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COMPUTER-AIDED THREE-DIMENSIONAL RECONSTRUCTION IN HUMAN COCHLEAR MAPS: MEASUREMENT OF THE LENGTHS OF ORGAN OF CORTI, OUTER WALL, INNER WALL, AND ROSENTHAL'S CANAL

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This paper describes the application of computer-aided three-dimensional reconstruction to measurements of the length of the organ of Corti (mean ± SD, 35.58 ± 1.41 mm), scala tympani outer wall (40.81 ± 1.97 mm), scala tympani inner wall (18.29 ± 1.47 mm), and Rosenthal's canal center (15.98 ± 1.33 mm) in eight adult male cochleas. The Rosenthal's canal center ranged between 1¾ and 2 turns, did not appear to be linearly related to the organ of Corti, and lay near the basal end of the latter. The length of the organ of Corti measured with three-dimensional reconstruction differed by 7.6% ± 3.2% ("cutting angle difference") from that derived from traditional two-dimensional reconstruction on the plane perpendicular to the plane of section, and by 2.6% ± 1.7% ("geometric difference") from that derived from two-dimensional reconstruction on the axial plane at right angles to the modiolar axis.

KEY WORDS — anatomic measurement, cochlear length, computer model, cutting angle difference, geometric difference.

INTRODUCTION

Computer-aided three-dimensional (3-D) reconstruction can provide much valuable information about 3-D structures that are so small, fragile, and obscure that we cannot observe them without histologic processing and microscopic study. Three-dimensional computer models have been generated from histopathologic specimens, computed tomography (CT) scans, and magnetic resonance imaging. They make it easy to recognize 3-D shapes of structures and relationships among structures and enable us to quantify the distances (lengths), angles, areas, surface areas, volumes, etc. Recent publications have highlighted the potential for 3-D study of the structures within the temporal bone, mainly from histologic sections, to define important anatomic relationships aimed at surgical anatomy of the stapes,[1] facial nerve,[2] vestibular end organ,[3] and cochlea,[4,5] etc. We are utilizing 3-D reconstruction from CT scans of the temporal bone in cochlear implant candidates as part of the preoperative examination and surgical planning.[6,7] On the other hand, a majority of investigators have used the approximate two-dimensional (2-D) graphic reconstruction technique introduced by Guild[8] and Schuknecht[9] to map the organ of Corti (OC) for assessing cochlear function and pathology. However, we believe it is difficult to recognize 3-D structures properly by using 2-D graphic reconstruction. Takagi and Sando[10] described one problem of studying temporal bones using traditional 2-D methods: the "cutting angle" (the angle between the plane of section and the modiolar axis). They compared the length of the cochlea by 2-D and 3-D methods in a single case.

We generated 3-D models of temporal bone section structures on a personal computer. This system enables us to measure several parameters (distances, angles, areas, surface areas, cross-sectional areas, volumes, etc) on 3-D structures, regardless of the angle at which the specimen was cut. This paper reports our method for the 3-D reconstruction of the cochlea and the quantification of cochlear structures: OC, outer wall (OW), inner wall (IW), and Rosenthal's canal center (RCC) from the basal end to the apical end. Knowledge of these distances is important for the placement of cochlear implants, as implant depth is apparently a factor in subsequent performance.[11] The lengths of the OC measured by 3-D reconstruction were compared with those measured by two 2-D methods. The lengths and fractional lengths of each parameter could be calculated for each quarter turn and for each corresponding position of the OC. That is, each structure could be mapped onto the OC.

MATERIALS AND METHODS

Materials. Eight temporal bones were used in this

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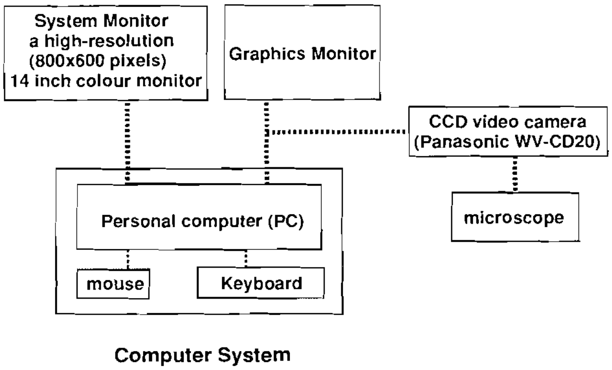

Fig 1. Block diagram of our system. Equipment consists of personal computer, high-resolution (800 × 600) 14-in color monitor as system monitor, graphics monitor, CCD video camera (Panasonic WV-CD20), and microscope.

study. They were obtained at postmortem examination and were from men ranging from 67 to 79 years of age. A brief medical history was obtained, and temporal bones from patients thought to have suffered otosclerosis, obliterative labyrinthitis, or congenital malformation, tumors, or fractures of the region were not included in this study. The bones were placed in formol-saline at 4°C for at least 48 hours, and then rinsed in distilled water. The cochleas were decalcified in 14% ethylenediaminetetraacetic acid in neutral buffered formalin and embedded in Spurr's resin. The blocked cochleas were sectioned at a thickness of 3 μm, and sections from every 130 μm were collected and stained with hematoxylin and eosin.

