ORIGINAL MANUSCRIPTS

RADIOLOGIC EVALUATION OF MULTICHANNEL INTRACOCHLEAR IMPLANT INSERTION DEPTH

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ABSTRACT

Postoperative plain film x-rays are necessary in all multichannel cochlear implant patients to confirm intracochlear position, detect possible electrode kinking, and provide a reference if postoperative slippage occurs. In addition, precise documentation of multichannel intracochlear electrode insertion depths is necessary for comparison of speech recognition results among patients and may be of use for future speech processing strategies. In the present study, a method has been devised, using a modified Stenver’s view, to more accurately document insertion depths of the electrode array and location of individual electrodes on 50 multichannel cochlear implant patients. Surgical estimates of insertion depth are shown to have great variability in regard to distance along the basilar membrane when compared with x-ray documentation. Additionally, there is preliminary evidence that insertion depth, as determined by x-ray studies, has a strong correlation with open-set speech discrimination.

Precise documentation of insertion depths and electrode positions for the Melbourne/Cochlear multichannel cochlear implants is vital to ensure correct intracochlear positioning and absence of electrode kinking. Surgical estimates of insertion depth have been shown to be a significant factor in predicting open-set speech understanding. It is important in patient studies to control for insertion depth, and therefore a precise method of report is needed. Future speech processing strategies may incorporate characteristic frequency mapping. In this form of mapping the electrodes are matched to the characteristic frequency of the surviving ganglion cells. Knowledge regarding the position of electrodes in respect to the characteristic frequency of the stimulated ganglion cells will facilitate mapping.

The insertion depth of the Melbourne/Cochlear multichannel implant is often taken from the operative report, but this method has several drawbacks. Surgeons counting the electrodes outside of the cochlea are hampered by a narrow view through the posterior tympanotomy and are looking down the axis of the electrode array. Secondly, there is no convention as to whether the counting should begin at the level of the scala tympani, at the beginning of the cochleostomy, or from the round window niche. Thirdly, cochleostomy sites vary between one case and the next. A round window insertion does not permit the surgeon to insert the electrode array as far along the basilar membrane as a more apically placed cochleostomy, for the same length of inserted electrode. In addition postoperative slippage may occur if the electrode array has not been fixed at the fossa incudis buttress. Lastly, surgical estimates of depth of insertion do not localize the individual electrodes. For these reasons we have devised a technique to more objectively document insertion depth utilizing a modified Stenver’s view.
MATERIAL AND METHODS

Patients were randomly chosen from the Melbourne cochlear implant clinic at the Royal Victorian Eye and Ear Hospital. The surgical depths of insertion were taken from the operative reports. The surgical team at the hospital counted the number of electrodes outside of the superficial aspect of the cochleostomy, and from this, the length of insertion depth was inferred. The x-ray study was performed in three parts. A dry human skull with a multichannel implant was x-rayed with multiple modifications of Stenver’s view, to obtain a range of views to be tested on patients, as well as to devise a measurement technique. A pilot study on 12 patients was then performed, utilizing four views, to obtain an optimum view for measuring insertion depth and to assess the insertion depth variability between views. The third part of the study included 50 patients x-rayed with the empirically derived optimum view to assess correlation with the surgical estimate of insertion depth.

Modification of Stenver’s View

A conventional Stenver’s view is an oblique posteroanterior projection of the petrous bone with the patient in the prone or sitting position. The head is adjusted such that the mid-sagittal plane is angled 45 degrees to the film plane and the infraorbitomeatal line (a line through the infraorbital rim and superior aspect of the external auditory meatus; also known as Frankfurt’s line) also perpendicular to the plane of the film. The central x-ray beam is then angled 12 degrees cephalad to the infraorbitomeatal plane, a plane containing the right and left infraorbitomeatal lines, which is also known as the horizontal plane. To select the modification of Stenver’s view that could give the optimum projection of an inserted intracochlear electrode array and other labyrinthine structures, multiple variations of the view were carried out on a dry human skull with an implanted electrode array. It was thought important at the outset that other labyrinthine structures, specifically the superior semicircular canal (SSC) and vestibule, as well as the inserted array, be well visualized to later serve as reference points from which to measure. In general, an optimum view would have the central ray parallel to the modiolar axis so that the electrode array is essentially parallel to the film plane and does not overlap itself. Simultaneously, the view would show a clearly definable reference point or points upon which measurements could be based. The pertinent structures to be visualized are shown in Figure 1.

