inter-rater variability

The aDOI of eight 22-electrode implants and ten 16-electrode implants was estimated utilizing the methodology described above, for a total of 336 electrode angle estimates. The process was repeated twice by the same rater to assess intra-rater variability. Another rater was asked to measure the angular depth of all 336 electrodes from the same eighteen X-rays to provide an inter-rater variability estimate. Both raters were neurotology fellows. The agreement within and across raters was assessed using Lin's concordance coefficient [20]. Additionally, measures of average measurement difference within and across raters were obtained, both for raw values (which could be positive or negative) and for absolute values.

Assessing error introduced by image acquisition angle: Simulated X-rays from a 3D model

Errors in aDOI measurement due to non-standardized angles between the X-ray tube and the patient's head were evaluated with two methods. For the first method, one postoperative high resolution CT temporal bone scan (taken years after implantation for suspected device failure) allowed for a three-dimensional image reconstruction of the cochlea and array complex. Two neuroradiologists (P.M.B. and A.J.D.) produced a volume rendered image (Vitrea Workstation V4.1, Vital Images, Minnetonka, MN) and isolated the region of interest with a box segmentation. A monochrome color scheme was used and the opacity decreased until the labyrinthine osseous structures and the metallic electrode were both well visualized. 2D projections (“simulated x-rays”) were produced from this volume rendering and were rotated around the vertical axis in 10 degree increments ranging from 0°-80°, moving from the anteroposterior to the lateral plane (**Figure 3**). aDOI measurements were performed as described above by both neurotology fellows, with the goal of assessing if the angle at which the intraoperative post insertion skull radiograph is taken, aX, influences the measured aDOI of the electrode array. We quantified the measurement errors as a function of departure from the cochlear view (50°) angle.

Assessing error introduced by image acquisition angle: Temporal bone fluoroscopic study

One temporal bone was implanted with a 22-lead array. The bone was fixed with a clamp around a rigid axis and rotated at 15° intervals from coronal (anteroposterior) to sagittal (lateral) plane. Fluoroscopic images of each of the positions were obtained (**Figure 4**). These images were analyzed for aDOI by the methods described above by both raters, and the measurement errors quantified as a function of departure from the angle closest to cochlear view (45°).

RESULTS

Intra and Inter-rater Variability

The average difference between the first and the second independent measurements taken by rater one was only 2.2°. The average of the absolute value of the difference between the first and the second measurements taken by rater one was 8.8°. This represents a very good level of intra-rater reliability. Inter-rater reliability was almost as good, with values of 4.5° and 10.1° respectively. Taken together, these numbers suggest that the errors introduced by test-retest or by using different raters are within 10°. These results were confirmed by extremely high values of Lin's concordance coefficient, 0.9957 for inter-rater reliability and 0.9909 for intra-rater reliability. According to the cutoff criteria for strength of agreement proposed by McBride [21] this represents near perfect agreement.

Assessing error introduced by image acquisition angle: Simulated X-rays from a 3D model

Volume rendered (“3D”) reconstruction of the cochlea with the array in place was rotated from 0° to 80° in the coronal to sagittal plane in 10° intervals. **Figure 3** shows five of the nine 2D projections obtained at different angles (20°, 40°, 50°, 60° and 80°) together with the estimated location for the RW, modiolus, and each one of the electrodes. It is clear that angular departure from the 50° image (cochlear view) creates a more distorted projection of the cochlear spiral. However, the aDOI of the most distal electrode maintains a relatively consistent angular position with respect to 0° reference line. **Table 1** shows the estimated value obtained by each rater of aDOI as a function of rotation angle. Departures of plus 30° to minus 50° from the 50°reference angle resulted in errors of up to +5.4° to −8.5° for rater one and +23.3°to −1.8° for rater two.

Assessing error introduced by image acquisition angle: Temporal bone fluoroscopic study

A left human temporal bone with an implanted 22-lead array was rotated in 15°intervals. **Figure 4** shows 3 of the captured six (90°, 75°, 60°, 45°, 30° and 15°) fluoroscopic images, as well as the estimated locations of the RW, modiolus and the most apical electrode. The image at 45° is closest to the cochlear view angle of acquisition, and shows the clearest landmarks. **Table 2** summarizes the measured aDOI (by both raters) as a function of the X-ray acquisition angle, aX. Departures of plus 45° to minus 30° from the 45° cochlear view reference angle resulted in calculated aDOI error of +13° to −9.8° for rater one and +9.4°to −12.5° for rater two.

