Use of Cone Beam Computed Tomography to Assess Cochlear implant Electrode position with Correlation to Performance

Original Article

Yasser Shewel[1], Mohamed Talaat[2], Mohamed Khaled[1], Mohamed Eid[3], Mokhtar Bassiouni[1]

Department of Otorhinolaryngology[1], Audiology[2] and Diagnostic Radiology[3], Faculty of Medicine, Alexandria University, Egypt.

ABSTRACT

Aim: Cone Beam Computed Tomography (CBCT) has been used in a variety of maxillodental applications and recently, it has proved to be effective in the otorhinolaryngology field. In this study, we used CBCT for assessment of scalar location, insertion length and distance between the cochlear implant electrode array and modiolus and correlate these factors to speech performance.

Patients and Methods: This study was carried out on 30 children with bilateral severe to profound prelingual sensorineural hearing loss that had undergone cochlear implantation. Radiological assessment of electrode arrays position using CBCT was performed and correlated with speech recognition score.

Results: CBCT revealed that the electrode array was inserted in the scala tympani in 26/30 children (86.66%) and showed better speech recognization score than scala vestibule insertion. The mean distance between the modiolus and electrode arrays was 0.53 ± 0.11 mm and the average length of insertion was 21.49 ± 3.65mm. Distance between the electrode array and modiolus was negatively correlated to audiological performance in all patients. Pearson test showed a statistically significant positive correlation between insertion length and speech recognition score.

Conclusion: CBCT is very effective in localizing cochlear implant electrode arrays. Depth of insertion and closer distance to modiolus are associated with statistically better speech outcome.

Key Words: Cochlear implant, cone beam computed tomography, modiolus.

Received: 31 March 2020**, Accepted:** 10 December 2020

Corresponding Author: Yasser Shewel, MD, Department of Otolaryngology, Faculty of Medicine, Alexandria, Egypt, **Tel.:** (+2)01220149937, **E-mail**: ayassermmmm@yahoo.com

ISSN: 2090-0740, March 2021 Vol.22, No.1

INTRODUCTION

Ever since the invention of cochlear implants, the need for postoperative follow up and assessment of the location of electrodes has been increasingly more important.

Originally, multi-slice computed tomography (MSCT) and conventional x-ray were used for this purpose, and MSCT was acceptable[1-6] except for the fact that:

- It gives a large radiation dose of about 3600 µSv which in young children that form the bulk of cochlear implant patients isn't acceptable[7].
- It needs a long time of being still in the CT machine, which may not be feasible without anesthesia.
- Any movement during the scan would have a disfiguring result in the output scan.
- Any metals or foreign body e.g. cochlear implant itself would produce considerable artifacts and interference with the image[8].
- Some MSCT systems don't allow for imaging of 22-electrode implants[9].
- Lastly, the high cost of MSCT scans nowadays was a barrier to some patients keeping up with a follow-up.

From here arose the need for an imaging tool that would be low budget, low radiation dose, has short scan time and still gives clear images[10]. Such a tool was CBCT which was found to be fulfilling the above criteria[7, 11].

Hasstedt *et al* assessed the position of cochlea implant electrode arrays in temporal bone specimens and demonstrated that cone beam computed tomography gave similar result regarding the position of the electrode in relation to modiolus compared to histological analysis[12].

The outcome of cochlear implantation is highly variable. Many studies were undertaken to determine factors that influence the performance of cochlear implants patients. Age, duration of hearing loss before implantation,

 DOI: 10.21608/ejentas.2020.25821.1187

causes of hearing loss and duration of use of the implant are factors that consistently found to affect the outcome of implantation[7, 13-15].

Scalar location, depth of insertion, and proximity of electrode array to the modiolus were reported to have a critical impact on the audiological performance. Many studies have shown that translocation of the array from scala tympani to vestibuli had a substantial negative prognosis on audiological outcomes[16, 17].

One crucial factor that has not been extensively studied and may determine the performance of cochlear implant users is the distance between the electrode array and modiolus that houses the spiral ganglion cells[15].

Multiple early studies showed that direct electrical excitation of auditory nerve using electrode positioned through modiolus was more efficient in the activation of the nerve fibres than Scala tympani stimulation[18, 19]. Marsh *et al*. reported diminished threshold current levels with modiolar electrodes[20].