Preparation of 3-D Reconstruction Images. The equipment consisted of a personal computer, a high-resolution (800 × 600 pixels) 14-inch color monitor as system monitor, a graphics monitor, a charge-coupled device video camera (the Panasonic WV-CD20), and a microscope (Fig 1).

Temporal bone sections were viewed through the microscope and digitized through the video camera connected to the personal computer via a Data Translation DT2851 frame-grabber card, as previously reported.[6] The contrast and brightness of each image could be adjusted to optimize the contrast for the features of interest. With the cursor we manually marked and stored coordinates of the union of the pillar cells' heads as the OC, the most lateral point of the scala tympani as the OW, the most medial point of the scala tympani as the IW, and a point in the center of Rosenthal's canal as the RCC (Fig 2). Each set of data points describing the location of a feature in a section constituted an entry in the data file, with a corresponding line in an index file. Each index entry included the section number and feature number of the data set, plus the number of points in the data. After all relevant points of a given section had been stored, they could be displayed as a red overlay on the real-time image of the next serial section. Thus, the next section could be maneuvered until the best visual fit with all the borders of the previous section had been obtained. This position was then used for the point detection on the new section. Takagi and Sando[10] put reference holes adjacent to the temporal bone specimen before sectioning, but our system allows us to use general histologic series with no artificial reference points. The 3-D reconstruction was made after all features obtained from sequential sections were sorted. Displaying the stored points for the OC alone showed a pseudo–3-D spiral (Fig 3[8-10]).

Measurement of Length of OC. A distance map of the OC was made by summing the distances between successive pairs of points, starting at the basal end in the hook region (as 0) and continuing to the apical end. We excluded the few points that were clearly out of position. Furthermore, we measured the length of every quarter turn as defined by the following method.

Definition of Quarter Turns of OC. The schema for deciding the position of quarter turns of the OC is shown in Fig 4.[12] First of all, the furthest point from the basal end (A0) on the OC is defined as one half turn (A0.5), and a line L0/0.5 is drawn through A0 and A0.5. The furthest point from L0/0.5 in the lower basal turn is one quarter turn (A0.25); the furthest point in the upper basal turn is three quarter turns (A0.75, Fig 4A). If the perpendicular line from L0/0.5 to A0.75 is extended and called L0.75, then the furthest point in the next half turn beyond A0.75 is A1.0, the end of the basal turn, and the perpendicular line from L0.75 to it is L1.0. Similarly, we now proceed iteratively, extending the current line, finding the point furthest from it in the next half turn, labeling that point as the end of the next quarter turn and the line perpendicular to it as the next current line (eg, Fig 4B).

In traditional 2-D reconstruction methods, Bredberg's[12] definition has been used (Fig 4C). He represented the locations based on the angle around the helicotrema. But significant error could be expected from this subjective choice of a center, because the OC is not concentric around it. The eccentricity caused by using the helicotrema–hook region line as an axis affects the axis crossings, and thus, the quarter turn points up to the apical end. On the other hand, our method does not need to set the axis of revolution. It works with only the points in the OC coordinate set, and it is easy to determine a quarter turn from a half turn as described above.

Measurement of Lengths of Every Quarter Turn and Every 4% Interval of OC. For each OC quarter turn, the lengths of the OC, OW, IW, and RCC were

Fig 2. Digitization of cochlear structures. Temporal bone sections were viewed through microscope and digitized through video camera connected to personal computer via Data Translation DT2851 framegrabber card. Organ of Corti (OC, pink dots) was defined as union of pillar cells' heads and was marked manually with cursor on display. Outer wall (OW, yellow points), inner wall (IW, light blue points), and Rosenthal's canal center (RCC, light green dots) were also marked manually.

measured and presented as absolute values and as fractions of the totals. The corresponding positions of the OW, IW, and RCC were selected on the plane perpendicular to the line of the OC at each quarter turn point (Fig 5). Furthermore, in view of individual differences, the lengths of the OW, IW, and RCC corresponding to every 4% interval of the OC were measured the same as quarter turn points.