Summary

If we restrict the analysis to a range of plus or minus 30° from the reference angle (which was 50° in the case of the simulated X-ray study and 45° in the case of the fluoroscopic study), the bottom line is that the worst case error in calculating aDOI in Tables 1 and 2 ranged from −12.5° to +15.8° across raters and studies.

CONCLUSIONS

Angular depth of insertion (aDOI) is an objective measure of the depth of the electrode array and can be used to compare two different electrode types, to assess placement when considering revision implants or to compare different insertion techniques. Depth of insertion has been shown to affect patient performance, with very shallow and very deep insertions correlating to poorer speech scores and the latter correlating to worse hearing preservation [16, 22, 23]. In such extreme cases, knowing the aDOI can help patient counseling with respect to performance expectations as well as serve as a quantifiable point of comparison when considering and performing revision surgery. We have also used this measure to evaluate the mismatch between the frequency presented at a given cochlear angle and the frequency expected by an acoustic hearing ear at the same angle [24]. Knowledge of the intracochlear position depth of each of the electrode contacts may be useful for fine tuning frequency maps during speech processor programming.

Two sources of potential measurement error were considered in this study. First, intra- and inter-rater variability were evaluated and we found that the worst-case error for estimating aDOI fell within 10°. Second, in order to assess how much the variability in angle at which the patient's head is rotated (the angle at which the X-ray is taken – aX) may affect the aDOI calculation, we utilized a simulated radiograph from a 3D model in addition to a separate analysis using an implanted temporal bone. Changing aX in the simulated radiograph or in the implanted temporal bone through a range of plus or minus 30° from the reference angle resulted in worst case errors of only −12.5° to +15.8° across two different raters. Other researchers have already suggested that the standard intraoperative oblique versus the anteroposterior view have limited bearing on the calculated aDOI [2, 25]. Taken together, these findings show that it is possible to obtain usable estimates of intracochlear electrode insertion angle even when using radiographs that depart significantly from the cochlear view.

The method proposed here has a number of advantages. The image processing software necessary to analyze the radiograph and measure appropriate angles is both readily-available and easy to use (PowerPoint and ImageJ). Additionally, specific patient head positioning is not necessary, and, more importantly, no additional postoperative radiographs or computed tomography are needed to obtain an estimate of intracochlear electrode insertion angle. This minimizes additional costs or radiation exposure outside of what is necessary for appropriate clinical care. The original work published by Xu, et al on the ideal cochlear view advocates for a postoperative radiograph taken a day or more after surgery with the patient sitting upright and the plane of the X-ray oriented at 50°[4]. While the Xu et al. method does allow for standardization between patients, it requires, in addition to specific positioning, an extra day of patient follow-up and additional radiation exposure.

On the other hand, the proposed method is not intended to replace computed tomography for precise assessment of intracochlear insertion angle and information about whether electrodes are in the scala tympani, scala vestibuli, or in an extracochlear position, or any information about the electrode contact proximity to the modiolus. Our study suggests that the “quick” intraoperative post-insertion radiograph is sufficient to obtain an estimate of the angular depth of electrode contacts and the aDOI, regardless of head positioning. Knowledge of the aDOI may be useful for different clinical and research purposes. This intraoperative radiograph already satisfies immediate clinical needs of ruling out electrode tip rollover or other insertion anomalies. Now, this same radiograph can also be used to quantify aDOI, which, when very shallow or very deep, has implications in patient performance. Additionally, a quantifiable aDOI, even if approximate, is useful in interpreting a wide range of behavioral, speech perception, and psychophysical experiments in cochlear implant users.

