Computed Tomography of Single-Channel Cochlear Implants

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Computed tomographic (CT) examinations were performed in seven patients after cochlear implant surgery. Preimplantation CT demonstrated the petrous anatomy well and revealed an abnormality in one case. Postimplantation CT adequately assessed electrode position in all cases. Malposition of the active electrode was identified in one patient. Electrode position was correlated with postimplantation audiometric testing. A "transpetrous" projection was used to image perpendicular to the active electrode within the basal turn of the cochlea. A potential pitfall was identified where the ground electrode tip appeared to be embedded in the carotid canal cortex due to partial-volume averaging. With further experience, the clinical utility of CT in cochlear implantation patients will be better defined.

Cochlear Implant Device and Surgery

Individuals with profound sensorineural hearing loss in whom conventional hearing aids do not significantly improve hearing may benefit from cochlear implantation devices [1–4]. The cochlear implant is an electronic auditory prosthesis that delivers an electrical signal to the cochlea in an attempt to bypass the damaged part of the cochlea and stimulate the cochlear nerve. Increasing numbers of patients are being implanted by otologic surgeons, and both single-channel and multiple-channel devices exist.

All implanted patients in our study received a single-channel House cochlear implant system (3M) (fig. 1). The external component consists of a signal processor with a microphone and external transmitter coil. The internal component consists of an internal receiver coil attached to an active electrode and a ground electrode. All but the distal 6 mm of the active electrode is electrically insulated. After mastoidectomy, the internal receiver coil is placed subcutaneously against the skull outer table superoposterior to the external ear (fig. 2). The active electrode is introduced via the facial recess passing inferior to the pyramidal eminence into the round window niche and then through the round window into the scala tympani of the basal turn of the cochlea [5, 6] (fig. 3). The course of the active electrode passes along the anterolateral aspect of the vertical mastoid segment of the facial nerve. Fascia is placed at the round window and fills the posterior tympanum. The ground electrode is introduced via the epitympanum, passing medial to the malleus-incus joint and into the eustachian tube (fig. 4).

After the surgical incision has healed, the external transmitter coil is coupled transcutaneously to the internal receiver coil using a magnet. The signal processor and microphone are worn in a convenient place such as a shirt pocket or attached to the belt. Sound is picked up by the microphone and converted to electrical signals by the signal processor, which in turn generates an electrical signal within the internal receiver coil by means of electromagnetic induction. Current density produced at the active electrode within the basal turn of the cochlea stimulates fibers of the cochlear nerve.

The cochlear implant provides timing and intensity cues from the sound environment [2, 7, 8]. While sound detection is achieved, only limited sound discrimination is possible and speech understanding is not possible through audition alone. The device does allow the user to be more aware of his/her surroundings. Lip reading is easier, as is modulation of his/her own voice, when the device is in use. Using a telephone code and the cochlear implant, it is possible for the deaf individual to use the phone. Many implant patients report a profound improvement in the quality of their lives [4, 9]. While normal hearing is not attained, the

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Fig. 1.—Single-channel cochlear implant system. External component (*top*) consisting of (*left to right*) microphone, signal processor, and external transmitter coil. Internal component (*bottom*) consisting of internal receiver coil (round disk) with active and ground electrodes (wires) attached.

benefits are significant, and it is hoped that improvements will provide more normal sound perception.

Study Objectives

Before implantation surgery, extensive testing is performed that includes radiographic evaluation of the temporal bone [4, 6, 10]. Conventional pleuridirectional tomography can be used for detailed evaluation of temporal bone structures. However, high-resolution computed tomography (CT) offers superior contrast resolution, the ability to clearly delineate soft-tissue structures, and decreased radiation exposure as compared with conventional pleuridirectional tomography [11].

A series of patients was evaluated with CT before and after cochlear implantation surgery in an attempt to evaluate the clinical utility of CT. A thorough literature review did not reveal any reports on the CT appearance of the single-channel cochlear implant device. In addition to determining the normal CT appearance of the cochlear implant, possible complications that could be detected by CT were sought. The smallest distance between the active and ground electrodes was correlated with postimplantation audiometric testing.

