Research Paper

Research software in cochlear duct length estimation, Greenwood frequency mapping and CI electrode array length simulation

Anandhan Dhanasingh

MED-EL GmbH, Fürstenweg 77a, 6020, Innsbruck, Austria

Abstract *Background and objective:* The size of the cochlea varies a lot among the human population bringing the necessity for electrode arrays to be available in various lengths irrespective of the cochlear implant (CI) brand. This research software helps in the estimation of the patient's cochlear duct length (CDL) which is then used for the simulation of the correct length electrode array matching the patient's cochlear size and as well in getting the patient specific cochlear frequency map.
Methods: Visual Studio Express 2012 for Windows Desktop is used in the architecture of this research software. The basal turn diameter of the cochlea ("A" value) needs to be measured from the pre-operative computed tomography (CT) image of the patient's temporal bone. This "A" will be taken as the input for the CDL equations proposed by Alexiades et al for estimating the CDL along the basilar membrane for various insertion depths. Greenwood's equation is then used in combination with the CDL for the full length of the cochlea in getting the patient specific frequency map.
Results: The research software with the help of the "A" value as input, with few button clicks, gives the patient specific CDL for various insertion depths and the Greenwood's frequency map. The users have the choice to select any electrode array of their choice and place it under the frequency map to see how good it fits to that particular patient's cochlea. Also, given the possibility to drag and move the electrode array picture to mimic the post-operative actual electrode insertion depth.
Conclusions: This research software simplifies the overall process of CDL estimation and in get-

E-mail address: Anandhan.dhanasingh@medel.com.

Introduction

Cochlear implant (CI) field is moving towards "individualized CI solution" especially with the electrode array length matching the variations in the patient's cochlear duct length (CDL).[1] Though there are several peer-reviewed publications showing different methods of estimating CDL from pre-operative imaging just by measuring the basal turn diameter ("A" value as it is generally called in the CI field),[1–4] still there is no single software type tool available (at the time of writing this article) that can picturize all the cochlear parameters in front of the clinicians eyes. Combining patient's pre-operative audiogram and the patient specific Greenwood frequency map would help in simulating the placement of different lengths of CI electrode array in the patient specific cochlear size to see how good the CI electrode matches with the patient's cochlear size. Software that simplifies the overall process of estimating the patient's CDL and just by a button click bringing the patient specific Greenwood frequency map would certainly help the clinicians and the audiologist in proper selection of the CI electrode array and in post-operative speech processor fitting. This software was already put in clinical use especially in estimating the CDL and in the CI electrode array length selection.[5] In that study, the operating surgeon was able to fully insert the CI electrode array that was suggested by the software based on the estimated CDL demonstrating the clinical effectiveness of this research software. To the best of author's knowledge, there are no other free software solutions available in the estimation of CDL along the basilar membrane, Greenwood frequency mapping, CI electrode array length selection and as well in mimicking the post-operative actual electrode insertion depth.

Methods

Software description

Visual Studio Express 2012 for Windows Desktop is used in the architecture of this research software. This research software takes the mathematical equations formulated by Alexiades et al[3] for the estimation of CDL along the basilar membrane and takes Greenwood frequency function in getting the patient specific frequency map.[6] The author of this article was also a co-author of Alexiades et al.[3] The software has four main modules as shown in Fig. 1.

The first module covers the CDL estimation with the help of CDL equation formulated by Alexiades et al.[3] The four equations by Alexiades et al[3] is given below.

(1) The full length of the cochlea (base to apex) covering an angular insertion depth of 900° = 4.16 × A - 3.98.
(2) The two turn length (2 TL) covering the basal turn and the middle turn of the cochlea covering an angular insertion depth of 720° = 3.65 × A - 3.63.
(3) The one and half turn length (1.5 TL) covering the basal turn and $^{1}/_{2}$ of the middle turn of the cochlea with an angular insertion depth of 540° = 3.12 × A - 3.12.
(4) The one turn length (1 TL) covering only the basal turn of the cochlea with an angular insertion depth of 360° = 2.43 × A - 2.43.

The "A" value in all these equations is the only variable that needs to be measured from the pre-operative image of the patient's cochlea as shown in Fig. 1 and the "A" value is the only input this research software needs to be given to get the estimated CDL along the basilar membrane for various insertion depths. The full length of the cochlea which is estimated from the "A" value is then used as the input for the Greenwood frequency function.