Shepherd *et al*. performed an experimental study on the cochlea of cats and stated that the close location of the electrode to the modiolus reduced the threshold significantly[21].

Timothy J Davis *et al* measured distance of electrodes from modiolus using CT and showed that this distance was negatively correlated to needed current to induce stimulus in adults with cochlear implants[22].

Marine Lathuilliere *et al*. performed a study about the utility of CBCT in evaluation the insertion depth angle of electrodes arrays in the pediatric age group and its effect on the electrically evoked compound action potential (ECAP) threshold and they found that neither type of electrodes nor the insertion depth angle of electrodes arrays have a significant effect on ECAP[23].

To our knowledge, no research has been used CBCT to measure the electrode modiolus distance and relate it to the actual audiological performance in the pediatric age group.

So, in this study, we used CBCT for assessment of scalar location, insertion length and distance between the cochlear implant electrode array and modiolus and correlate these factors to speech performance.

PATIENTS AND METHODS:

We acquired informed written consent from 30 patients that previously had bilateral prelingual profound sensorineural hearing loss and underwent cochlear implantation before the age of 5 years from 2010 to 2018. The institutional committee approved this study. All children are fulfilling the next criteria:

- The surgery was carried out for patients using a classic facial recess approach.
- Cochlear implant electrodes were inserted through the round window.
- All received Sonata MED-EL cochlear implant (MED-EL GmbH, Innsbruck, Austria).
- All participants had IQ above 75 and within normal ranges.
- All had got a minimum of 1 year phoniatrics and audiological regular follow-ups in our departments.
- None had any congenital anomalies, syndromic hearing loss, meningitis, jaundice or history of major head trauma.

Participants were subjected to extensive medical history taking, review of previous audiological tests and imaging scans, full otorhinolaryngological examination, recent audiological assessment and CBCT of the temporal bone.

Audiological assessment:

Patients were seated in a sound-treated room facing the loudspeaker at a distance 1 meter and 0-degree azimuth. Signals were presented using Itera II diagnostic audiometer.

Pure tone audiometry: Warble tones were presented at 60 dB HL and decreased in 5 dB steps across the frequency range 250-4000 Hz until no response was obtained. The threshold was defined as the lowest pure tone level at which the patient responded.

Speech audiometry: Arabic Monosyllabic words list were presented at 40 dB above pure tone average dB and the response was repeating the word. Percentage of correct words was measured.

Radiological assessment:

CBCT of temporal bone using J. Morita R100 cone beam 3D imaging system (Morita 3DX; J Morita Mfg corp., Kyoto, Japan) by a protocol that was decided upon after multiple pilot studies for best quality images, which was a multi-planar reconstructed 0.260 mm isometric voxel size using a field of view (FOV) 100 mm x H 80 mm, tube voltage of 90 kVp and current of 8 mA with an exposure time of 20 seconds.

Results of the scan were assessed by OnDemand 3D viewer software (Cybermed, Seoul, South Korea) to get

the scalar position, insertion depth, and average distance between the electrode arrays and modiolus for each participant for correlation with their corresponding speech scores.

The software was very helpful in increasing image quality even more by using sharpening filters and 3D multi-planar functions to reduce motion blur and any minute artifacts from either electrodes or motion (Figure1, 2).

Two senior otologists and one senior radiologist independently assessed the image quality.

First, we identified the osseous spiral lamina on the axial/sagittal oblique views and location of the electrode array in relation to the osseous spiral lamina was determined. Then, measurements were taken from each intracochlear electrode contacts to the modiolus and an average distance was calculated for each subject (Figure 3).

Using 3D curved multi-planar reconstruction, the insertion length of each CI was measured. the insertion length was considered as the spiral route from the insertion site of the cochlea along the centre of electrode arrays toward its terminal end[24].

Statistical analysis:

Statistical analysis was calculated using GraphPad Prism program, version 5 for Windows (GraphPad Software, San Diego, California, USA). T-test was used to compare means. Correlation of speech score and electrode modiolus distance, depth of insertion and other parameters were examined using Pearson's correlation analysis. A value of $P<0.05$ was regarded as significant.