Subjects and Methods

Patients

Nine patients (five women, four men) aged 27–77 years (average, 46.5 years) were evaluated. Seven preimplantation and seven postimplantation CT examinations were performed. Two patients were evaluated before implantation only and did not receive an implant device. Five patients were evaluated both before and after implantation. Two patients were evaluated after implantation only. The average time between surgery and postimplantation CT evaluation was 105 days (range, 29–209 days).

CT Technique

All examinations were performed on a GE 9800 CT scanner. All patients (pre- and postimplantation) were initially examined with 1.5-mm axial sections at 30° above the Reid baseline (infraorbital-meatal line). Four preimplantation evaluations included direct coronal 1.5-mm or 3.0-mm sections. Six postimplantation evaluations included 1.5-mm sections in a plane perpendicular to the long axis of the petrous bone. This "transpetrous" projection (fig. 5) was chosen in an effort to obtain a cross section of the basal turn of the cochlea, which contains the active electrode. This technique was performed with the patient in one of two positions: (1) supine, neck hyperextended, head turned 45° toward the side examined; or (2) supine, neck hyperflexed, head turned 45° toward the side examined. In both of these positions, maximum comfortable neck hyperextension or hyperflexion coupled with 20° of gantry angulation allowed scanning perpendicular to the skull base. Appropriate head turning allowed scanning perpendicular to the long axis of the petrous bone. Zonneveld et al. [12] used a different technique to obtain essentially the same projection and called it the axiopetrosal plane.

Preimplantation CT was performed to ascertain the presence of normal temporal bone anatomy, in particular the posterior tympanum and inner ear structures, and to exclude other causes for sensorineural hearing loss. Postimplantation CT was performed in an effort to evaluate the surgical result, particularly the position of the electrodes. The smallest distance between the noninsulated distal 6 mm of active electrode within the basal turn of the cochlea and the ground electrode within the middle ear was determined on both axial and "transpetrous" sections. Because of their serpiginous route through the middle ear and small size, it would be difficult or impossible to accurately measure the distance between electrodes using plain radiographs.

Audiometric Testing

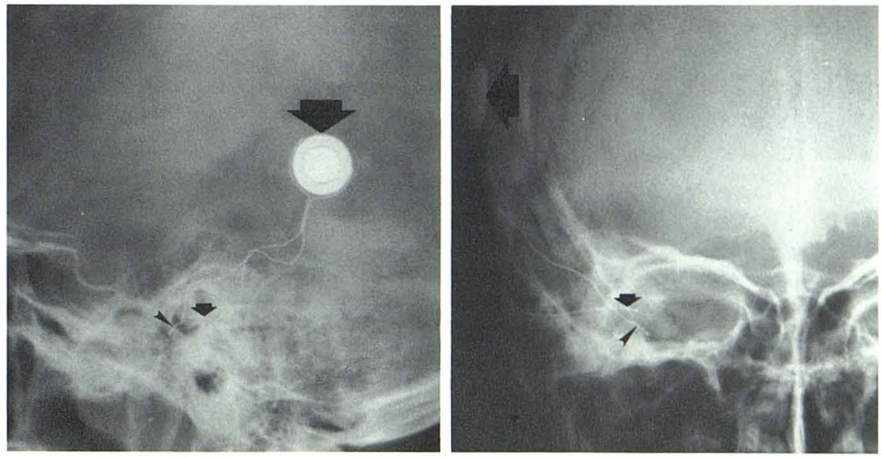
The hearing threshold level in decibels is determined by measuring responses to pure tone stimuli at various frequencies. In addition, a speech detection threshold was determined using a standardized list. Pure tone threshold levels were determined for our patients at 500, 1000, 2000, and 3000 Hz. Averaging these four threshold levels yielded an average detection threshold for frequencies in the speech range.