The second module is the frequency mapping that uses the Greenwood's frequency function.[6]

$$F = A \times (10^{ax} - k)$$

"A = 165.4", "a = 2.1" and "k = 0.88)" are constants leaving the "x" as the only variable. "x" is expressed as the proportion of the basilar membrane length which is derived from the full length of cochlea.

The third module is the electrode array selection which combines the CDL estimation module and the Greenwood patient specific frequency mapping module. For the profound deaf condition, an electrode array length covering the 2 turn length is preferable and the user can select the electrode array length of their choice and the software automatically places it under the CDL and Greenwood frequency function to see how good the CI electrode array fits to that particular cochlear size. For cases with partial deaf condition, the CDL, the Greenwood frequency map and the pre-operative audiogram will help to find the correct length electrode array without overlapping with the functional residual hearing in the low-frequency region. The details of all the 3 modules are given in Fig. 1 in a flow-chart format.

The fourth module covers the post-operative actual electrode insertion depth. Upon looking at the post-operative image that shows the actual electrode insertion
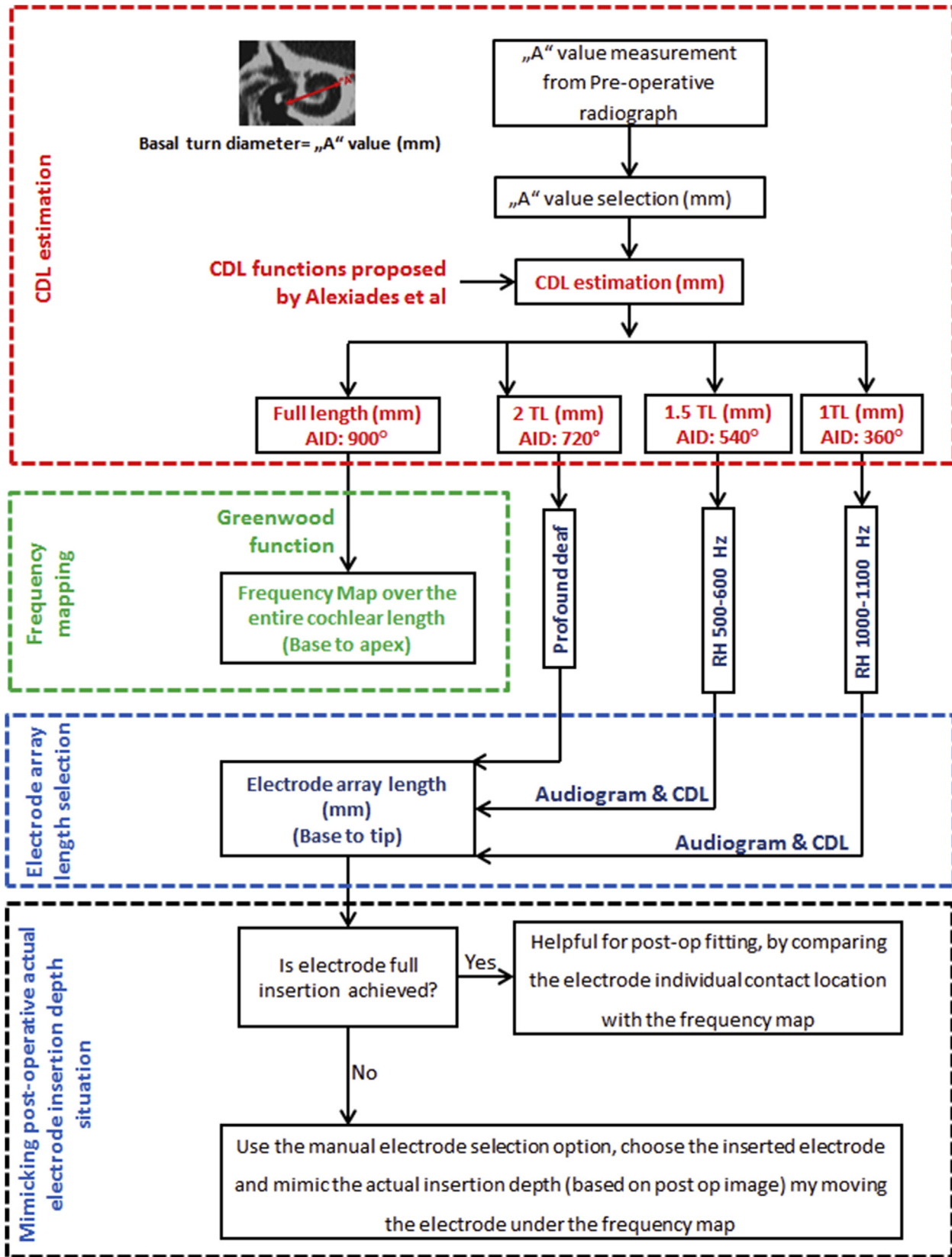
Fig. 1 Flowchart showing the four main modules of this software. CDL estimation using the Alexiades et al[3] equations is covered by the CDL estimation module (red box). Application of Greenwood frequency function is covered by the frequency mapping module (green box). Correct length electrode array selection is covered by the third module in blue box. Post-operative actual electrode insertion depth can be mimicked by the fourth module given in black box.