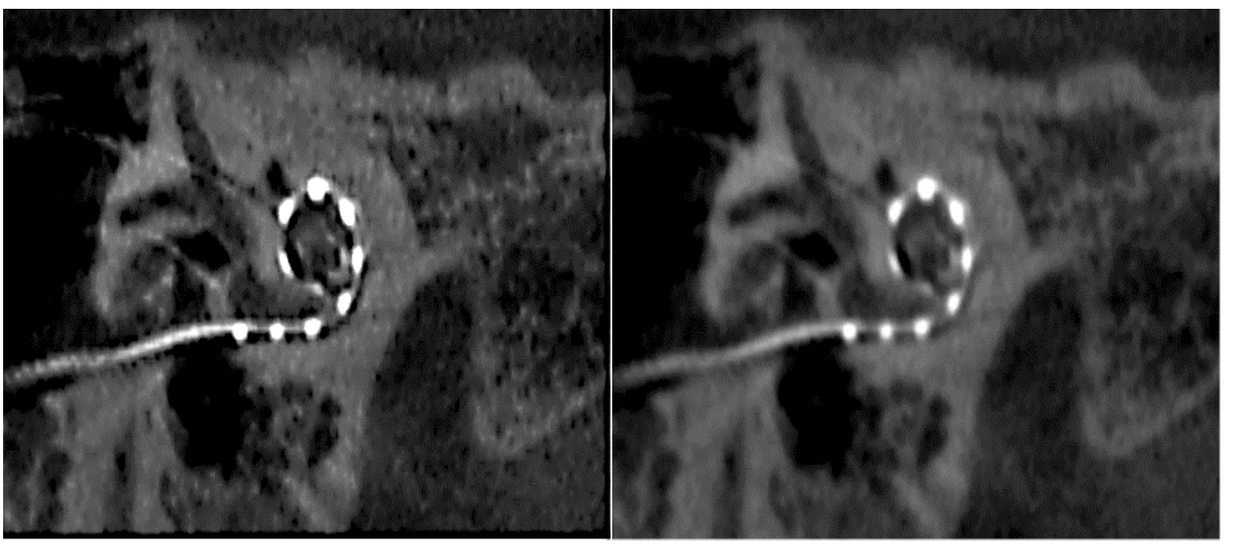

Fig. 1: Unedited image acquired with excellent resolution (A) the Same image after sharpening to emphasize electrodes over surrounding structures (B).