Each patient's detection and discomfort thresholds in response to electrical stimulation were measured. The electrical threshold information was used to set the voltage of the carrier wave in the externally worn signal processor unit. To allow continuous but inaudible stimulation of the active electrode, the voltage was decreased to a level just below the electrical threshold. This setting is referred to as the carrier level. Both the electrical threshold and the carrier level were determined in all seven postimplantation patients.

Results

Preimplantation CT

The round window niche appeared normal in all cases, and bone at the round window measured no greater than 1 mm. In case 1 the basal turn of the cochlea was poorly demonstrated bilaterally because of narrowing and/or ossification of the bony canal. The otic capsule was thick and dense bilat-



A B

Fig. 2.—Lateral (**A**) and anteroposterior (**B**) skull radiographs demonstrating internal component of single-channel cochlear implant system. Internal receiver coil (*large arrows*), active electrode entering basal turn of cochlea (*small arrows*), and ground electrode within eustachian tube (*arrowheads*).

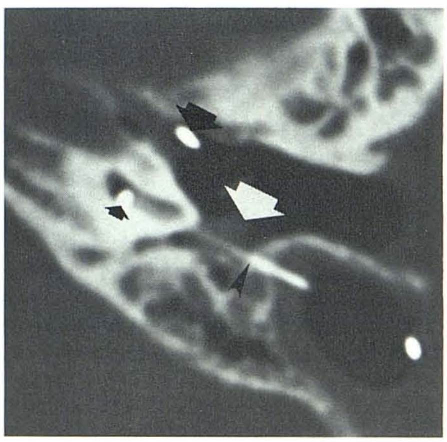


Fig. 3.—Axial CT section of left petrous bone. Active electrode (*arrowhead*) enters posterior tympanum via facial recess and extends into cochlea via round window. Active electrode tip (*small black arrow*) easily seen within basal turn of cochlea, ground electrode (*large black arrow*) entering eustachian tube, and soft-tissue density fascia (*white arrow*) within posterior tympanum.

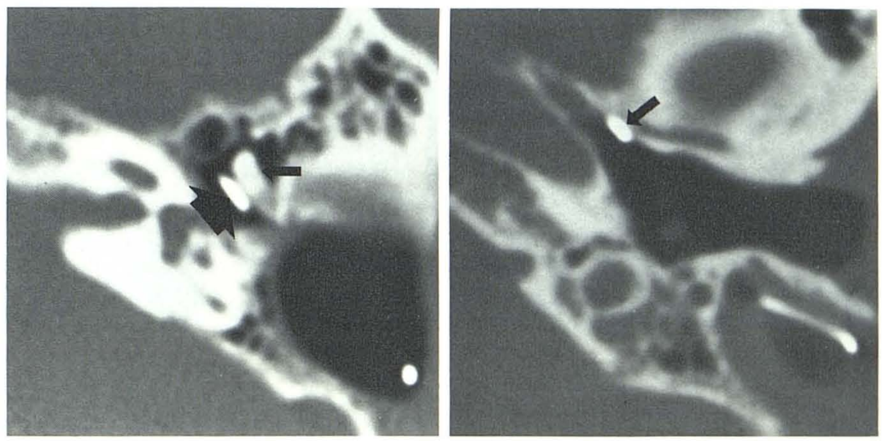


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Fig. 4.—Axial CT sections of left petrous bone. **A**, At level of epitympanum. Ground electrode (*large arrow*) passes medial to malleus-incus joint (*small arrow*). **B**, At level of mesotympanum. Ground electrode (*arrow*) enters eustachian tube.

