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Review Article

Cochlear duct length along the outer wall vs organ of corti: Which one is relevant for the electrode array length selection and frequency mapping using Greenwood function?

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Abstract Cochlear duct length (CDL) measurement or estimation is a hot topic for various research groups in the cochlear implant (CI) field as of today. Getting the CDL along the outer wall (LW) and organ of corti (OC) is possible but considering the clinical application especially in the selection of the electrode array length and applying Greenwood's frequency function, we need to have a clear understanding on the CDL in general and as well on the Greenwood's frequency function. It is very clear from the histology images of the cochlea with straight electrode inside, that the electrode locates itself right under the basilar membrane. Also the Greenwood's frequency function involves a variable that corresponds to the CDL at the basilar membrane/organ of corti level. This brings us to conclude that the CDL at the OC is relevant for the selection of electrode array length and in applying Greenwood's frequency function. The ratio between CDL (LW) and CDL (OC) is 0.9 which is a very important number that needs to be remembered when converting CDL (LW) to CDL (OC).

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Introduction

Cochlear duct length (CDL) estimation or measurement has become a hot topic in the recent times in the cochlear implant (CI) field. CDL is the length of cochlear duct measured from the natural entrance of the cochlea all the way to helicotrema. Though it makes absolute sense in knowing the CDL prior to surgery for various applications, with the understanding from the literature that every cochlea is unique and it differs in its size, shape, number of turn and as well in its anatomy,[1–3] measuring/estimating the CDL at which location inside the cochlea has a big implication. The CDL can be measured following the outer bony edge of the cochlea (LW) (Fig. 1B, D),[4–6] at the basilar membrane level or at the organ of corti (OC) (Fig. 1C, E) and as well at the modiolus/inner wall level (MW).[7–9] Measuring/estimating the CDL at various levels inside the cochlea will give different results with CDL (LW) will be the longest, CDL (MW) will be the shortest and the CDL (OC) will be greater than CDL (MW) and smaller than the CDL (LW).[9] Which of these CDLs can be applicable in the selection of correct length electrode array and anatomy based speech processor fitting by getting the patient specific cochlear frequency mapping using Greenwood function,[10] needs to have a clear understanding on the basics of CDL and Greenwood function.

This paper attempts to give an acceptable explanation especially on the difference between the CDL measured along the lateral wall and along the organ of corti and its clinical applications related to the cochlear implantation.

Material and methods

Clinical imaging is the *state-of-the art* in measuring the cochlear parameters in live patients. Majority agrees that measuring the basal turn diameter which is also called as "A" value of the cochlea (Fig. 1A) from the pre-operative CT image of the cochlea, is relevant in estimating the full length of the cochlear duct length.[11–21] Escude et al[4] and Erixon et al[5] have proposed mathematical equations that involve "A" value as the input in estimating the $CDL_{(LW)}$ position, whereas the equations proposed by Alexiades et al[8] and Koch et al[22] estimates the $CDL_{(OC)}$ position. Equation proposed by Koch et al[22] is a further fine-tuning of the Alexiades's equations.[8] Greenwood frequency function involves the $CDL_{(OC)}$ and the function itself is given in Table 1 along with the all the CDL equations proposed by various studies.