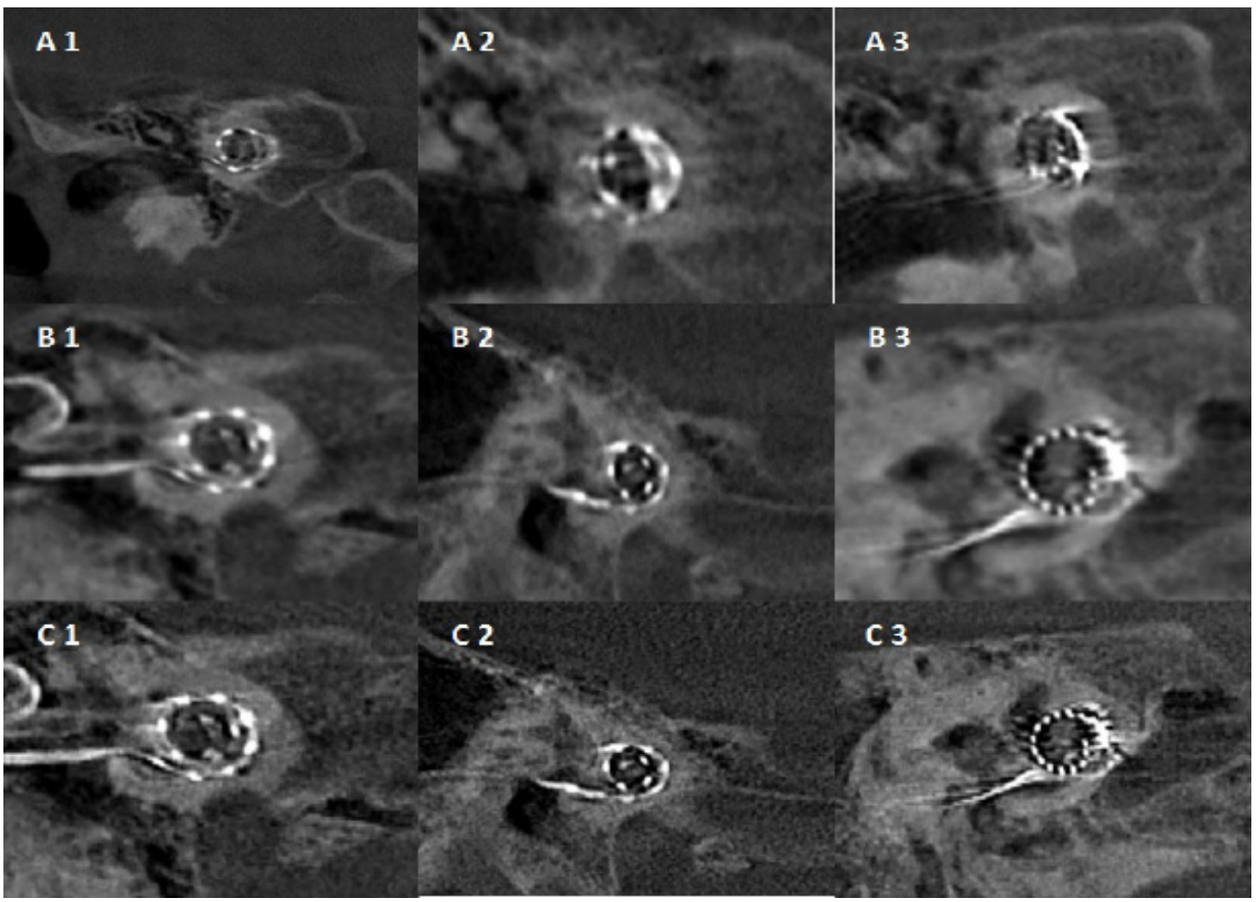

Fig. 2: Unedited images with motion blur and artefacts from patients 19, 21, 24 respectively (A1-3), Images after initial modification (B1-3), Images final sharpening (C 1-3)