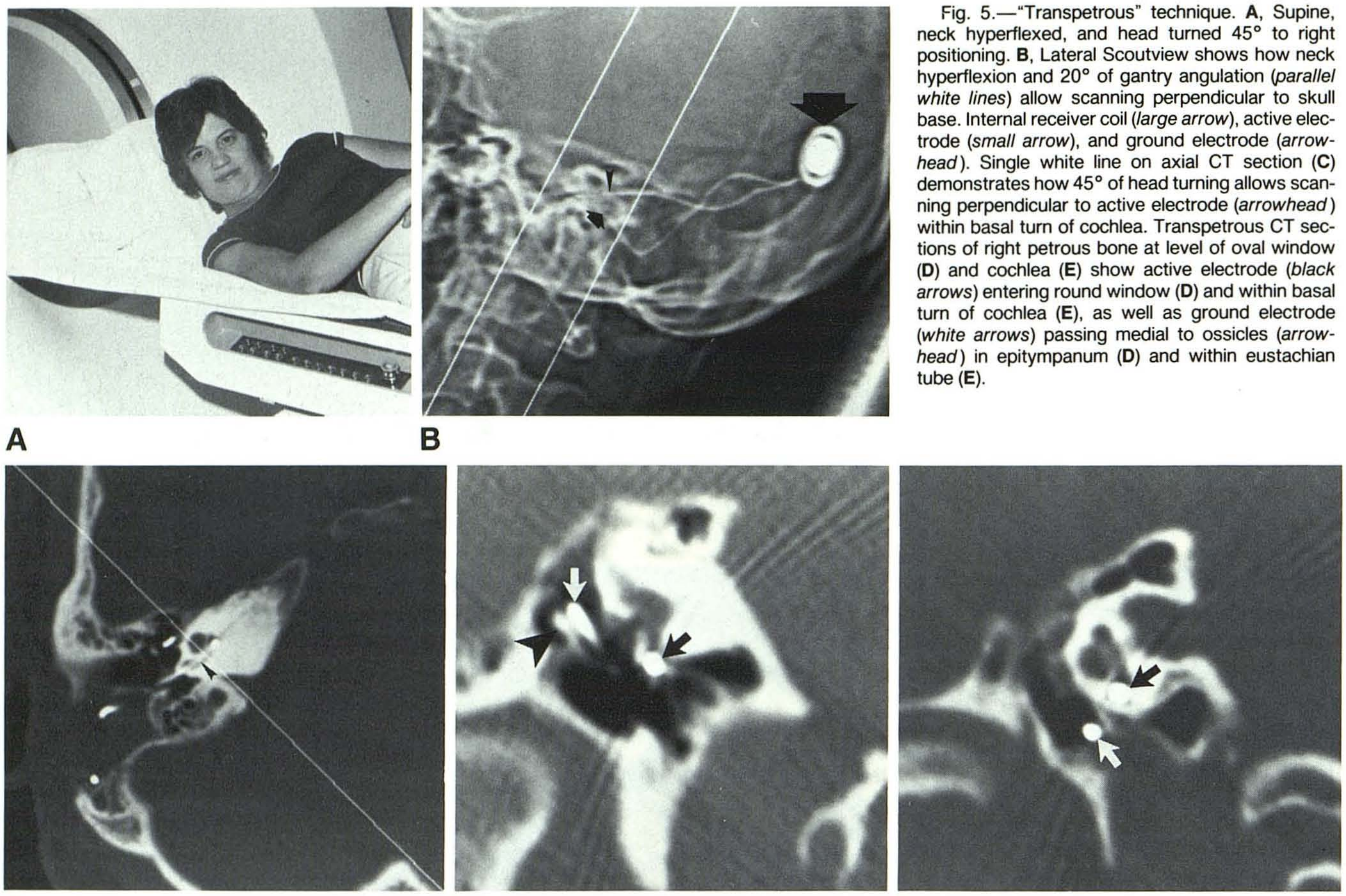
erally in this patient. At implantation surgery, the basal turn was ossified and had to be drilled out to insert the active electrode. The cochlea appeared normal bilaterally in all other patients. The posterior tympanum, facial nerve, and facial recess appeared normal in all cases. Two temporal bones had partly opacified mastoid air cells, and one patient had decreased pneumatization on a congenital basis. Three temporal bones contained a high jugular bulb, and in one patient there was thinning of cortical bone along the posterior petrous bone on one side.

