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CT-scan contouring technique allows for direct and reliable measurements of the cochlear duct length: implication in cochlear implantation with straight electrode-arrays

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Abstract

Objectives The advent of hybrid electro-acoustic implants requires precise positioning of the electrode-array (EA) within the cochlea. The cochlea size, that is, the length of the cochlear scala tympani, is often indirectly estimated from distance A by Escudé's method. This technique has been confirmed by anatomical studies, in a bunch of cadaveric specimens, but it is not yet widely established in the field of computed tomography (CT). We compared cochlear duct length obtained by Escudé's method to those directly acquired on CT images.

Materials and methods The lengths of cochlear scala tympani were directly measured on CT scans by contouring the external cochlear wall (contouring technique-CoT). In fifteen patients implanted with a straight EA, the length of the EA and the measured length of the cochlea by the CoT were compared, to check the reliability of the CoT. Then, in 200 CT-scans, the length of the cochlear duct was measured by the CoT then compared to Escudé's method.

Results In the 200 CT-scans which served for cochlear length measurements, a significant variability between the cochleae were observed, as expected. At 360°, the correlation between the measurements of the length of the cochlear scala tympani between the two techniques differed, with a difference of 0.2 ± 0.7 mm at 360° (extreme: 2 mm; $p < 0.001$) and 2.2 ± 1.2 mm at 540° (extreme: 5.6 mm; $p < 0.001$).

Conclusion The CoT can predict with accuracy the length of EA-insertion depth, more precisely than estimation methods such as Escudé's.

Keywords Cochlea anatomy · Cochlear implant · Straight electrode-array · Hearing preservation · CT scan

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Introduction

Cross-sectional imaging plays an essential role in cochlea pre-implantation. In modern cochlear implantation surgery, an important goal is preserving residual hearing and auditory structures. To this end and to avoid cochlear trauma during operation, the length of the cochlear duct is often measured in the preoperative assessment to plan the depth of insertion of the electrode array (EA) individually to stimulate only the most basal lost auditory areas, in line with the cochlear tonotopy, maintaining the possibility of acoustic stimulation of more apical auditory areas encoding low frequencies [1]. There are large inter-individual variations in cochlear anatomy [2–8]. This anatomy determines the insertion depth and residual hearing preservation [9, 10]. Some studies suggest that the best functional results are obtained with deep insertions [11], but the rate of cochlear trauma appears to increase with insertion depth [12, 13]. Furthermore, patients present range types of hearing loss, typically in the regions of high and medium frequencies. Patients with partial deafness who are candidates for cochlear implantation generally have usable residual hearing at 125–750 Hz and deafness at above frequencies: the EA should avoid to stimulate residual functioning areas of the organ of Corti, to preserve the residual hearing coding the regions of low frequency [14, 15].

The length of the cochlea is often indirectly estimated by the “distance *A*” using Escudé’s method [16–19]. This method has been validated by a number of well-conducted anatomical studies, but on only few specimens [16, 20]. With the current accuracy of CT-scans, and the availability of large numbers of cochlear images, we directly measured the cochlear size on CT-scans by contouring the external wall of the cochlea, lateral to the scala tympani, mimicking the route of a straight EA of ta cochlear implant.

A preliminary study has been achieved to check the reliability of our direct measurements of the cochlea length on an oblique para-coronal reformatted CT image, then a main study has been conducted to evaluate the reliability of Escudé’s method by comparing estimated measurements to those on CT images.

Materials and methods

This study aimed at comparing Escudé’s method and direct measurements of the length of EA-insertion into the cochlea, the so-called herein contouring technique, detailed below.

Inclusion criteria

The study included all temporal bone CT scans from any subjects who underwent this imaging technique, irrespective of indication, provided that there were no cochlear malformations.

Exclusion criteria

Were excluded from analysis, data from patients with ear malformations or diseases known to be associated with abnormalities of the cochlea, patients whose examinations were uninterpretable owing to motion artifacts; patients with cochlear implants; patients with previous surgery of the inner ear, ensuring the analysis of those cochleae considered normal *de visu only*.