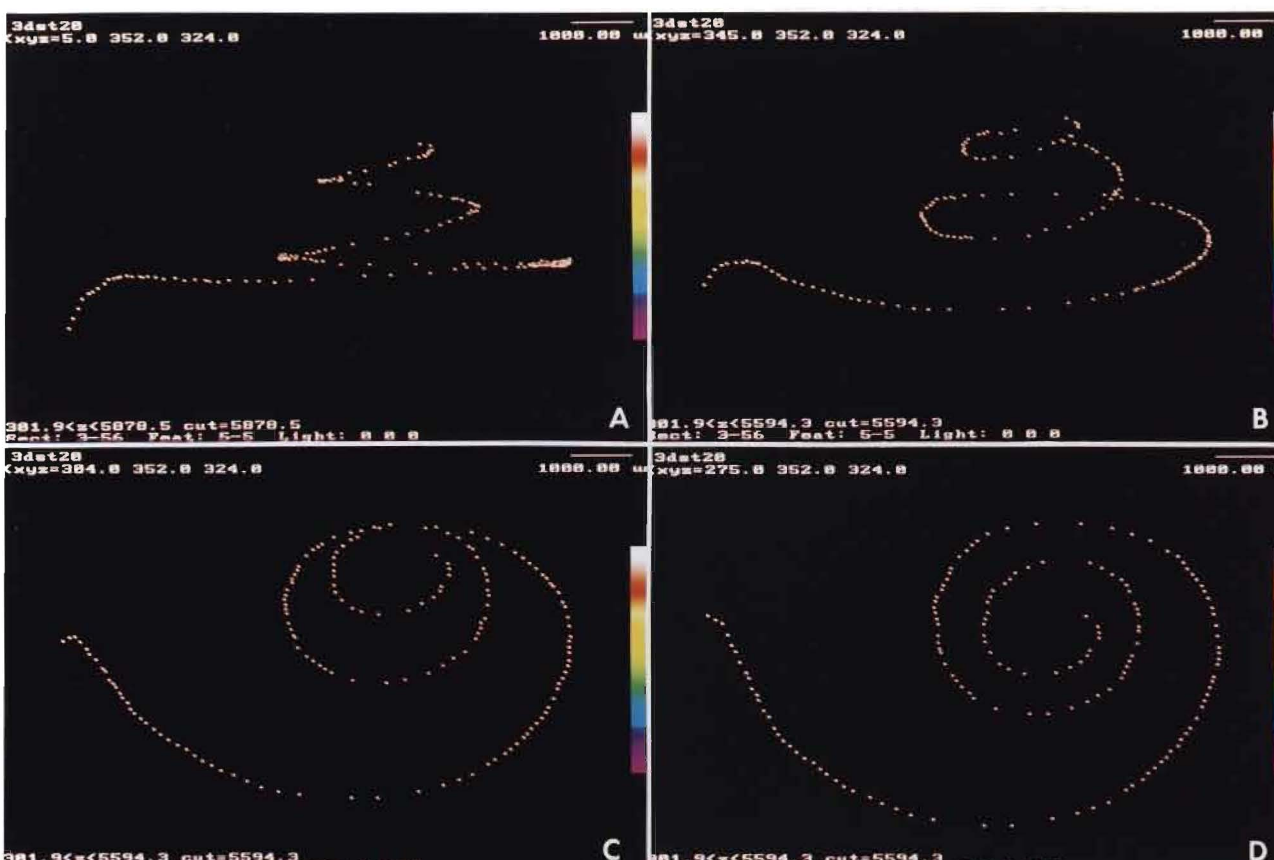

Fig 3. Comparison of 3-D and 2-D reconstruction (OC, No. 20). Displaying stored points for OC alone, 3-D reconstruction showed 3-D spiral. A) Side aspect (modiolar axis vertical). B) Oblique aspect, modiolar axis tilted 20° toward observer. C) Oblique aspect along original plane of section; "cutting angle" is 29° in this case; this is view as used by Guild[8] and Schuknecht.[9] D) Axial view aspect, projected onto plane perpendicular to modiolar axis ("cutting angle" compensated to 0° as described by Takagi and Sando[10]).