In no case did the preimplantation CT findings aid in selecting the side for surgery. All observations considered pertinent to cochlear implantation surgical planning were observed on the axial sections. In no case did the coronal sections provide additional information. The degree of mastoid aeration, position of the mastoid segment of the facial nerve, posterior tympanum and facial recess, round window, and cochlea were better evaluated on axial scanning.

Postimplantation CT

In all patients the active electrode could be identified passing through the mastoidectomy defect, then immediately anterolateral to the vertical segment of the facial nerve before entering the posterior tympanum via the facial recess. The active electrode then passed through the round window niche into the basal turn of the cochlea via the round window.

A straight active electrode was identified within the basal turn of the cochlea on all projections. On axial sections, measurements were made from the round window to the tip



A B C D E

Fig. 5.—"Transpetrous" technique. **A**, Supine, neck hyperflexed, and head turned 45° to right positioning. **B**, Lateral Scoutview shows how neck hyperflexion and 20° of gantry angulation (*parallel white lines*) allow scanning perpendicular to skull base. Internal receiver coil (*large arrow*), active electrode (*small arrow*), and ground electrode (*arrowhead*). Single white line on axial CT section (**C**) demonstrates how 45° of head turning allows scanning perpendicular to active electrode (*arrowhead*) within basal turn of cochlea. Transpetrous CT sections of right petrous bone at level of oval window (**D**) and cochlea (**E**) show active electrode (*black arrows*) entering round window (**D**) and within basal turn of cochlea (**E**), as well as ground electrode (*white arrows*) passing medial to ossicles (*arrowhead*) in epitympanum (**D**) and within eustachian tube (**E**).

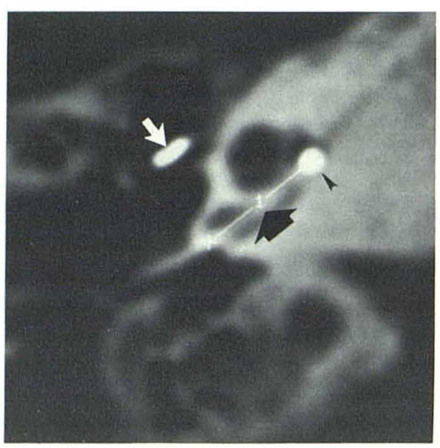


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Fig. 6.—Axial CT section of right petrous bone demonstrates computer measurement (*white line with no. 1*) of active electrode (*black arrow*) within basal turn of cochlea. Active electrode tip (*arrowhead*) and ground electrode within middle ear cleft (*white arrow*).

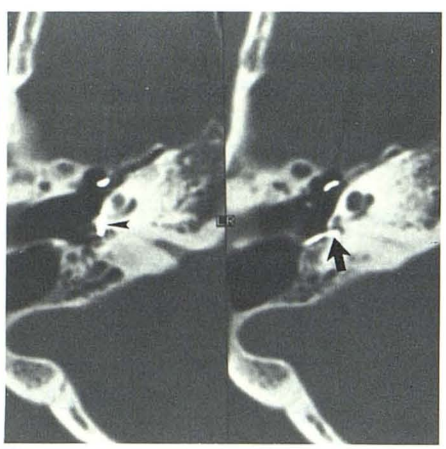

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Fig. 7.—Case 1. Contiguous axial CT sections of right petrous bone demonstrating active electrode entering round window niche (*arrow*) before making sharp turn with only 2 mm of tip entering round window and basal turn (*arrowhead*).

of the active electrode in the basal turn of the cochlea (fig. 6). This measurement was 8 mm in three patients, 7 mm in one patient, and 6 mm in two patients. In case 1 the active electrode made a sharp turn in the round window niche, and only 2 mm of active electrode was seen within the basal turn (fig. 7). The distance between the active and ground electrodes could be measured on both axial and transpetrous sections in all patients on every section that contained active electrode within the basal turn of the cochlea and ground electrode within the middle ear.