Selection of Optimum Modification of Stenver’s View

A range of possible modifications of Stenver’s view meeting the above criteria were selected from dry-skull study. These were then tested on implanted human subjects, to determine the optimum view for patients and to assess variability among the views. A pilot group of 12 patients implanted with a Melbourne/Cochlear multichannel implant were x-rayed with four modifications of Stenver’s view that were suggested by our dry-skull study (Table 1, Fig. 2).
Table 1. Study on Modification of Stenver's View

<table>
<thead>
<tr>
<th>Modification</th>
<th>Angle X</th>
<th>Angle Y</th>
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<tr>
<td>1</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>50</td>
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<td>3</td>
<td>10</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>50</td>
</tr>
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</table>

(See Fig. 2 and text for definitions of angle X and angle Y.)

Angle X is the angle between the central x-ray beam and the horizontal plane; angle Y is the angle between the mid-sagittal plane and the plane of the film (see Fig. 2). A bather's cap, with a line along the mid-sagittal axis, and a protractor are used to mark the correct angle Y. The central x-ray beam is perpendicular to the film plane, and the head is adjusted to obtain the correct angle X. An optimum view for patients was empirically selected from the four tested views. The use of fine focus and a small localizing cone are essential. Enlargement techniques (i.e., macrographs) are also employed. Every effort is made to obtain good contrast and accurate positioning of the patient.

Radiologic Evaluation of Electrode Insertion Depth

The view utilized in common with this portion of the study was based on the empirically derived optimum view. Fifty patients were included in this portion of the study, including the 12 from the pilot study utilizing the view with \( Y = 50 \) degrees and \( X = 0 \) degrees (see Results). To objectively document the depth of insertion and to localize individual electrodes, the radiograph had to be subdivided in respect to fixed reference points. We chose the apex of the SSC and the mid-point of the vestibule to define a baseline to which other lines would be referred. Preliminary studies of Silastic molds and 3-D computer reconstructions of the labyrinth indicate that this baseline passes near the round window.

Dividing the Cochlea

The cochlea is divided by drawing vertical and horizontal lines so as to create quadrants of the cochlea on the x-ray film itself or on translucent paper (Fig. 3). The first vertical line (VL1) is drawn through the superior semicircular canal, which optimally, should be nearly parallel to the axis of the central x-ray beam and usually appears as a single radiolucent shadow. If the axis of the x-ray beam is not parallel to the plane of the SSC, the SSC appears as an elliptical loop. Nevertheless a vertical line (VL1) is drawn through the center of the SSC apex and through the center of the vestibule, which is measured directly. The vestibule is always well visualized if the radiologic technique permits SSC visualization. This is the baseline (VL1) on which the other lines are oriented, and therefore care should be taken in its construction.

The first horizontal line (HL1) is drawn perpendicular to VL1 at the level of the lowest point of the basal turn. The lowest point of the basal turn at times is directly visualized, but more frequently it is suggested by the curvature of the inserted array, because the electrode array often rests on the outer wall of the scala tympani. The second vertical line (VL2) is drawn parallel to VL1 (perpendicular to HL1) across the anterior margin of the basal turn (tangent to the ascending basal turn). The margin may be directly visualized, but is usually marked by the electrode array along the outer wall of the scala tympani. The second horizontal line (HL2) is perpendicular to VL1 and is drawn tangentially to the superior-most portion of the basal turn, thus enclosing the cochlea in a rectangle defined by VL1, HL1, VL2, and HL2.
The superior-most portion of the basal turn may be directly visualized, but if not, it can be defined by the electrode array, if present to this point.

To begin dividing into quadrants, the distance between HL1 and HL2 is measured and a line is drawn horizontally through the mid-point perpendicular to VL1 and VL2. This is the horizontal quadrant line (HQL).

The last line is the most difficult to draw. A vertical line is drawn perpendicular to HL1 and HL2 (parallel to VL1) through the mid-point of the portion of HQL defined by VL2 and the posterior (vestibular) margin of the apical end of the basal turn, which is directly visualized. This margin is almost always visualized with good radiologic technique. If the cochlear margin is not directly visualized, the mid-point between VL2 and the posterior edge of the electrode array (if present at this point) along HQL is utilized. This is the vertical quadrant line (VQL). The intersection of HQL and VQL is the center of the basal turn.

Quantifying Insertion Depth

Once the cochlea has been divided into quadrants by the HQL and VQL, the depth of insertion is quantified. The number of electrodes are counted for each quadrant. The first quadrant of the basal turn begins at VL1 and ends at VQL. (VL1 is used as the starting point because it is likely to cross near the round window area, as seen in the dry-skull study and Silastic molds of the osseous labyrinth.) Subsequent quadrants are based on HQL and VQL. For example the fourth quadrant of the basal turn is defined by the superior arm of VQL and the vestibular (posterior) arm of HQL. Electrodes that fall on the dividing lines are counted one half for each of the contiguous quadrants. For example, in Figure 3(bottom) the electrodes in each quadrant would be documented as 6.5 E 1st B (6.5 electrodes in the 1st quadrant of the basal turn), 5.5 E 2nd B, 6 E 3rd B, 5 E 4th B, 4 E 1st M (M = middle turn), 3 E 2nd M.