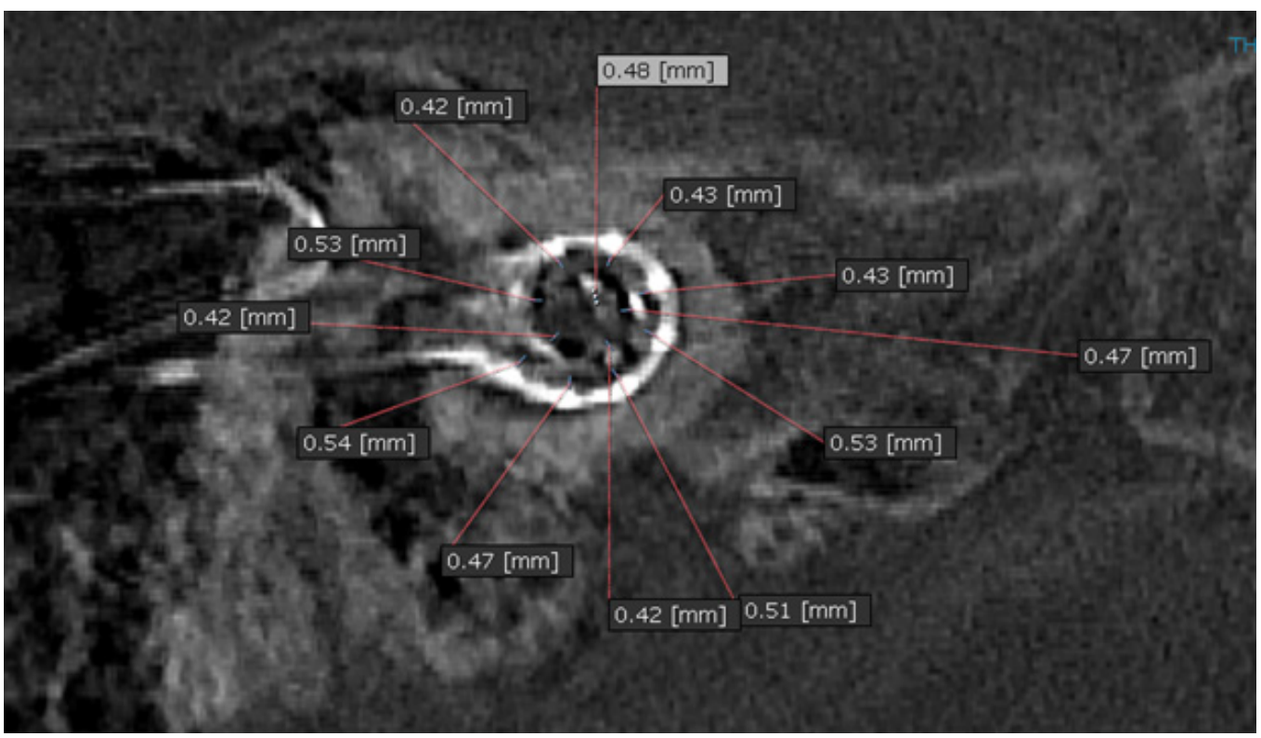

Fig. 3: Measurement of electrode- modiolus distance.

RESULTS:

This study was carried out on 30 (12 males and 18 females) children with bilateral prelingual severe to profound sensorineural hearing loss. The demographic data of children were shown in (Table 1).

Word recognition score:

The word recognition score ranged from 52 to 92% with an average score of 72.9±14.05%. None of the following variables has a significant impact on word recognition score including age at implantation, age at audiological assessment in this study, gender and consanguinity ($p > 0.05$). (Table 2)

Position of the electrode arrays in the cochlea:

CBCT revealed that the electrode arrays located below osseous spiral lamina indicating that they were present in scala tympani in 26/30 patients (86.66%) while electrode arrays situated in scala vestibuli in 4/30 patients (13.34%).

The average speech recognition score was 74.77 ± 11.88% in children with scala tympani insertion while it was 60.75±22.53 % in scala vestibuli insertion showing better performance in children with scala tympani insertion, however, this difference was statistically insignificant (*p-value = 0.06*).

Distance between the electrode arrays and modiolus

The average distance between the modiolus and electrode arrays ranged from 0.31 – 0.82 mm with an average distance of 0.53 ± 0.11 mm.

In terms of correlating these findings by CBCT to the speech performance, we found a statistically strong negative correlation between distance to modiolus and speech recognition scores (r -0.781 - *P<0.001*). (Table 2, Figure 4)

Length of electrode arrays insertion:

The insertion length of cochlear implant electrode arrays varied from 12.80 to 26 mm with an average depth of insertion of 21.49 ± 3.65mm. Pearson test showed a statistically significant positive correlation between the depth of electrode array insertion and speech recognition scores (r = 0.4842, *p=0.006*).

There was one case with a partial electrode insertion of the electrode (12.8mm) without any noticeable clinical or radiological cause of obstruction.

Table 1: Distribution of the studied children according to demographic data (n=30)

Sex	No.	%
Male	12	40.0
Female	18	60.0
Age (years)	No.	%
<5	2	6.7
5 – 10	24	80.0
>10	4	13.3
Min. – Max.	4.60 – 13.0	
Mean ± SD.	8.13 ± 2.15	
Median (IQR)	8.20 (6.40 –9.20)	
Age at operation		
Min. – Max.	1.50 – 5.0	
Mean ± SD.	3.39 ± 1.12	
Median (IQR)	3.30 (2.40–4.30)	
Consanguinity	No.	%
No	7	23.3
Yes	23	76.7

Table 2: Correlation between word recognition score and different parameters (n=30)

	Speech score	
	r	*p*
Age at operation	-0.150	0.429
Age at Audiological assessment	0.1135	0.5504
Distance to modiolous (mm)	-0.781*	<0.001*
Length of electrode insertion	0.4842*	p=0.006*

r: Pearson coefficient
*: Statistically significant at $p \leq 0.05$

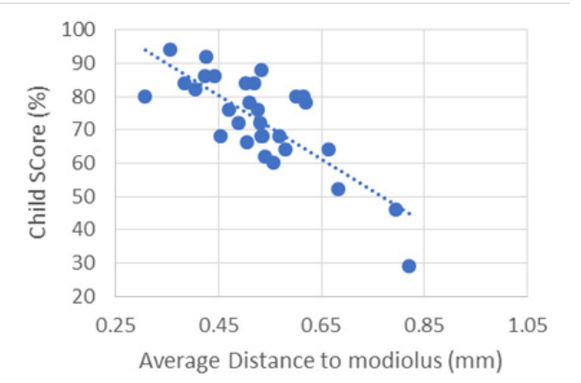

Fig. 4: Correlation between electrode- modiolus distance speech recognition scores.