depth, the research software helps to mimic a similar same situation by holding the selected electrode array by the left mouse click and can be dragged in the horizontal position. This will be of much help in the post-operative audio processor fitting by the audiologists.

Results

Program description

To perform all four functionalities (refer Fig. 2), it starts with the selection of the "A" value from the drop down menu. Upon selecting the "A" value, the button1 captioned "1. CDL LW based on Escude's" should be clicked followed by buttons 2 and 3 captioned "2. CDL LW to CDL OC" and "3.CDL OC for various insertion depths". These 3 button clicks will provide the CDL for various insertion depths. For the patient specific frequency map click the button 4 captioned "4.Greenwoods frequency (kHz)". For the electrode selection, select the electrode array of the user's choice from the drop down menu followed by clicking the button 5 captioned "5. Electrode". This functionality will

place the electrode of user's choice right under the frequency map. In case if the patient's pre-operative audiogram shows any functional low frequency hearing, it can be mimicked by selecting the appropriate residual hearing level from the drop down list just above the button 7 captioned "7. Residual hearing" and upon clicking this button, the corresponding residual hearing level will be highlighted in the Greenwood frequency map. This research software additionally gives the possibility to click and drag the selected electrode array in the horizontal direction (back and forth) under the Greenwood frequency map in mimicking the actual post-operative electrode insertion depth. This will be highly interesting during the post-operative audio processor fitting.

Software specification

For computers that are running in windows English version has the decimal separated by dot (.) whereas the windows running in other European languages has the decimal separated by comma (,). Therefore before selecting the "A" value, please select either "$&£" or "€" radio button for dot or comma respectively depending on the windows
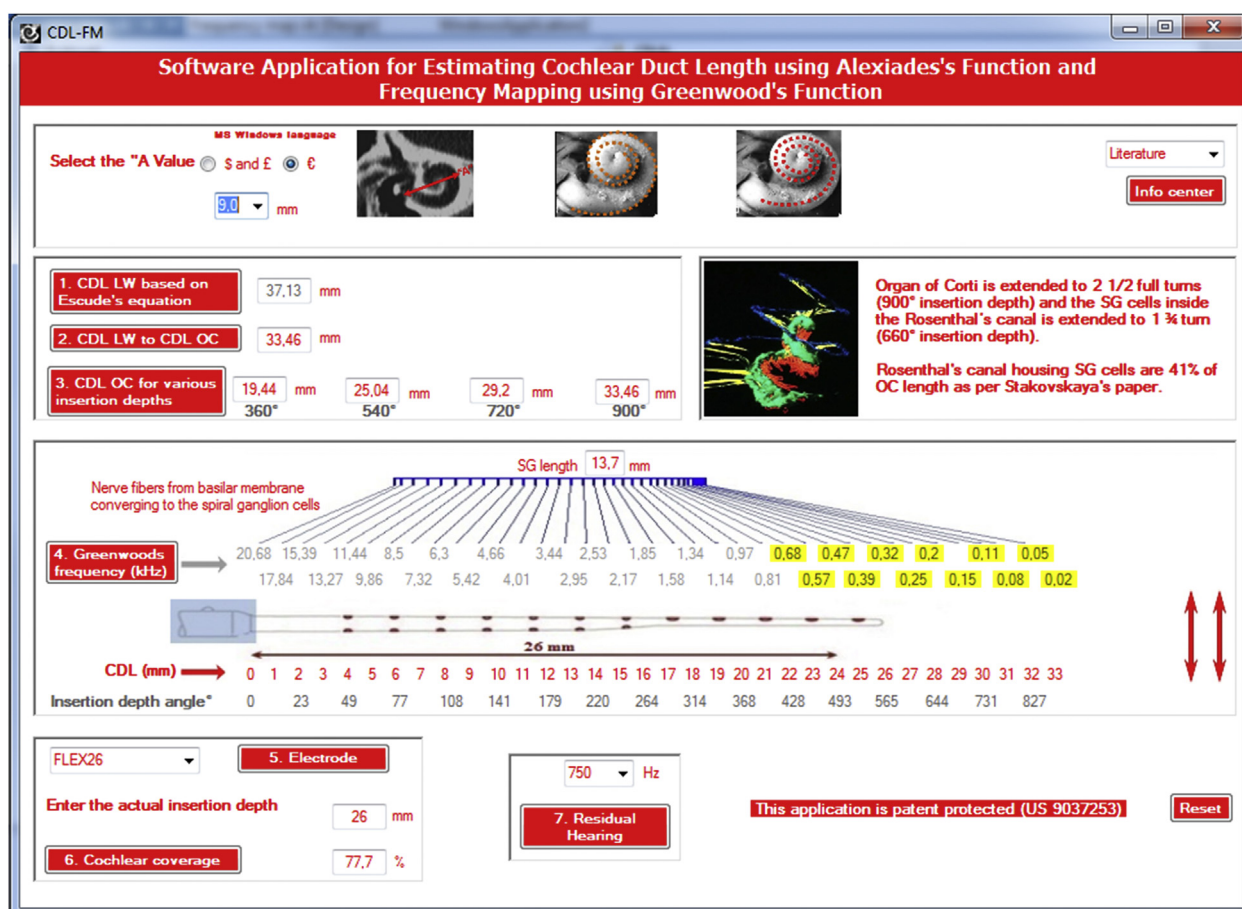