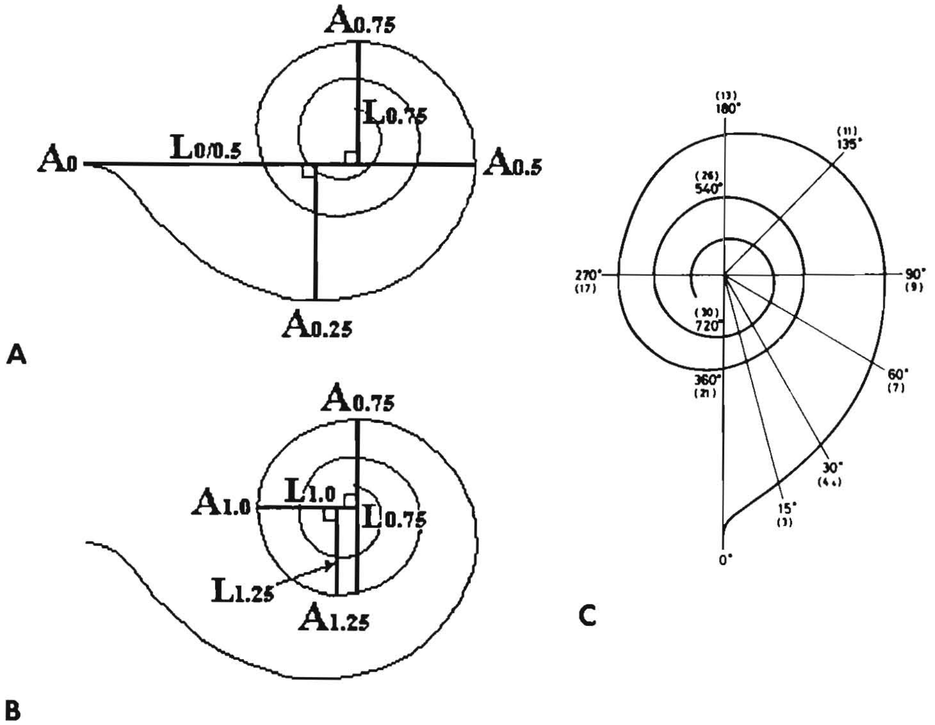

Fig 4. Schema for defining position of every quarter turn of OC. Details are described in text. A) Points in basal turn. B) Points in upper basal and middle turns. A0 — basal end of basal turn; A0.25 — point of one quarter turn; A0.5 — point of one half turn; A0.75 — point of three quarter turns; A1.0 — point of one turn; A1.25 — point of 1¼ turns; L0.25 — line at one quarter turn; L0.5 — line at one half turn; L0.75 — line at three quarter turns; L1.0 — line at one turn; L1.25 — line at 1¼ turns. C) 2-D reconstruction described by Bredberg.[12] It shows locations of different angular measurements along OC. He set helicotrema as axis of revolution of OC, but OC is eccentric around helicotrema, and his quarter turn points are thus closer to apical end than ours.

Measurement of Lengths of OC by 2-D Reconstruction Methods. For comparison, we also measured lengths of the OC from two 2-D reconstruction methods. In one case, it was performed by traditional 2-D reconstruction on the plane perpendicular to the plane of section[8,9] (Fig 3C), and in another case, 2-D reconstruction at right angles to the modiolar axis by rotation of the OC in 3-D space[10] (Fig 3D). In the first case, we call the angle between the modiolar axis and the plane of section the "cutting angle," and the difference attributed mainly to this the "cutting angle difference"; it represents the difference between 2-D reconstruction on the plane perpendicular to the plane of section and 3-D reconstruction. In the second case, we call the difference attributed to the pseudospiral structure of the OC the "geometric difference."

RESULTS

Lengths of OC, OW, IW, and RCC. Table 1 shows the numbers of turns of the OC and RCC, and the total lengths of the OC, OW, IW, and RCC. The number of turns of the OC ranged from $2^5/8$ (in six cochleas) to 3, with an average of 2.69. The number of turns on the

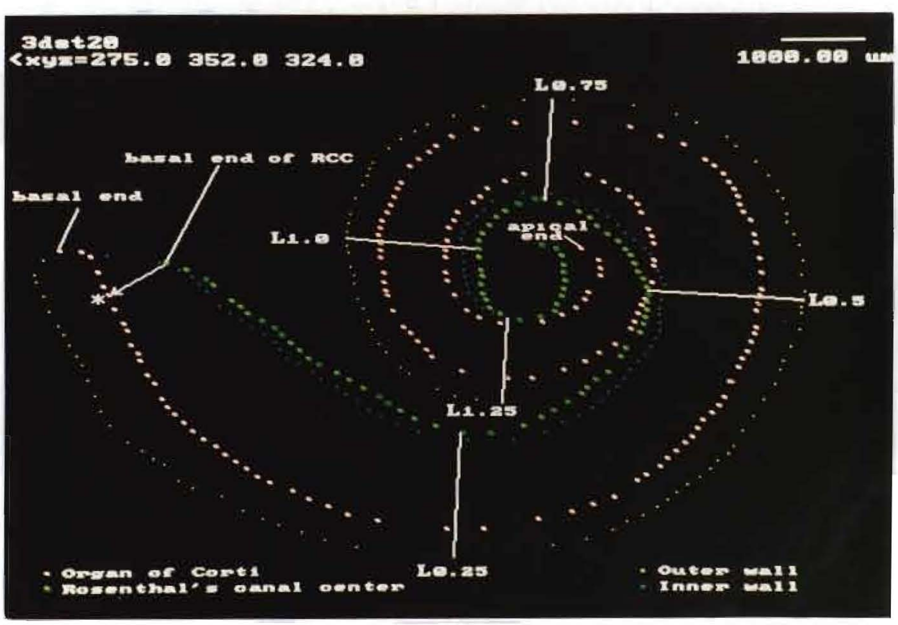

Fig 5. Graphic reconstruction and definition of every quarter turn of OC, OW, IW, and RCC. Five lines show positions of quarter turns from basal end to 1¼ turns on plane at right angles to modiolar axis. IW and RCC are not drawn beyond 1¼ turns. Pink dots — OC; yellow points — OW; light blue points — IW; light green dots — RCC; asterisk — position on OC corresponding to basal end of RCC.

TABLE 1. NUMBERS OF TURNS ON OC AND RCC, AND TOTAL LENGTHS OF OC, OW, IW, AND RCC FROM BASAL END

Cochlea No.	*Turns of OC*	*Turns of RCC*	*Length of OC (mm)*	*Length of OW (mm)*	*Length of IW (mm)*	*Length of RCC (mm)*
4	$2^{5}/_{8}$	$1^{6}/_{8}$	34.15	37.93	17.51	15.38
6	$2^{5}/_{8}$	$1^{6}/_{8}$	34.77	40.60	17.53	15.47
7	$2^{6}/_{8}$	$1^{7}/_{8}$	34.52	39.67	17.04	14.73
8	$2^{5}/_{8}$	2	35.44	40.20	18.27	16.96
9	$2^{5}/_{8}$	2	34.16	39.52	16.99	14.73
13	$2^{5}/_{8}$	$1^{7}/_{8}$	36.75	41.51	18.04	15.12
17	3	2	36.98	43.22	21.17	18.38
20	$2^{5}/_{8}$	$1^{6}/_{8}$	37.90	43.81	19.81	17.07
Mean	$2^{5.5}/_{8}$ (2.69)	$1^{7}/_{8}$ (1.88)	35.58	40.81	18.29	15.98
SD	0.11	0.12	1.41	1.97	1.47	1.33
Max	3	2	37.90	43.81	21.17	18.38
Min	$2^{5}/_{8}$	$1^{6}/_{8}$	34.15	37.93	16.99	14.73

OC — organ of Corti, RCC — Rosenthal's canal center, OW — outer wall, IW — inner wall.