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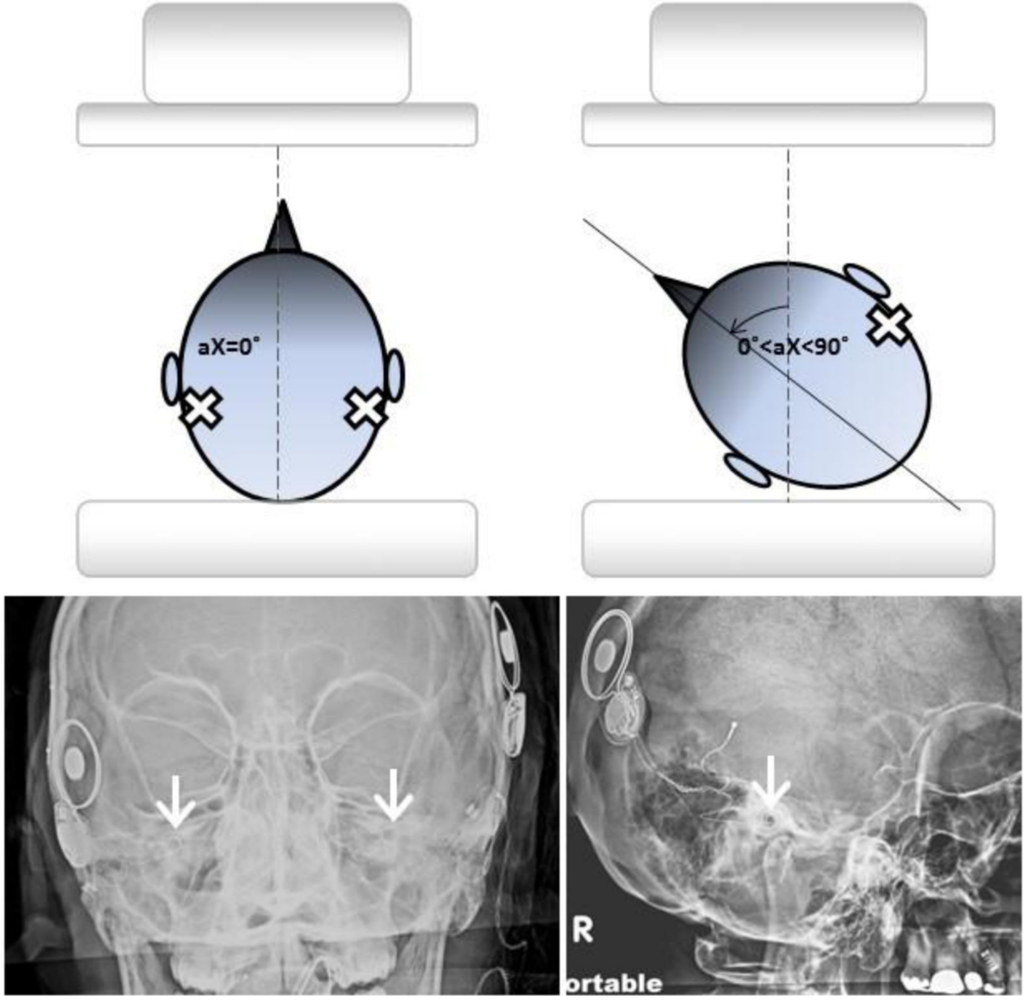

Figure 1. Typical intraoperative patient orientation and resultant skull radiographs

Intraoperative anteroposterior orientation (top left) of the patient's head for sequential or simultaneous implants with the resultant post insertion skull radiograph (bottom left). The angle of the X-ray (aX) relative to the anteroposterior head orientation is 0°. Oblique orientation of the patient's head performed for unilateral implants (top right) produces a variable rotation angle relative to the X-ray beam, 0°<aX<90°. The resultant oblique skull radiograph in shown (bottom right). Open arrows: cochlear implant electrode coil.