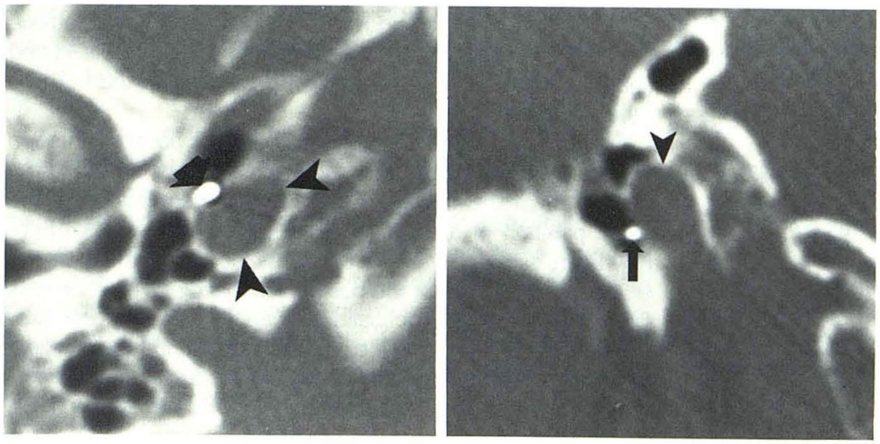

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Fig. 8.—**A**, Axial CT section of right petrous bone at level of hypotympanum. Ground electrode tip (*arrow*) appears embedded within cortex of carotid canal (*arrowheads*). **B**, Transpetrous CT section of right petrous bone demonstrates relation of ground electrode tip (*arrow*) along anterior inferolateral aspect of carotid canal (*arrowhead*), not embedded within carotid canal cortex.

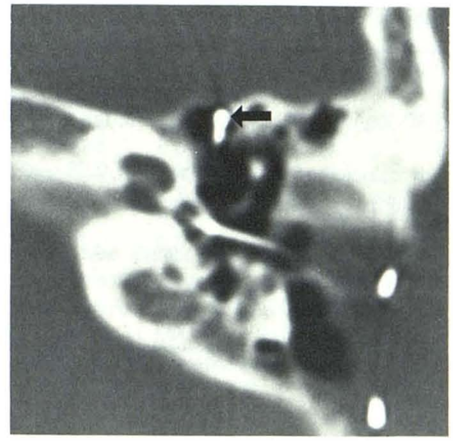

Fig. 9.—Axial CT section of left petrous bone shows more posterolateral location of ground electrode tip (*arrow*) within middle ear cleft.