RCC were from $1^{3}/_{4}$ to 2, with an average of 1.88. The total lengths of the OC ranged between 34.15 and 37.90 mm, with an average of 35.58 ± 1.41 mm (mean ± SD). Similarly, the total lengths of the OW, IW, and RCC were 40.81 ± 1.97, 18.29 ± 1.47, and 15.98 ± 1.33 mm, respectively.

The lengths and the percentages of totals of the OC, OW, IW, and RCC from the basal end to every quarter turn are shown in Table 2 and Fig 6. The average lengths of the basal turn, the second turn, and the apical turn of the OC were 20.91 mm (58.8%), 10.15 mm (28.5%), and 4.52 mm (12.7%), respectively. Rosenthal's canal is not found at the basal end of the OC (within 1.90 ± 0.38 mm from the basal end), or beyond the second turns. The RCC ranged between $1^{3}/_{4}$ and 2 turns; the average length of the basal turn was 12.87 mm (80.6%); that of the second turn was 3.11 mm (19.4%). The halfway point of the OC is located at about three quarters of its basal turn, and

TABLE 2. LENGTHS, AND PERCENTAGE LENGTHS IN PARENTHESES, OF OC, OW, IW, AND RCC FROM BASAL END, CALCULATED AT EVERY QUARTER TURN

Turns	*OC*	*OW*	*IW*	*RCC*
0	0	0	0	(0)
0.25	7.75 ± 0.62 (21.8 ± 1.4)	7.92 ± 0.83 (19.4 ± 1.7)	6.03 ± 0.40 (33.1 ± 2.7)	5.81 ± 0.47 (36.5 ± 3.28)
0.5	12.94 ± 0.87 (36.3 ± 1.9)	13.85 ± 1.13 (33.9 ± 2.2)	9.05 ± 0.82 (49.6 ± 3.63)	8.92 ± 0.68 (55.9 ± 3.3)
0.75	17.48 ± 0.96 (49.1 ± 1.4)	19.25 ± 1.31 (47.2 ± 1.9)	11.67 ± 0.95 (63.8 ± 2.1)	11.29 ± 0.92 (70.7 ± 2.0)
1	20.91 ± 1.08 (58.8 ± 1.3)	23.32 ± 1.52 (57.1 ± 2.1)	13.53 ± 1.16 (74.0 ± 2.6)	12.87 ± 1.07 (80.6 ± 2.1)
1.25	23.97 ± 1.23 (67.3 ± 1.4)	27.07 ± 1.64 (66.3 ± 1.9)	15.05 ± 1.20 (82.3 ± 2.61)	14.09 ± 1.17 (88.2 ± 1.7)
1.5	26.52 ± 1.30 (74.5 ± 1.3)	30.21 ± 1.82 (74.0 ± 2.0)	16.14 ± 1.24 (88.2 ± 2.2)	15.02 ± 1.19 (97.4 ± 1.1)
1.75	28.85 ± 1.36 (81.1 ± 1.2)	33.18 ± 1.86 (81.3 ± 2.2)	16.99 ± 1.21 (93.0 ± 2.3)	15.58 ± 1.28 (97.4 ± 1.1)
1.875				15.98 ± 1.33 (100)
2	31.06 ± 1.45 (87.3 ± 1.6)	35.81 ± 2.01 (87.8 ± 2.7)	17.67 ± 1.27 (96.7 ± 1.3)	
2.25	32.95 ± 1.52 (92.6 ± 1.5)	38.37 ± 2.05 (94.0 ± 2.4)	17.96 ± 1.27 (98.2 ± 1.1)	
2.5	34.63 ± 1.55 (97.3 ± 1.2)	40.25 ± 1.88 (98.6 ± 0.9)	18.17 ± 1.40 (99.4 ± 0.5)	
2.625 (Total)	35.58 ± 1.41 (100)	40.81 ± 1.97 (100)	18.29 ± 1.47 (100)	