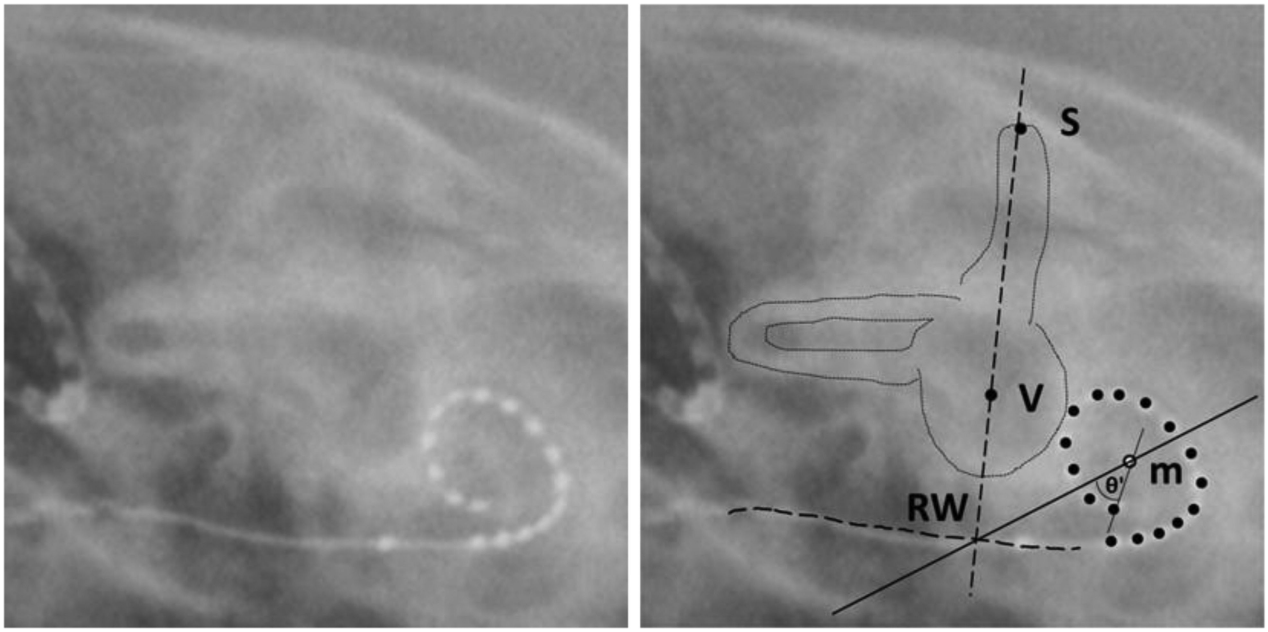

Figure 2. Landmark markers on the post-insertion skull radiograph for determining angular depth of insertion

The left image is an unmarked radiograph of a right cochlea. The right image contains markers, added as follows: the apex of the superior semicircular canal (S) and the center of the vestibule (V) are determined by visual inspection of the plain film (dotted outline of vestibule, horizontal and superior semicircular canals) and a vertical line is drawn through them (dashed vertical line); the point where this line intersects the electrode lead (dashed curved line) approximates the round window (RW). The modiolus (m) is determined at the center of the electrode spiral (outlined by the individual electrode leads) and defines the 0° reference line (full line) from the RW. The aDOI is the angle of rotation the most distal electrode assumes with respect to the 0° reference line (in this example, 360°+ θ’).

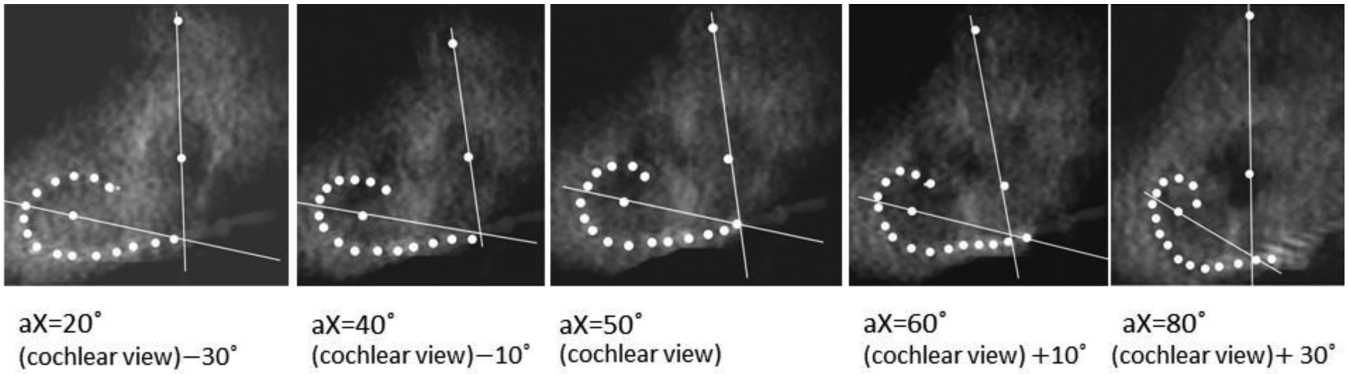

Figure 3. Simulated X-rays from 3-D Computed Tomography (CT) reconstructions

The 3-D reconstruction is rotated from aX=0° to aX=80° in 10° increments and the 2-dimensional projections are termed "simulated X-rays." Shown are simulated X-rays in departures up to −30° and +30° from the cochlear view (50°) angle of a left cochlea.