DISCUSSION

As shown in the literature, CBCT has been advancing and utilized in a variety of maxillodental applications and recently, it has proved to be effective in the otorhinolaryngology field. It can at least show the same quality images as MSCT in a much easier and less risky way. CBCT takes a considerable shorter time to scan with at least 30 times with less radiation dose than its predecessor that had monopolized the role of temporal bone imaging in the past[7, 12, 25-34].

All these facts with the increasing need for post cochlear implant imaging for assessing the position of electrode arrays, trauma and other parameters have made CBCT as an ideal tool for intraoperative and postoperative imaging for cochlear implant patients. Intra and postoperative assessment will allow the otologists to see if there is any displacement of the electrode from scala tympani to vestibuli which significantly has a deleterious effect on the preservation of hearing. The other important issue for intra- or postoperative evaluation is to visualize electrode kink, buckle or tip folding and take a countermeasure by switching off the contacts in that region to improve the patient's performance[35].

To the best of our knowledge so far, all studies in the literature have only studied the ability of CBCT to localize cochlear implant electrode arrays within the ear accurately and measuring currents needed for function in correlation to the position in the cochlea[22] but none have attempted to correlate cochlear implant electrode arrays position from modiolus to audiological function and performance. So, in our study besides testing CBCT as an imaging tool for localizing and visualizing cochlear implant electrode array, we attempted to show the relation between scalar position, length of insertion and average electrode array modiolar distances and actual speech performance.

Zou *et al*. evaluated CBCT in detecting the variability of cochlear morphology and position of cochlear implant electrode arrays in the human temporal bone. They can visualize all key anatomical landmarks of cochlea accurately, in addition, they measured the length of insertion and interval between the electrode arrays and modiolus but did not study the influence of these factors on the performance[35].

In the role of visualizing and showing inner ear anatomy, the CBCT system was very effective in showing excellent images with very little if no artefact from the metallic electrodes but these images were not always easy to acquire as some patients found it hard to stay still for the 20 seconds of the scan duration and sometimes minute movements would ruin some images but with the help of viewing software, these motion blurs were reduced significantly[10].

This study revealed the anatomical details of the cochlea, such as modiolus, scala vestibuli, scala tympani, osseous spiral lamina, and round window. Osseous spiral lamina is a key structure to decide the site of insertion of the electrode array. When the electrode array was below the osseous spiral lamina, it was regarded as being located in scala tympani, when it was above it, the electrode array was placed in scala vestibuli.[36]

In our study, the electrode arrays were implanted into scala tympani in 26/30 of children and showed better audiological performance compared to scala vestibuli insertion. However, this difference was statistically insignificant. This finding was in agreement with multiple previous studies revealed that implantation of the electrode arrays in scala tympani had superior speech perception performance when compared to scala vestibule counterpart.[17, 37, 38]

In this study, there was no significant impact of age, gender, consanguinity on performance as demonstrated by statistical tests ($p>0.05$).

By correlating with the respective scores and analyzing the data, we found that the smaller the electrode modiolar distance, the better the performance of the subject, namely if less than 0.45 mm, the speech recognition score would be equal to or above 80%.

Reviewing the literature showed that several studies indicated that the perimodiolar position produced a significant decrease in charge for equal stimulation at the threshold and suprathreshold comfort levels and reduced EABR thresholds[39-41]. However, other researches did not have similar results[42, 43].

Davis *et al*. studied the relation between the distance of the electrode array and modiolus using CT and current levels for suprathreshold stimulation in adult patients with cochlear implantation. They found only a little correlation for perimodiolar electrodes[22].

Esquia Medina *et al*. used CT to estimate the distance between the modiolus and electrode and correlated it to the speech discrimination score in adults. They mentioned that was a significant negative correlation between electrode modiolar distance and speech score at 6 months however no correlation was present at one year after the operation[44].