To calculate the linear insertion depth, the total number of electrodes distal to VL1 are counted and multiplied by 0.75 mm (distance between electrodes) and 0.3 mm added (length of tip). The turns are divided into 24ths (6/24ths per quadrant) and the number or fraction of turns occupied is converted into degrees of insertion. For example, Figure 3(bottom) shows the entire basal turn occupied (24/24) and half of the middle turn (12/24), that is, 1.5 turns were occupied by the array, giving 540 degrees (1.5 x 360).

RESULTS

View Selection

An analysis of variance (ANOVA) with radiologic view as the independent variable showed no significant difference between the four modifications of Stenver's view with respect to radiologic insertion depth, as measured in degrees ($p > 0.997$) or mm ($p > 0.993$) from VL1. The range of difference of insertion depth, as measured in degrees, was not more than 16 degrees in any patient for the four modifications tested, and the mean of the difference between views per patient was 3.6 degrees (SD = 6.9 degrees). The range of difference of insertion depth, as measured in millimeters, was not more than 1.5 mm in any patient, and the mean of the difference between views per patient was 0.81 mm (SD = 0.34 mm). Therefore there is little error introduced in terms of degrees or millimeters of insertion from VL1, if one of the modifications listed in Table 1 is used. Since there is little variability noted among several different views, it is unlikely that repeated measures on any individual view would show significant variability. Utilizing our measurement technique, documentation of insertion depth is reliable and repeatable. In three of our patients the electrode array had passed into the second quadrant of the middle turn. In these patients the optimum view was $Y = 50$ degrees and $X = 0$ degrees, in that the other views at times resulted in overlap with the array in the basal and middle turns (Fig. 4). This view more commonly resulted in the central x-ray beam being in the plane of the SSC. Radiographs with $Y = 45$ or $50/X = 20$ degrees were tried in the early portions of the study but were discarded secondary to electrode overlap. It appears, though, electrode overlap does not affect quantification of insertion depth. Because the SSC, vestibule, and electrode array were the major orienting landmarks, optimum viewing was essential. For these subjective reasons, the 50/0 degree view was chosen as the optimum view, even though minor angulation changes do not affect depth quantification.

Figure 4. Magnified 50/20 degree posteroanterior oblique view of patient 49. Note the overlap of the electrode array image between the middle and basal turns.
Correlation of Surgical and Radiologic Depth of Insertion

Comparison of the surgical insertion depth in millimeters with the radiologic linear insertion depth in millimeters from VL1 is shown in Figure 5. There is great variability of millimeters of insertion radiologically for any given surgical insertion depth. For example 25 mm of surgical insertion depth corresponds to a range from 13.8 mm to 25 mm, or 210 to 540 degrees of radiologic insertion depth. Thus, the surgical depth of insertion does not give a consistent distance along the basilar membrane.

DISCUSSION

Postoperative radiographic documentation is necessary for all implant patients to ensure intracochlear position, detect electrode kinking, and serve as a reference, in addition to future uses, for speech processing strategies and research purposes. Although high resolution CT is a significant advancement in the radiographic evaluation of small structures of the temporal bone, the plain radiograph of a modified Stenver's view is the best way to demonstrate the whole intracochlear electrode array. It takes several tomograms to cover the cochlea and each tomogram shows only part of the electrode array. In addition, the artifact caused by metal electrodes blurs the image. A single, plain radiograph of a modified Stenver's view is sufficient to demonstrate the electrode array as a whole and clearly shows the position of each individual electrode.

The 50/0 degree posteroanterior oblique view with the mid-sagittal plane forming an angle of 50 degrees with the plane of the film and the central ray 2 cm above and parallel to the horizontal plane (infraorbitomeatal plane) is the empirically derived best choice for showing the electrode array. The SSC is approximately perpendicular to the axis of the petrous bone, which is angled 40 to 54 degrees to the mid-sagittal plane depending on various head morphologies and ages. The plane of the SSC and the cochlear axis are roughly parallel. The 50/0 degree oblique view of the petrous bone results in a radiograph in the majority of patients that shows the SSC as a vertical lucent line, the vestibule as an oval lucency, and the intracochlear electrode array located in basal and middle turn as a non-overlapping spiral (see Fig. 3). Although the other views did not significantly alter the depth of insertion, as measured in degrees or millimeters, they were less than optimum qualitatively, because of electrode overlap and identification of the SSC (see Fig. 4).