CT protocol

All patients underwent high-resolution CT imaging on the same machine with the same protocol (General Electric 750 HD 64 slices, acquisition protocol: 0.625 mm slice thickness, 512 × 512 matrix, FOV 32 cm, 120 kV).

Images analysis

The CT measurements were made on a workstation (Advantage Workstation Volume Share Version 4.4). The multiplanar reconstructions were performed using the “Volume Viewer” program with 2D images. Two radiologists with 3 years and > 30-year experience reviewed the images.

Escudé’s methods

Distance *A* was defined as the length of a line drawn from the midpoint of the round window (zero point) through the mid-portion of the modiolus to the opposite end of the outer cochlear wall on a reconstructed oblique coronal section through the round window, the basal turn and the modiolus (Fig. 1). The lengths of the cochlear canal at 360° and 540° were measured by both Escudé’s technique, and by the contouring technique (Fig. 2).

The lengths of the cochlea estimated from the distance *A* in the equations proposed by Escudé was achieved as follows:

$L = 2.62A \times \log_e (1.0 + \Theta/235)$.

With $\Theta = 360°$, the formula gives: $L_{360°} = 2.434A$.

With $\Theta = 540°$, the formula gives: $L_{540°} = 3.126A$.

The cochlea lengths $L_{360°}$ and $L_{540°}$ as measured by Escudé’s technique were compared with those acquired by the contouring technique.

Contouring technique (CoT)

From the “zero point” as defined above, direct measurements of the cochlea length from the round window along the outer

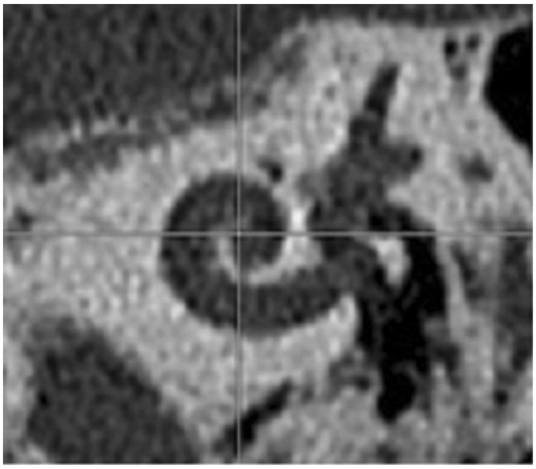

Fig. 1 Oblique coronal reformatted CT images used to measure the distance *A* from the midpoint of the round window to the opposite lateral wall of the basal turn, through the mid-modiolar axis ($L_{360°}$ and $L_{540°}$)

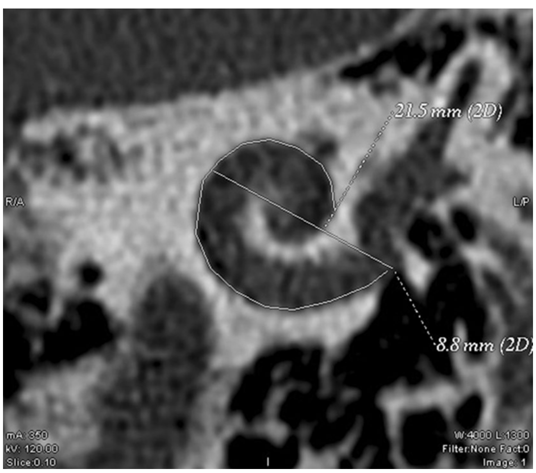

Fig. 2 Illustrating how to measure the dimensions of the cochlea at 360° on the oblique para-coronales CT reformatted images