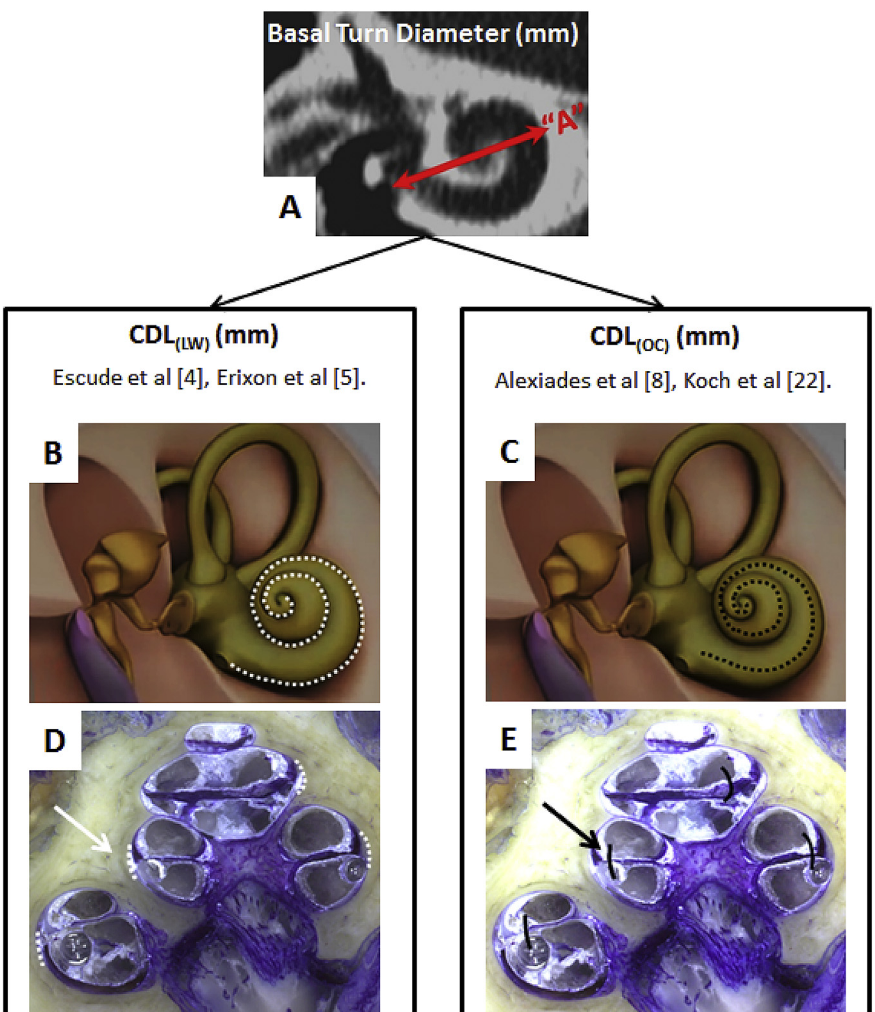

Fig. 1 Showing the possibility of estimating the CDL at the LW and OC positions using the "A" value (basal turn diameter) from the pre-operative image.

Results

Fig. 1 show where exactly the CDL is being measured/estimated along the LW and along the OC. $CDL_{(LW)}$ follows the outer bony edge of the cochlea whereas the $CDL_{(OC)}$ follows the basilar membrane which is inner to the LW position. The input value for all the CDL equations given in Table 1 is the "A" value which is the basal turn diameter of the cochlea. Literature reports the range of "A" value among the human population as 7.0 mm and 10.5 mm with an average value of approximately 9.0 mm.[4–6,13]

Table 2 gives a comparison between Escude's $CDL_{(LW)}$ and Alexiades's $CDL_{(OC)}$ was made for 3 different "A" values corresponding to the shortest, longest and the average value.

From Table 1, it is inferred that the $CDL_{(OC)}$ measures 10% shorter than the $CDL_{(LW)}$. The histology section of the human cochlea with the straight lateral wall electrode inside, at the mid-modiolar section (Fig. 2A) shows the position of the straight lateral wall electrode right under the basilar membrane or organ of corti (OC). The high resolution micro-CT image in the cochlear view (Fig. 2B) shows the electrode lying slightly inside the bony edge because of the spiral ligament that lines the outer bony edge (LW) and that separates the electrode from touching the outer bony wall.[20]

Application of the Greenwood frequency function involves $CDL_{(OC)}$. Just for illustration, let's assume $CDL_{(OC)}$ as 35 mm and with unrolling the cochlea, the round window entrance would take up the zero position and the helicotrema (the most apical portion) as the 35 mm. The frequency at any specific location inside the cochlea is calculated as shown in Fig. 3.

Taking the CDL_{OC} and using Greenwood frequency function, the frequency map corresponding to any particular sized cochlea can be made. Fig. 4 shows the Greenwood frequency map for three different cochlear sizes with a 20 mm long straight electrode underneath it. "0" at the CDL (mm) corresponds to the RW/cochlear opening. One length electrode array will give different insertion depths covering different frequency range in different sized cochlea.