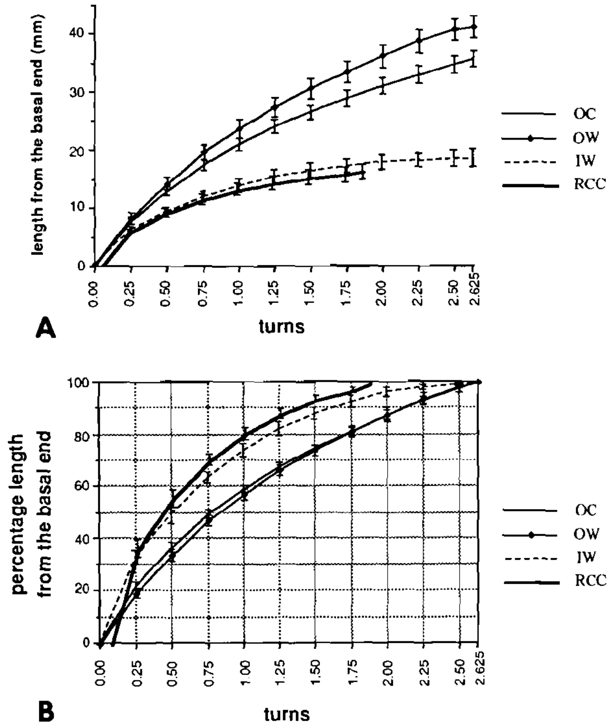

Fig 6. A) Lengths and B) percentage lengths of OC, OW, IW, and RCC from basal end, calculated at every quarter turn.

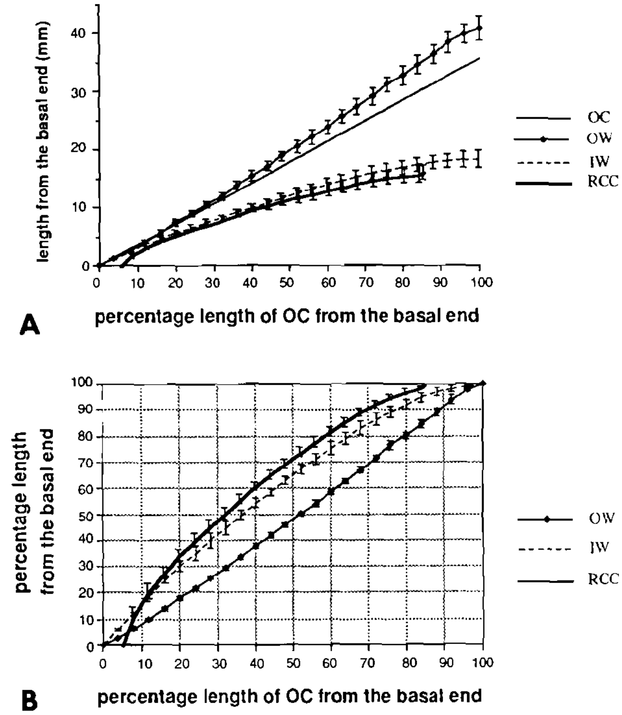

Fig 7. A) Lengths and B) percentage lengths of OW, IW, and RCC at 4% intervals along OC. RCC does not appear to be linearly related to OC, and shifts toward basal end.

that of the RCC is just before half of the OC basal turn.

The lengths and the percentages of the totals of the OW, IW, and RCC corresponding to the OC positions at 4% intervals are shown in Fig 7. The RCC started from the point corresponding to 5.3% ± 1.9% of the OC; the points at 30%, 50%, and 70% of the RCC corresponded to those at 17.4%, 21.9%, and 48.6% of the OC, respectively; and the apical end of the RCC was at 85.0% of the OC length. The RCC does not appear to be linearly related to OC, lying closer to the basal end of the latter. Comparing the percentage lengths of the OC, OW, IW, and RCC, that of the OW is close to that of the OC, and that of the IW is close to that of the RCC generally, as would be expected from their physical proximity. The standard deviations of lengths at each quarter turn point and at 4% intervals tend to increase closer to the apical end, because the lengths of the eight cochleas are somewhat different.

Lengths of OC by 2-D Reconstruction Methods. Table 3 lists the lengths of the OC measured by 2-D reconstruction on the plane perpendicular to the plane of section (A*, Fig 3C), by 2-D reconstruction at right angles to the modiolar axis by rotation of the OC in 3-D space (B*, right-angle plane, Fig 3D), and by 3-D reconstruction (C). The value of A* was 32.88 ± 1.29

TABLE 3. COMPARISON OF LENGTHS OF OC BY 2-D AND 3-D METHODS

Cochlea No.	*4*	*6*	*7*	*8*	*9*	*13*	*17*	*20*	*Mean*	*SD*
2-D length (mm) on plane perpendicular to plane of section (A*)	31.58	31.02	33.17	33.96	31.94	33.43	34.88	33.06	32.88	1.29
"Cutting angles" (degree)†	13.5	9.2	5.8	10.2	5.4	7.8	7	29	10.99	7.73
2-D length (mm) at axial plane (B*)	33.55	33.74	33.69	34.74	33.47	34.32	36.40	37.47	34.67	1.49
3-D length (mm) (C)	34.15	34.77	34.52	35.44	34.16	36.75	36.98	37.90	35.58	1.44
Percentage "cutting angle difference"† (C–A*)/C	7.53	10.79	3.90	4.17	6.48	9.04	5.69	12.78	7.55	3.15
Percentage "geometric difference"† (C–B*)/C	1.76	2.96	2.40	1.96	2.03	6.63	1.57	1.13	2.56	1.73

2-D reconstructions were performed by two methods: A* was traditional 2-D reconstruction on plane perpendicular to plane of section, and B* was 2-D reconstruction at right angles to modiolar axis by spatial rotation of 3-D model. 3-D results are denoted by C.