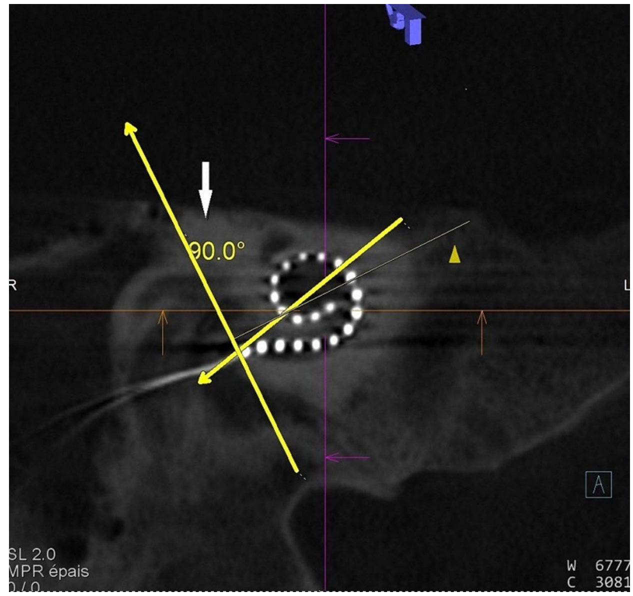

Fig. 3 Dyna-CT SMART acquisition images realized by a syngo DynaCT software by GE, to calculate the length of insertion of the electrode-array from the round window up to the 360° distal, knowing the electrode and interspace length. Note that by contouring the external wall of the cochlea, the desired length of insertion can be directly measured (contouring technique), with no need of complex calculation

edge of the bony canal (at the level of the scala tympani) to the 360° and 540° distal references were performed (General Electrics, Advantage Workstation Volume Share Version 4.4, 3D Volume Viewer). This contouring technique provides with very accurate measurements of straight-EA insertion, since it follows the insertion route of such EAs within the cochlea, against the external wall of the scala tympani (Fig. 3).

Statistical analyses

The population was described statistically, with average ± standard deviation and range for continuous variables and frequency (percentages) for discrete variables. Distance *A*, and cochlear canal lengths at 360° and 540°, were first measured by the contouring technique then estimated by Escudé's method. These continuous variables were compared by sex and by side, using a Student *t* test or Mann–Whitney test if normality conditions failed the Shapiro–Wilk test.

The relationship between two quantitative parameters was analyzed using the Pearson correlation coefficient (or Spearman if normality conditions were not met), with graphical representations in the form of scatter plots with a linear trend-line equation. We looked for correlations between the distance *A*, age, lengths measured directly at 360° ($L_{360°}$) and at 540° ($L_{540°}$) and the corresponding lengths estimated from Escudé's method.

Analysis of concordance between the measured and calculated $L_{360°}$ and $L_{540°}$ was performed using a Student *t* test on paired data, followed by an effect size calculation to judge the relevance of the differences found. The data were recorded on 2010 EXCEL software and analyzed using STATA V12 software (Stata Corp, College Station, Texas, USA). All the tests were performed bilaterally for a type 1 error of 5%.

All CT-scans were acquired in routine practice for an accepted medical reason, whatever the cause, but never for this study only. All patients being treated in our institution accept their data to be used for medical or scientific research, if anonymous.

Table 1 Average, standard deviation and range of direct measurements, ($n=200$)

n=200	Diameter A (mm)	Measured $L_{360°}$ (mm)	Measured $L_{540°}$ (mm)	Calculated $L_{360°}$ (mm)	Calculated $L_{540°}$ (mm)
Mean	9.01	21.7	25.9	21.9	28.2
SD	0.41	0.9	1.4	1.0	1.3
Range	8–10.4	18.8–24.7	21.3–29.6	19.4–25.3	25.3–32.5

Table 2 Mean, standard deviation and range of measurements by sex

	Female ($n=64$)	Male ($n=36$)
Diameter A (mm)	8.92 ± 0.38	9.16 ± 0.42
	8.2–10.4	8–10
Measured $L_{360°}$ (mm)	21.5 ± 0.87	22.0 ± 1.0
	19.7–24.7	18.8–24.1
Measured $L_{540°}$ (mm)	25.7 ± 1.3	26.2 ± 1.5
	23–29.6	21.3–29.5

Table 3 Mean, standard deviation and range of measurements by side

	Right	Left
Diameter A	8.9 ± 0.41	9.0 ± 0.4
	8–10	8.2–10.4
Measured $L_{360°}$ (mm)	21.7 ± 0.9	21.7 ± 0.9
	18.8–22.6	19.4–24.3
Measured $L_{540°}$ (mm)	25.9±1.4	25.9±1.3
	21.3–29.6	23–29.3