Discussion

Literature teaches us that the $CDL_{(LW)}$ is 10%–12% longer than the $CDL_{(OC)}$.[6] This is exactly seen from Table 2 with the ratio between $CDL_{(OC)}$ to $CDL_{(LW)}$ is 0.9 which in other words $CDL_{(OC)}$ is 10% shorter than the $CDL_{(LW)}$. The reason for just considering the Escude's and Alexiades's equation in finding the ratio between $CDL_{(OC)}$ and $CDL_{(LW)}$ is that these two equations are the root from which several fine-tuned equations came up. Kawano et al[9] measured the CDL at the level of OC and as well at the LW from eight cochlear samples and the ratio between the CDL_{OC} to CDL_{LW} came around $0.87 \approx 0.9$. For argument, a sample number of eight may be considered too small to cover the complete population but at least it gives a rough estimation on the difference between $CDL_{(LW)}$ and $CDL_{(OC)}$. Converting the Escude's CDL_{LW} to CDL_{OC} can now be simply done by multiplying CDL_{LW} by a factor of $0.87 \approx 0.9$. The "A" value ranges from the shortest length of 7.5 mm to a longest length of 10.5 mm.[4–6,13] The CDL_{OC} which varies between 28 mm and 39 mm is in-line with what was already published.[7,9] It makes absolute sense that CDL_{LW} of 43 mm for an "A" value of 10.5 mm as given in Table 2 cannot be used in the electrode array length selection as the longest electrode array available in the market is only 31.5 mm which is designed to give the maximum angular insertion depth. It may be relatively easier for the radiologist to detect the outer bony edge of the cochlea from the preoperative image, especially the spline method proposed by Würfel et al[6] but understanding the difference between the $CDL_{(LW)}$ and $CDL_{(OC)}$ is very essential if the proposed method is to be used for electrode array selection clinically.

The other issue with the $CDL_{(LW)}$ is that it cannot be used in combination with Greenwoods frequency function as the Greenwood frequency function uses the length at the basilar membrane level.[10] Greenwoods frequency function is $F = A \times (10^{ax}\text{-}k)$ where 'x' is expressed as the proportion to the total basilar membrane length. Fig. 3 and 4 attempts to explain how the Greenwood frequency function is to be used when finding the frequency at the corresponding intracochlear location and as well for various cochlear sizes respectively.

Advanced surgical pre-planninig tool like OTOPLAN (www.otoplan.ch) is now CE marked and is available to be clinically used in the application of "A" value measurement. As more and more partial deaf candidates are being implanted with CI, it could be highly beneficial if the electrode array length is selected based on the

Table 1 CDL equations proposed by various studies along with Greenwood frequency function.

Studies	CDL equations
Escude et al[4]	$CDL_{(LW)} = 2.62 \times A \times \log_e (1+ (\Theta/235))$
Erixon et al[5]	$CDL_{(LW)} = 3.08 \times A + 12.44$
Alexiades et al[8]	$CDL_{(OC)} = 4.16 \times A - 4$
Koch et al[22]	$CDL_{(OC)} = 4.16 \times A - 5.05$
Greenwood et al[10]	$F = A\ (10^{ax} - k)$

Where A is a constant (165.4) and k = 0.88. x is the proportion of the basilar membrane length.

Table 2 $CDL_{(LW)}$ and $CDL_{(OC)}$ measured using proposed equations from various studies for three different "A" values.

"A" value (mm)	$CDL_{(LW)}$ (mm) Escude et al	$CDL_{(LW)}$ (mm) Erixon et al	$CDL_{(OC)}$ (mm) Alexiades et al	$CDL_{(OC)}$ (mm) Koch et al	Ratio between Alexiades (OC) and Escude (LW)
7.5 (min)	30.9	35.5	27.2	26.2	0.9
9.0 (avg)	37.1	40.2	33.4	32.4	0.9
10.5 (max)	43.3	44.8	39.7	38.6	0.9

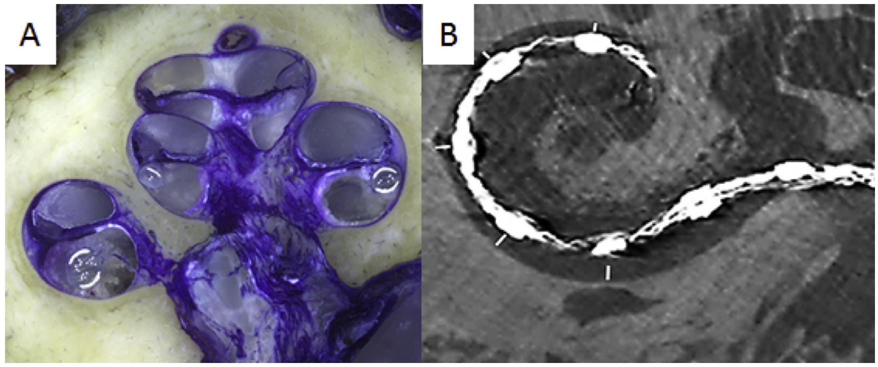

Fig. 2 Histology section at a mid-modiolar human cochlear section showing the position of the straight lateral wall electrode right under the basilar membrane (A). Micro-CT image (Courtesy: Prof. Ilmari Pyykko, Tampere, Finland) shows the position of the electrode well inside from the bony edge of the cochlea (B).