Fig. 2 Screenshot of the main window of the research software with the selection of the "A" value of 9.0 mm. The full length of the cochlea is estimated to be 33.46 mm based on the "A" value. The corresponding Greenwood frequency map is shown. An electrode array length of 26 mm has been selected and it is given below the frequency map. The residual low frequency has been assumed to be 750 Hz and this is highlighted in the frequency map by the yellow shades. The inside picture of the SG cells is taken from Rask-Andersen et al.[7] Copyright® 2010 Karger.

version of the users computer. The selection of the "A" value from the drop down list is the only input this research software requires to calculate the remaining of the cochlear parameters.

Click buttons 1, 2 and 3 to get the estimated CDL for various insertion depths. Button 4 will provide the Greenwoods frequency map based on the CDL value provided by the button 2. For the electrode selection, just for example FLEX 26 electrode array was selected and upon clicking button 5 shows the selected electrode under the frequency map. For this example we assume the patient is having residual hearing starting from 750 Hz and selecting that value from the drop down list and clicking button 7 will highlight the residual hearing in the Greenwood frequency map. The electrode picture can also be selected by the left-mouse click and dragged back and forth in the horizontal direction to mimic the post-operative imaging showing the actual electrode insertion depth. Click the below hyperlink to view to the source code and the executable file https://github.com/anandhandhanasingh/Research-Software (See Fig. 3) of this research software (In case if this link does not works, please contact the author directly).