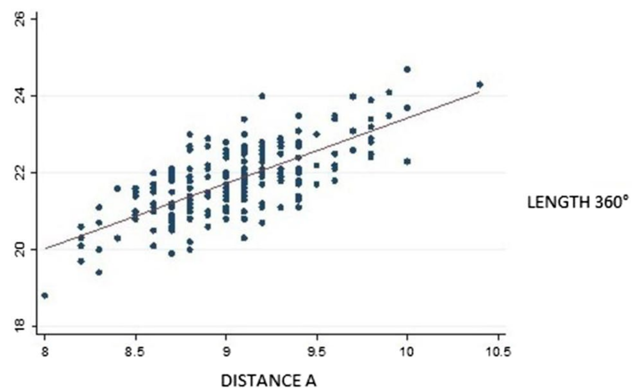

Fig. 4 Graph showing the correlation between the distance A and the directly measured length at 360° ($y=1.71 * x+6.36$, $R^2=0.54$)

Results

Population characteristics

100 consecutive patients with 200 temporal bones were included in this retrospective study. Patients had average age 53.3 years (13–85 year old); male/female ratio was 0.56. The indications were predominantly unilateral or bilateral transmission deafness, pre-implantation medical report, suspected cholesteatoma and trauma.

Results of cochlear measurements

The results of measurements of the length of scala tympani are shown in Table 1. There was a broad inter-individual variability in the cochlea lengths.

- *Age* there was no significant relation between measurements (lengths, distance A) and age ($R<0.001$). There was no significant correlation between the distance A and age, or length and age.
- *Sex* there was a significant difference in the distance A and $L_{360°}$, $L_{540°}$ according to sex ($p<0.05$). The distance A and $L_{360°}$ and $L_{540°}$ were significantly greater in men than in women (Table 2).
- *Side* there was no significant difference for any of the dimensions measured between the right and left sides ($p>0.05$) (Table 3).

Correlations between the distance *A* and the directly measured lengths, and between estimated and measured lengths by the contouring technique

We found a close correlation between the distance A and $L_{360°}$ measured directly ($R^2=0.54$, $p<0.001$) (Fig. 4), and a good, but weaker, correlation between the distance A and $L_{540°}$ measured directly ($R^2=0.41$, $p<0.001$) (Fig. 5).

The intra-individual mean difference between Escudé's methods and contouring technique for $L_{360°}$ was 0.2 ± 0.7 mm and ranged from − 1.6 mm to + 2.0 mm. This difference was statistically significant ($p<0.001$). However, the effect size was considered low (effect size = 0.19).

Intra-individual difference of measurements between the two methods for $L_{540°}$, was on average 2.2 ± 1.2 mm and ranged from − 1.3 mm to + 5.6 mm. This difference was both significant ($p<0.001$) and clinically relevant (effect size = 1.63).

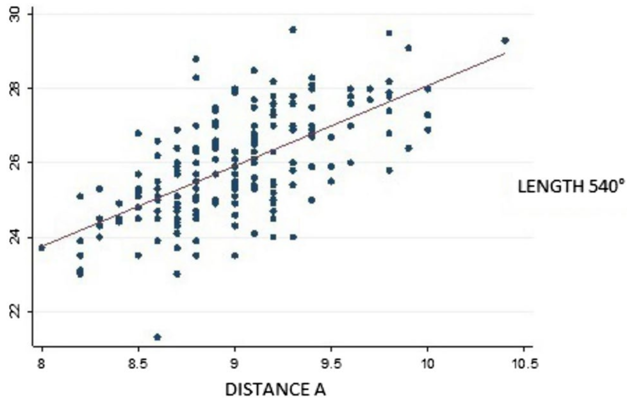

Fig. 5 Graph showing the correlation between the distance *A* and the directly measured length at 540° ($y = 2.17 * x + 6.37$, $R^2 = 0.41$)

Discussion

Many teams have made efforts to optimize electrode-array cochlear insertion [22–26]. Indeed, an anticipated precise length of insertion depth can help preserving residual hearing [27–29]. Also, it may influence hearing outcome. Although this point remains controversial, some teams have reported that a slight difference of insertion depth can affect hearing outcome [28, 30, 31]. It is also likely that the simultaneous electric and acoustic stimulation of a given hearing zone of the cochlea may alter the hearing perception from this electroacoustic stimulated area, although little is known about this point.