The construction of the baseline (VL1) is critical in maintaining low intrasubject variability and repeatability. In the technique presented, a line is drawn between two points (the apex of the SSC radiolucency and the measured center of the vestibule), chosen after the consideration of alternatives. Other procedures considered, but not tested statistically were to bisect the SSC, but at times the posterior limb of the loop was not visualized, or to draw a line between the apex of the SSC and the center of its base (i.e., where the SSC joins the vestibule), but again some radiographs of the same patient did not clearly visualize the base. The radiographer's attention to detail is essential for good quality films. The vestibule is always well visualized if the SSC is well visualized, although its margins are sometimes indistinct. Nevertheless, a small error in estimating the center of the vestibule would not magnify the error of drawing VL1 as much as a similarly small error with the other two techniques, since the defining points are further apart. Thus the present technique of constructing VL1 minimizes intrasubject variability.

The authors obtain postoperative modified Stenver's views on all implant patients. It is difficult to have all children less than 3 to 4 years of age maintain the optimum positioning in the awake state, therefore 50/0 degree AP oblique projections, instead of a posteroanterior oblique view, are routinely performed on all young children just prior to extubation intraoperatively, to document electrode position. In the AP projection the patient is in the supine position, and the head is turned away from the implanted side, similar to the posteroanterior projection, so that the sagittal plane is again 50 degrees to the plane of the film and the central x-ray beam is parallel to the horizontal line. It should be noted that AP radiography delivers a higher radiation dose to the lens of the eye, which is considered radiosensitive. Using leaded glass or a small field of view can minimize potential injury to the lens.

It is common to report intracochlear implant insertion depths from the operative report, based on
The technique of quantifying insertion depth is a way to do this utilizing a plain film. Although a line window (based on Silastic molds of the labyrinth and 3-D renderings of histology slides) this cannot be relied upon until further studies are completed. To simplify matters, we have chosen to describe depth of insertion as degrees of insertion from VL1 or as linear distance in millimeters by counting electrodes from VL1. The technique of quantifying insertion depth radiologically is simple and reliable. Once the technique is mastered it requires less than 5 minutes; it is resistant to radiologic positioning error within a certain range, and with experience, there is excellent reproducibility.

We have x-rayed the first patient with bilateral multichannel implants and correlated the psycho-physical results, surgical report, and x-ray study to corroborate the accuracy of x-ray insertion depth over surgical insertion depth. The x-rays predicted that there would be a six-electrode difference (i.e., the right implant inserted six electrodes further). Psychophysical testing also found exactly a six-electrode difference (right deeper than left). The surgical reports, however, stated the right had a 21-mm and the left a 23-mm insertion, which was contradicted by both the x-ray estimate and the psychophysical results. As the electrodes had not been fixed at the fossa incudis, the likely explanation for this discrepancy is postoperative slippage. Further clinical experience has shown the present x-ray technique to correlate well with mapping discrepancies in difficult cases. In particular, it is possible to determine accurately which electrodes are outside the cochlea, since many times the cochleostomy can also be visualized. The present technique is expected to find its most immediate application in sorting out mapping problems and as a routine procedure prior to mapping, especially in young children.

Correlation of patient performance with radiologic insertion depth is pending. Blamey et al have shown that surgical estimates of insertion depths are correlated with open-set CID sentence scores with a correlation coefficient, R, of 0.225. A preliminary analysis was performed on the 20 patients in this study who were post-linguistically deafened adults, spoke English as a native language, and had speech results using a WSP III speech processor. The results of open-set CID sentence scores were correlated with the surgical or radiologic insertion depth. Linear regression with the CID score as the dependant variable showed an R = 0.33 (p < 0.15) with the surgical insertion depth as the independent variable and R = 0.59 (p < 0.006) with the radiologic insertion depth, in millimeters from VL1, as the independent variable. Multiple regression analysis with other pertinent variables will be required in the future to test these preliminary results. If the correlation between open-set CID sentence scores and radiologic insertion depth remains around the level found in this study then radiologic insertion depth will be an important variable to control for in future studies, because it may account for 30 to 40 percent of CID score variability (R2).

For the purpose of characteristic frequency mapping, the insertion distance in millimeters or degrees from VL1 cannot be directly related with distance along the basilar membrane or as a percentage of total cochlear length as required by Greenwood's cochlear frequency-position function. It may in fact be more useful to consider angular distance for characteristic frequency mapping, since the electrode array may not always lie along the outer wall of the scala tympani. Bredberg has performed temporal bone studies that correlate the degrees along the basilar membrane to the distance. The degrees of insertion of the electrode array or polar coordinate of a particular electrode, as determined by our plain film technique, cannot be correlated with Bredberg's study at this time, since he referred to an origin at the helicotrema, which cannot be pin-pointed radiologically. Studies are presently under way to make the correlation between radiologic insertion depth and Greenwood's frequency-position function. The eventual aim would be to facilitate characteristic frequency mapping.

REFERENCES

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