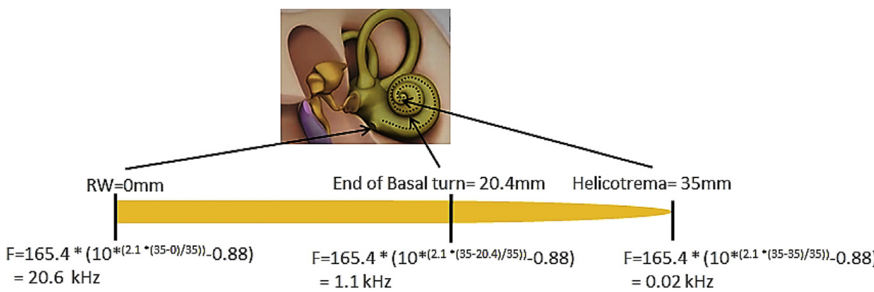

Fig. 3 Application of Greenwood function in finding the corresponding frequency at specific insertion depth inside the cochlea.

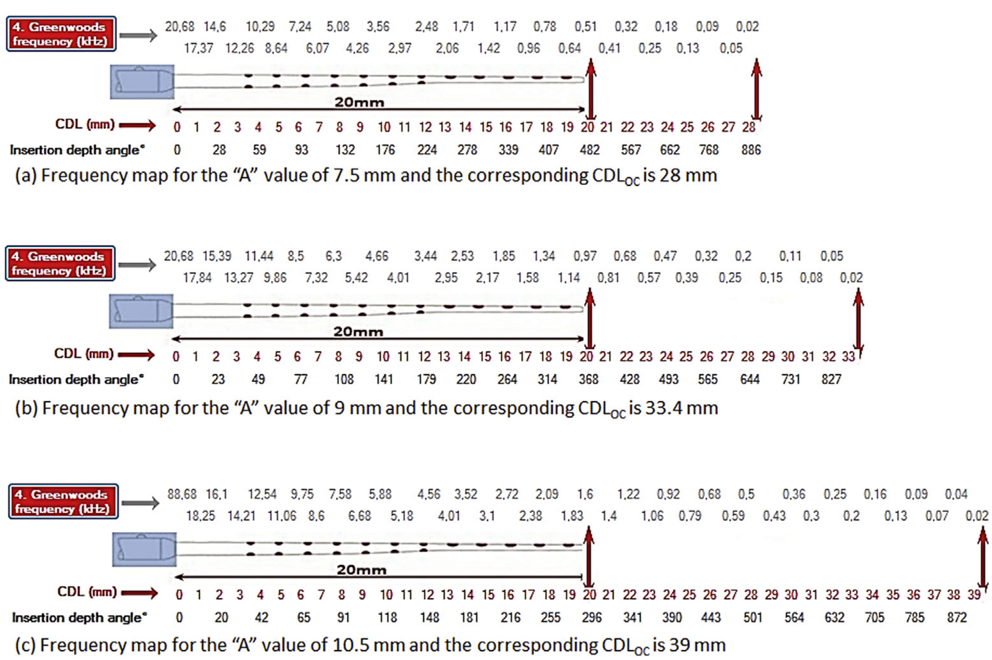

Fig. 4 Greenwood's Frequency map for 3 different sized cochleae with one electrode array length underneath it. Also given is the angular insertion depth (AID) (°). Electrode array length of 20 mm is at an AID of 490° in the smallest cochlea (A), whereas the same electrode array length would cover an AID of 300° in the biggest cochlea (C).

patient's residual hearing level so that the acoustic hearing is not disturbed by the electrode's physical presence. Also it is important to understand how a different electrode array length will contribute to the differences in the angular insertion depth in different sized cochleae.

Conclusion

Estimating the CDL_{OC} is relevant in selecting the correct lateral wall electrode array length and as well in the application of Greenwood frequency function. As the CDL topic is very sensitive in terms of making errors, researchers should get a good understanding on the difference between $CDL_{(LW)}$ and $CDL_{(OC)}$.

Conflict of interest

Author is an employee at MED-EL GmbH Austria at the time of writing this article.

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