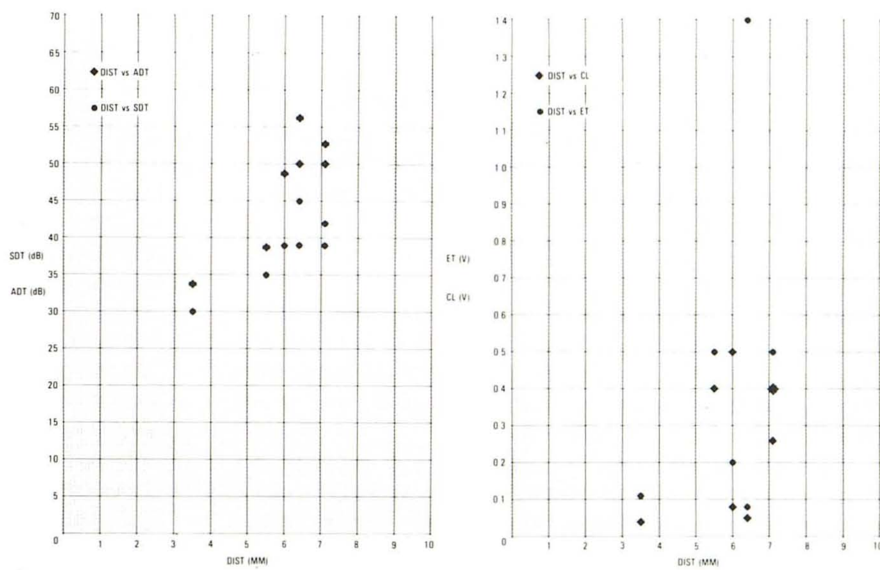

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Fig. 10.—Scatter diagrams of relations between active electrode–ground electrode distance (DIST) and speech detection threshold (SDT) (*circles*, **A**); average detection threshold in speech range (ADT) (*diamonds*, **A**); electrical threshold (ET) (*circles*, **B**); and carrier level (CL) (*diamonds*, **B**).

In five patients the posterior tympanum and round window niche were well aerated. In two patients, a soft-tissue density within the round window niche and posterior tympanum representing fascia was identified (fig. 3).

The ground electrode could be identified passing medial to the malleus-incus joint in the epitympanum and then within the bony eustachian tube in all cases on both axial (fig. 4) and transpetrous (figs. 5D and 5E) sections. In five patients the ground electrode tip was in the most anteromedial aspect of the bony eustachian tube. In four of these five patients the ground electrode tip appeared on one axial section to be embedded in the cortex of the petrous internal carotid artery near the junction of its vertical and horizontal segments or along the horizontal segment (fig. 8A). Transpetrous sections, however, demonstrated the true position of the ground electrode tip along the anterior inferolateral aspect of the carotid canal, not embedded in the cortex (fig. 8B). In two patients the ground electrode was in a more lateral or posterolateral aspect of the eustachian tube (fig. 9).

Postimplantation Audiometric Testing

For all seven patients, the smallest distance between active and ground electrodes (DIST), the electrical threshold (ET), the carrier level (CL), the speech detection threshold (SDT), and the average detection threshold in the speech range

TABLE 1: **Postimplantation Audiometric Testing**

Case No.	DIST (mm)	ET (V)	CL (V)	SDT (dB)	ADT (dB)
1	6.4	1.40	0.50	45	56
2	7.1	0.40	0.26	38	50
3	3.5	0.11	0.04	30	34
4	6.4	0.08	0.05	38	50
5	7.1	0.50	0.40	43	53
6	5.5	0.50	0.40	35	39
7	6.0	0.20	0.08	38	49
Correlation coefficient (r)	...	0.31	0.45	0.81	0.87
Probability (p)	...	0.49	0.31	0.03	0.01

Note.—DIST = distance between active and ground electrodes; ET = electrical threshold; CL = carrier level; SDT = speech detection threshold; ADT = average detection threshold in speech range.

(ADT) are shown in table 1. Scatter diagrams of the relationships between DIST and the other four parameters were prepared (fig. 10), and correlation coefficients (r) were calculated (table 1). There was a statistically significant correlation between DIST and SDT ($r = 0.81$, $p = 0.03$) and between DIST and ADT ($r = 0.87$, $p = 0.01$). There was no statistically significant correlation between DIST and ET ($r = 0.31$, $p = 0.49$) or DIST and CL ($r = 0.45$, $p = 0.31$).

Case 1, in which the active electrode made a sharp turn in the round window niche and entered only 2 mm of the basal turn, had the highest SDT and ADT. This is the same patient who had narrowing and/or ossification of the cochlea bilaterally on preimplantation CT.

Discussion

The size and development of the mastoid air cells and the presence of a normal posterior tympanum and inner ear are important information for surgical planning. "Sclerosing labyrinthitis" or other pathology could make placement of an implant device difficult or impossible.