†Details are described in text.

TABLE 4. SUMMARY OF STUDIES OF OC LENGTH IN HUMANS

Authors	Date	Length of OC (mm) Mean	SD	Range	No. of Cases	Reference Specimens	Method of Measurement
Hardy[13]	1938	31.5	2.3	25.3 - 35.5	68	Human	2-D reconstruction method
Walby[14]	1985	32.6	2.1	30.1 - 36.4	20	Human	2-D reconstruction method
Pollak et al[15]	1987	28.4	3.4	24.0 - 33.5	9	Human	2-D reconstruction method
Retzius[16]	1884	33.5	0.8	32.0 - 34.0	5	Human	Direct method
Bredberg[12]	1968	33.2	3.8	28.2 - 40.1	9	Fetal	Direct method
		34.7	1.1	33.5 - 37.6	18	Adult	
Wright et al[17]	1987	32.8	2.6	28.8 - 36.6	12	Human	Direct method
Takagi and Sando[10]	1989	36.4			1	Man	3-D reconstruction method
Sato et al[18]*	1991	37.1	1.6	33.5 - 38.9	9	Men	3-D reconstruction method
		32.3	1.8	29.7 - 34.7	9	Women	
This study		35.6	1.4	34.2 - 37.9	8	Men	3-D reconstruction method

*Sato et al[18] measured length of outer and inner margins of basilar membrane and used their average.

mm; the "cutting angle difference" was 7.6% ± 3.2%, and the "cutting angle" was 11.0° ± 7.7°. The value of B* was 34.67 ± 1.49 mm, and the "geometric difference" was 2.6% ± 1.7%. The lengths by both 2-D methods (A* and B*) were shorter than that from the 3-D method (C). Among the eight cochleas, the OC of No. 20, which had the highest "cutting angle" (29°), had the highest "cutting angle difference" (12.8%, A*: 33.06 mm, Fig 3C, C: 37.90 mm); the "geometric difference" was 1.13% (B*: 37.47 mm, Fig 3D).

DISCUSSION

There are several reports about computer-aided reconstruction of the temporal bone and on the length of the human cochlea. Three types of methods of measuring the length have been described. First is the 2-D reconstruction method (indirect method) used by Guild,[8] Schuknecht,[9] Hardy,[13] Walby,[14] and Pollak et al[15]; second is the direct method (surface specimen technique) used by Retzius,[16] Bredberg,[12] and Wright et al[17]; and last is 3-D reconstruction, used by Takagi and Sando[10] and Sato et al[18] and in this study. The measured lengths of the human OC from these studies are listed in Table 4.[10,12-18]

The first method, the traditional 2-D reconstruction method, was developed by Guild[8] and revised by Schuknecht[9]; relevant features marked on all serial sections are reconstructed and analyzed in one plane. Guild[8] described the prerequisites for use of the 2-D reconstruction method as 1) good fixation and embedding of the cochlea and 2) serial sections of the cochlea in the approximate plane of the modiolar axis. He estimated the shortening error in graphic reconstruction of the guinea pig as less than 5%. This shortening error, which we call "chord error," arises because the real distance between two points on the OC is that along the arc of the spiral connecting the points; the measured distance is that along the chord of the arc connecting the points. Thus, the lengths measured by the 2-D reconstruction method tend to be shorter than the true lengths. Other factors may also account for differences in measured length. Takagi and Sando[10] suggested the cutting angle as one source of error, because most horizontal temporal bone sections are cut parallel to the middle cranial fossa surface, which is not the horizontal plane anatomically. Also, the modiolus itself is too thick to permit accurate judgment from midmodiolar sections as to whether it was cut exactly along the axis. In one particular example of a cochlea specimen with a 35° cutting angle, they measured and compared the length of the OC by traditional 2-D versus 3-D reconstruction. The "cutting angle difference" was considerable (15.4%). In our cases also, the 3-D method yields considerably greater OC lengths; the average cutting angle difference was 7.6% (32.9 mm versus 35.6 mm). We investigated the correlation between the cutting angle and the cutting angle difference. In our eight cases there was not a not-quite-significant correlation ($r = .696$, $R^2 = .484$, $p = .0554$). But when we included Takagi and Sando's case as the ninth, a significant correlation was found ($r = .841$, $R^2 = .708$, $p = .0045$). Our cases included seven with a relatively small cutting angle (5.4° to 13.5°), so that no certain relation was noted, but the above results demonstrate that Takagi and Sando's[10] one case strongly influences the analysis. Viewing a cochlea with the same cutting angle, we can easily understand that the 2-D reconstruction varies considerably according to the plane of section, whether it is close to the major axis (the direction of $L_{0/0.5}$ in Fig 4) or to the minor axis (the direction of $L_{0.25}$ and $L_{0.75}$ in Fig 4), and this results in various cutting angle differences. But higher cutting angles lead unequivocally to higher cutting angle differences, as in Takagi and Sando's case and our case 20. In conclusion, the length of the cochlea on 2-D reconstruction is much shorter than the actual value when the plane of section is oblique to the midmodiolar axis, and the major source of error in 2-D reconstructions may be the cutting angle.