Discussion

Individualized CI electrode solution matching the patient's cochlear size is the direction in which the current CI field is moving on and to complement this concept, this research software has been developed. Especially for partial deaf condition with functional low frequency hearing, the electrode array length selection is very critical as the physical placement of the electrode in the low frequency region carries the risk of of negatively affecting the residual hearing and this is how it is widely understood in the CI field. The application of this research software helps in the combination of patient specific frequency map and pre-operative audiogram that would show the exact insertion depth at which the residual hearing starts. Based on this information, a suitable electrode array lengt can be safely implanted. In contrast to the idea of choosing shorter electrode array for patients with functional low frequency residual hearing, Manjali et al[8] (2018) reported on the low-frequency residual hearing preservation possibilities with the standard length (28 mm) electrode insertion. If the residual hearing can be preserved initially with standard length electrode, it will be beneficial to the patient in the future when the residual hearing deteriorates over time and still the cochlea can be equipped with maximum electrical coverage. As described by Stefanescu et al[5] (2018), the application of this research software in the clinical practice helps the surgeon in knowing the patient's CDL pre-operatively and it is of much help in selecting the safe electrode array length and in planning the surgery well. This research software is mainly useful for clinicians, audiologists and basic researchers in the CI field. The OTOPLAN (http://otoplan.ch, from Cascination AG, Bern Switzerland), now the commercially available CE marked


```vb
Frequency map.vb    Frequency map.vb [Design]    WindowsApplication2
Button4                                          Click

    ' If TextBox5.Text > 44 Then
    ' MsgBox("Seems your system's Microsoft Windows language is European. Please select the € symbol for the A value select
    'End If

If ComboBox1.Visible = True Then
    If ComboBox1.Text = "" Then
        MsgBox("Please select an A value")
    Else
        Dim H As Decimal
        '     H = 0.89 * (2.62 * ComboBox1.Text * Math.Log(1 + (360 / 235)))
        H = (2.43 * ComboBox1.Text) - 2.43
        H = Math.Round(H, 2)
        TextBox7.Text = H

        Dim I As Decimal
        ' I = 0.89 * (2.62 * ComboBox1.Text * Math.Log(1 + (540 / 235)))
        I = (3.13 * ComboBox1.Text) - 3.13
        I = Math.Round(I, 2)
        TextBox8.Text = I

        Dim J As Decimal
        '     J = 0.89 * (2.62 * ComboBox1.Text * Math.Log(1 + (720 / 235)))
        J = (3.65 * ComboBox1.Text) - 3.65
        J = Math.Round(J, 2)
        TextBox9.Text = J

        Dim K As Decimal
        ' K = 0.9 * (2.62 * ComboBox1.Text * Math.Log(1 + (900 / 235)))
        K = (4.16 * ComboBox1.Text) - 3.98
        K = Math.Round(K, 2)
        TextBox10.Text = K
        Button5.Enabled = True

    End If
End If
```

Fig. 3   A screen shot of the source code used in the architecture of this research software.

otological preplanning software uses the concept of this research software in its electrode visualization module, but with fine-tuned CDL equations taking both the basal turn diameter "A" and the basal turn width "B" as inputs. The presented research software has additional features like moving the selected electrode under the Greenwood frequency map in the horizontal direction to mimic the actual post-operative electrode insertion depth and as well in highlighting the functional low frequency residual hearing level in the frequency map.

Conclusions

The research software described in this article has the following applications. (1) The software helps in the estimation of CDL along the basilar membrane for various insertion depths and this is very handy in understanding the patient's cochlear parameters. (2) The application of Greenwood function in getting the patient specific frequency map is now possible just by a button click. (3) Selection of the correct electrode array length matching the patient's cochlear size is now possible and it provides the opportunity to the clinicians in selecting the electrode array length of their choice and match with the patient's cochlear size. (4) By combing the pre-operative audiogram with the Greenwood frequency function, it helps the operating surgeon and the audiologist in understanding the intra-cochlear position at which the residual hearing starts. This research software was made with the intention of simplifying several steps in the CI treatment, especially with the electrode array length selection as given above.

Declaration of Competing Interest

Author is employed at MED-EL GmbH Austria as the Head of Translational Science Communication, which is purely a scientific role with no sales or marketing activities.

Acknowledgement

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.wjorl.2018.12.002.

References

1. Iyaniwura JE, Elfarnawany M, Ladak HM, Agrawal SK. An automated A-value measurement tool for accurate cochlear duct length estimation. *J Otolaryngol Head Neck Surg*. 2018; 47:5.
2. Erixon E, Rask-Andersen H. How to predict cochlear length before cochlear implantation surgery. *Acta Otolaryngol*. 2013; 133:1258—1265.
3. Alexiades G, Dhanasingh A, Jolly C. Method to estimate the complete and two-turn cochlear duct length. *Otol Neurotol*. 2015;36:904—907.
4. Anschuetz L, Weder S, Mantokoudis G, Kompis M, Caversaccio M, Wimmer W. Cochlear implant insertion depth prediction: a temporal bone accuracy study. *Otol Neurotol*. 2018;39: e996—e1001.
5. Stefanescu EH, Motoi S. Selection of the appropriate cochlear electrode array using a specifically developed research software application. *J Laryngol Otol*. 2018;132:544—549.
6. Greenwood DD. A cochlear frequency-position function for several species-29 years later. *J Acoust Soc Am*. 1990;87: 2592—2605.
7. Rask-Andersen H, Liu W, Linthicum F. Ganglion cell and 'dendrite' populations in electric acoustic stimulation ears. *Adv Otorhinolaryngol*. 2010;67:14—27.
8. Manjaly JG, Nash R, Ellis W, et al. Hearing preservation with standard length electrodes in pediatric cochlear implantation. *Otol Neurotol*. 2018;39:1109—1114.