There are several possible complications of cochlear implant surgery: (1) risks of mastoid surgery (infection, facial nerve paralysis, fluid drainage, meningitis, anesthesia complications); (2) risks of implantation and physical presence of electrodes and induction coil (cochlear damage during active electrode insertion, lack of material biocompatibility, transmission of infection from middle ear to inner ear and mastoid); (3) risks of electrical stimulation of auditory system (electrical damage, osteogenesis); and (4) increase in vestibular symptoms (tinnitus, dizziness) [2, 3, 5, 13–15]. To date none of our patients have experienced any of these complications.

Several other complications might be identified with CT: malposition or breakage of an electrode, opacification of the middle ear (possible infection), or damage to the mastoid segment of the facial nerve. Neither infection nor facial-nerve dysfunction occurred in any of our patients. Currently, case 1 has suboptimal positioning of the active electrode, making a sharp turn in the round window niche and only entering 2 mm of the basal turn of the cochlea (fig. 7). At the time of surgery 5 mm of bone was removed from the round window into the basal turn, and the active electrode was placed at 5 mm. The CT findings suggest a shift in the active electrode position. This patient has high threshold testing (table 1) and finds the cochlear implant device of less benefit than do the other patients.

The transpetrous technique was used for postimplantation CT evaluation to determine if sectioning perpendicular to the basal turn of the cochlea would allow determination of the exact position of the active electrode within the basal turn. However, since the active electrode occupies most of the cross-sectional area of the basal turn, this determination was difficult and of little practical significance. However, this projection does afford a second plane for measuring the smallest distance between the distal active electrode within the basal turn of the cochlea and the ground electrode within the middle ear.

A potential pitfall was noted on axial sections in four of seven postimplantation CT evaluations. The distal tip of the ground electrode within the eustachian tube was seen on axial sections immediately adjacent to the inferior part of the petrous internal carotid artery near the junction of its vertical and horizontal segments or along the proximal horizontal segment (fig. 8A). In these cases the tip appeared to be embedded within the carotid canal cortex. This represents partial-volume averaging of the ground electrode tip with the curving surface of the carotid canal cortex. Transpetrous imaging (fig. 8B) demonstrated the relation of the ground electrode tip along the anterior inferolateral carotid canal and proved that the tip was not embedded within the cortex.

The distance between active electrode within the basal turn of the cochlea and ground electrode within the middle ear had a statistically significant correlation with postimplantation speech detection threshold and average detection threshold in the speech range (fig. 10A, table 1). That is, the smaller the distance, the lower the threshold. However, it must be cautioned that only a small number of patients have been studied. In addition, the exact properties of the electrical field created at and around the electrodes is not entirely known and may be affected by distance between electrodes in an unknown or complicated manner.

From our investigation, several observations and conclusions have been made.

1. CT is useful in the preimplantation evaluation of temporal bone structures.
2. The axial plane +30° from the Reid baseline is the best projection for evaluating those structures pertinent to preimplantation surgical planning, specifically, the mastoid segment of the facial nerve, posterior tympanum, round window, and cochlea. If axial sections are normal, additional projections are of no value.
3. CT is probably useful for postimplantation evaluation only if there is clinical suspicion of a complication or problem. Routine postimplantation CT evaluation in those patients with satisfactorily functioning cochlear implant devices is probably of no value.
4. As with preimplantation evaluation, the axial plane is the most useful in postimplantation evaluation.
5. The "transpetrous" projection is useful for obtaining a cross-section view of the basal turn of the cochlea and for

demonstrating the relation of the ground electrode tip to the petrous part of the internal carotid artery. However, it is probably of little value in routine evaluation of patients post-implantation.

6. On axial sections the ground electrode tip may appear to be embedded in the cortex of the petrous segment of the internal carotid artery. This appearance is due to partial-volume averaging and should not be viewed with alarm.

7. In our small series the distance between the active and ground electrodes correlated positively with speech detection threshold and average detection threshold in the speech range. This correlation is statistically significant. Further investigation is needed to determine if these observations are valid, if these measurements are of practical value, and if any other parameters of electrode placement correlate with threshold testing and ultimately with patient performance.

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