That is the reason why we have put the question of the reliability of the preoperative calculation of cochlear length in cochlear implant candidates.

Our observations are consistent with the literature: we found broad variations in inter-individual dimensions, liable to influence the choice of EA insertion length and shape. In agreement with the literature [32, 33] the length measurements of our human cochleae showed no significant difference for either age or side. We found the cochlea to be longer in men than in women.

We found a close correlation ($R^2 = 0.54$) between the length measured directly at 360° in the cochlea and the distance *A*, derived from the work of Xu et al. on CT images [21]. But this correlation, however, was weaker than in the work of this author on anatomical material. Furthermore, the difference calculation with this estimation can lead to a 2 mm error, which is not neglectable, in terms of tonotopy.

To validate their estimation method, Escudé et al. [19] did not compare cochlea length estimated from the distance A versus the length actually measured, but compared calculated length with the length of electrode insertions performed in 15 cases.

The measurement of the length at 540° from the distance *A* has also been proposed in the literature [17] and an excellent correlation ($R^2 = 0.92$) has been reported with the directly measured lengths. In actuality, the authors did not themselves directly measure actual length at 540° in patients, but referred to previously published anatomical studies.

Herein, the correlation between the distance *A* and $L_{540°}$ measured directly in CT was only moderate ($R^2 = 0.41$) with a variation of up to 5.6 mm between CoT measurements of $L_{540°}$ and $L_{540°}$ estimated from the distance *A*, which was statistically significant.

The estimation of $L_{360°}$ and $L_{540°}$ from the distance *A* has so far only been validated by Erixon et al. [16], and only on anatomical material and not in patients explored by CT. These authors obtained the following results: average distance $A = 9.3$ mm, $L_{360°} = 22.8$ mm and $L_{540°} = 35.1$ mm. Linear regression analysis showed a correlation coefficient (R^2) of 0.74 between the distance *A* and $L_{360°}$, 0.70 for $L_{540°}$, and 0.39 for the total length of the cochlea. We obtained a coefficient R^2 of 0.54 between the distance *A* and $L_{360°}$ and 0.41 between the distance *A* and $L_{540°}$. These results suggest that the correlations may be weaker in a clinical situation than in experimental work on anatomical material. Some hypotheses can be advanced on why the results we obtained by in vivo CT were different. One reason may be slight shrinkage of anatomical material caused by drying or preparation techniques. The sectional plane used to make measurements in patients could be slightly different from that used experimentally. Possible minor motion artifacts could explain some differences between the two methods. We also note that the measurements we made are essentially valid for straight EAs. We calculated the cochlear length for a given coiling considering the external edge of the cochlea bone, very close to the positioning of a straight EA but very different from a peri-modiolar one. Thus, the CoT appeared to be more accurate than Escudé's one for measuring the length of the cochlea.

We acknowledge that one limitation of the CoT is that it does not consider the three dimensions of the cochlea. Maybe in the future 3D measurements could allow to choose the ideal EA perfectly adapted to the shape and volume of the cochlea, as recently proposed [e.g. 34].

In conclusion the CoT provides highly reliable measurements of cochlear duct length. The CoT was more reliable than Escudé's method, which could lead to up to 5.6 mm for deeper insertion. As cochlear measurements can be easily acquired by the CoT, we now favor this technique before cochlear implantation with a straight EA, when hearing preservation is attempted.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

Ethical approval All data acquired and analyzed herein were done off-line after routine acquisition of temporal CT scans for medical reasons independent of this study and presented totally anonymously. The study was approved by the local ethical committee of our institution.

Informed consent All data were anonymously analyzed. All patients taken in charge in our institution are aware their personal data may be anonymously used for scientific purpose, except if they refuse.

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