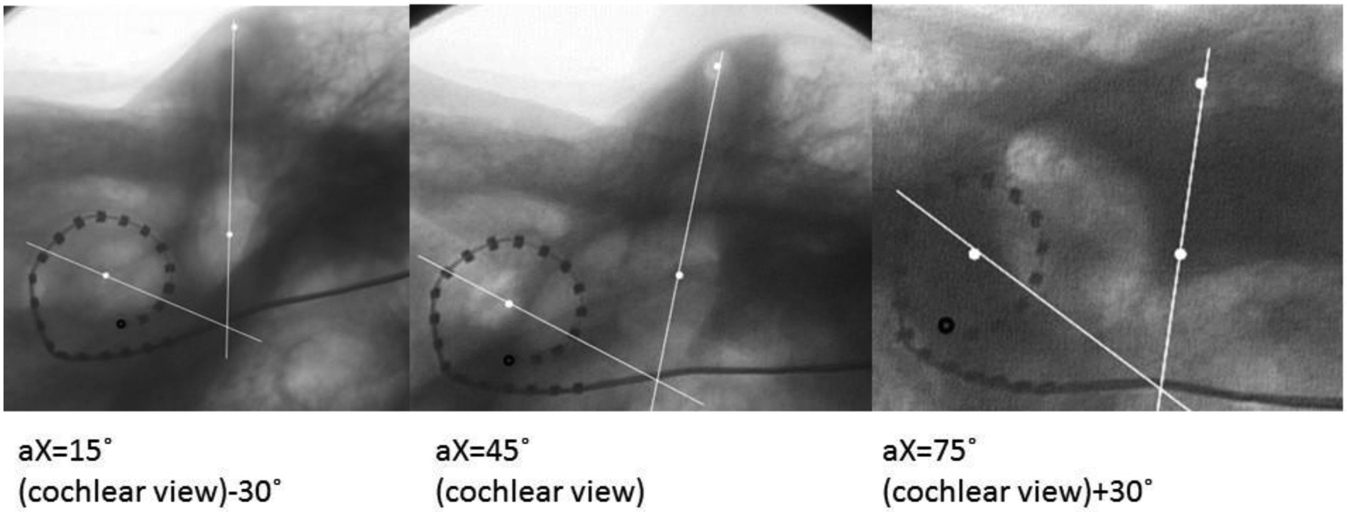

Figure 4. Fluoroscopy of temporal bone with implanted 22-lead array

A left Temporal bone and cochlear implant are rotated in 15° intervals. Fluoroscopy-generated images are shown for 30°, 45° (close to cochlear view) and 60° rotations.

Table 1

Dependence of calculated aDOI on simulated X-ray angle (sim aX)

sim aX (degrees)	Departure from cochlear view (degrees)	Rater 1 aDOI	Rater 2 aDOI
0	−50	313.4	308.8
+10	−40	310.4	301.7
+20	−30	309.9	291.0
+30	−20	310.1	292.0
+40	−10	305.8	297.1
+50	0	308.0	285.5
+60	+10	311.8	298.0
+70	+20	310.5	283.7
+80	+30	299.5	301.3

The calculated angular depth of insertion (aDOI) varies little with the change in simulated X-ray angle. Rater one and rater two calculations are shown.

Table 2

Dependence of calculated aDOI on temporal bone X-ray acquisition angle (aX)

aX (degrees)	Departure from cochlear view (degrees)	Rater 1 aDOI	Rater 2 aDOI
+15	−30	413.2	422.2
+30	−15	424.2	432.8
+45	0	423.0	434.7
+60	+15	434.5	444.1
+75	+30	436.0	437.7
+90	+45	424.9	434.8

The calculated angular depth of insertion (aDOI) varies little with the change X-ray acquisition angle (aX). Rater one and rater two calculations are shown.