When the cutting angle was compensated to be 0° by rotation of the 3-D model in space, the length of the OC was 34.7 ± 1.5 mm; the average difference between this and the 3-D results was 2.6%. This difference is the "geometric difference" due to the pseudospiral structure of the cochlea; in brief, the cochlear spiral changes its radius of curvature, axis of revolution, and inclination from the basal end to the apical end, as previously described by Schuknecht.[9] He made a geometric side-view projection for the upper 2½ turns of the cochlea of a cat — excluding the hook region — and estimated a difference of 2.8% between the length in the simple top-view reconstruction and the length of this projection. Takagi and Sando[10] reported the 2-D length of a cochlea made from a projection of a 3-D reconstruction method was very close to the 3-D value (the geometric difference was 0.3%). Similarly, in our data there is a smaller geometric difference. But the data from 2-D reconstruction include some geometric difference whenever the cutting angle requires compensation to 0°, and results in shorter-than-actual values.

The second method, for direct measurement of cochlear length, was described first by Retzius,[16] who used a micrometer, and later Bredberg[12] and Wright et al,[17] who measured the cochlea using surface specimens (measurement by looking straight at the OC under a microscope). This technique seems to be more reliable than indirect measurement (traditional 2-D reconstruction); the average OC length varies from 32.8 mm to 34.7 mm and is longer than that from indirect measurement. But compared with our data, it is still shorter, because there is still the possibility of difference due to the viewing angle — similar to the cutting angle difference — or to destruction or loss of parts of the OC during the segmentation of the cochlea.

Bredberg[12] measured the length of the OC from the basal end according to the angle of the turn around the helicotrema (Fig 4C). The percentage lengths in the basal turn (61.5%) and basal and middle turns (88.5%) were slightly longer than ours (58.8% and 87.3%, respectively). The OC is not concentric around the helicotrema, which Bredberg set as the center of the angle to be measured, and his quarter turn points are always further toward the apical end than ours.

The third method, 3-D reconstruction, can easily be done by computers. The length of 3-D structures can be measured by procedures described by Takagi and Sando,[10] Sato et al,[18] and this paper. Sato et al[18] measured the lengths of the outer and inner margins of the basilar membrane and calculated the average, and reported that the mean cochlear length was significantly longer in males (37.1 ± 1.6 mm) than in females (32.3 ± 1.8 mm). Their measured parameters are not directly comparable with ours, but their results were longer than the previous ones from other methods. Although our method requires considerable time and practice to make a 3-D reconstruction, the length between any two points can be calculated quickly by selecting the points. Furthermore, the calculated lengths have neither a "cutting angle difference" nor a "geometric difference." However, the 3-D method still retains the possibility of "chord error," which decreases as the distance between successive sections becomes shorter.

Finally, a possible source of error that affects most methods could be shrinkage during the embedding process. The fact that the lengths measured by 3-D methods are generally greater than those from other methods shows at least that the histologic processing for the former does not cause more shrinkage artifact than that for the latter. More specifically, we decalcify at room temperature with ethylenediaminetetraacetic acid in formalin; this method is slow, but causes a minimum of artifact. Even after decalcification, the tissue of the otic capsule is more rigid than "normal" soft tissue, and embedding usually is done as soon as the decalcification is sufficient for sectioning. Although we feel that there is a minimum of shrinkage involved in the process, clearly, more systematic studies need to be done.

Despite differences in absolute cochlear length, the percentage distances along the basilar membrane have been reported to be similar in cat[19] and chinchilla.[20] If this hypothesis is true, the frequency map on the basilar membrane may be different in cochleas of different lengths. Generally, cochlear length refers to the length of the OC, so in this study the lengths of the OW, IW, and RCC were mapped onto the OC at 4% intervals. Our computer-aided 3-D reconstructions revealed that Rosenthal's canal is much shorter than the OC; the lengths of the RCC and IW were only half of the OC's length. The RCC started at the position of 5.3% of the length of the OC and ended within two turns — at 85.0% of the OC — as described by Ariyasu et al.[21] Ariyasu et al also reported that the spiral ganglion dendrites within the osseous spiral lamina project radially in the basal turn and become increasingly oblique to the axis of the modiolus as the ganglion extends apically. Our results corroborate theirs. According to our comparative analysis on the lengths of the OC and RCC (Fig 7), the percentage length of the RCC was not linearly related to that of the OC; the RCC tended to shift toward the basal end. There are few reports in the literature on the length of the human Rosenthal's canal. The 12 mm reported by Pfingst[22] was shorter than our finding of 16.0 ± 1.3 mm, probably, again, because of differences between 2-D and 3-D reconstructions, as previously described.

These results should clearly influence the design of future cochlear implants. Insertion along the inner scala tympani wall is clearly preferable because of its closer proximity to Rosenthal's canal and the considerably shorter insertion depth necessary to achieve stimulation of the apical end of Rosenthal's canal.

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