Chakravorti and colleagues in their study emphasized on the importance of electrode location on speech performance and concluded that the most

significant positional factors that influence the results of the pre-curved electrode were full insertion in scala tympani and modiolar distance while for lateral wall electrode; the insertion depth plays a crucial role[15].

Van der Beek and colleagues noted that Speech perception was not significantly correlated with the insertion depth or the distance from the electrode array to the modiolus[45].

Regarding the depth of electrode array insertion, we found a statistically positive correlation between depth of insertion and word recognition score. This finding is consistent with many authors who reported that increased depth of insertion is associated with better speech performance[17, 38, 46]. Others reported no correlation or even a negative impact of deep insertion on the audiological performance[13, 16, 47, 48].

We have only one child with partial electrode insertion (12.8mm) with no preoperative or intraoperative reason and this finding was reported also by many authors[49, 50]. Lee j *et al*.[50] performed a histopathological study on the temporal bones with a history of incomplete insertion of electrodes and they found an obvious cause of obstruction by bone (labyrinthitis ossificans or bony spicules) or soft tissue in only 6/27 temporal bones (22%). They examined the remaining 21 temporal bones in which there was no scalar obstruction and concluded that trauma to the spiral ligament with associated dissection to the cochlear wall increases significantly the incidence of partial insertion of the electrodes.

CONCLUSION

Our study showed that CBCT had the ability to visualize the position of the cochlear implant electrode array, its distance to modiolus and length of insertion in a convenient way as each scan only needed 20 seconds without anaesthesia and considerably lower radiation dose.

The decreased distance between the electrode arrays and modiolus and deeper insertion were significantly related to good speech scores.

Scala tympani insertion of electrode arrays had better speech performance than scala vestibuli counterpart.

CONFLICT OF INTEREST

There are no conflicts of interest.

REFERENCES

1. Lecerf P, Bakhos D, Cottier JP, Lescanne E, Trijolet JP, Robier A. Midmodiolar reconstruction as a valuable tool to determine the exact position of the cochlear implant electrode array. Otology & neurotology: official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2011 Sep;32(7):1075-81. PubMed PMID: 21817940. Epub 2011/08/06. eng.

2. Lane JI, Witte RJ, Driscoll CL, Shallop JK, Beatty CW, Primak AN. Scalar localization of the electrode array after cochlear implantation: clinical experience using 64-slice multidetector computed tomography. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2007 Aug;28(5):658-62. PubMed PMID: 17558341. Epub 2007/06/15. eng.

3. van Wermeskerken GK, Prokop M, van Olphen AF, Albers FW. Intracochlear assessment of electrode position after cochlear implant surgery by means of multislice computer tomography. European archives of oto-rhino-laryngology:official journal of the European Federation of Oto-Rhino-Laryngological Societies (EUFOS):affiliated with the German Society for Oto-Rhino-Laryngology - Head and Neck Surgery. 2007 Dec;264(12):1405-7. PubMed PMID: 17632730. Epub 2007/07/17. eng.

4. Verbist BM, Frijns JH, Geleijns J, van Buchem MA. Multisection CT as a valuable tool in the postoperative assessment of cochlear implant patients. AJNR American journal of neuroradiology. 2005 Feb;26(2):424-9. PubMed PMID: 15709150. Epub 2005/02/15. eng.

5. Aschendorff A, Kubalek R, Hochmuth A, Bink A, Kurtz C, Lohnstein P, *et al*. Imaging procedures in cochlear implant patients--evaluation of different radiological techniques. Acta oto-laryngologica Supplementum. 2004 May(552):46-9. PubMed PMID: 15219047. Epub 2004/06/29. eng.

6. Todt I, Rademacher G, Wagner J, Gopel F, Basta D, Haider E, *et al*. Evaluation of cochlear implant electrode position after a modified round window insertion by means of a 64-multislice CT. Acta oto-laryngologica. 2009 Sep;129(9):966-70. PubMed PMID: 18979288. Epub 2008/11/04. eng.

7. Ruivo J, Mermuys K, Bacher K, Kuhweide R, Offeciers E, Casselman JW. Cone beam computed tomography, a low-dose imaging technique in the

postoperative assessment of cochlear implantation. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2009 Apr;30(3):299-303. PubMed PMID: 19174709. Epub 2009/01/29. eng.

8. Helbig S, Mack M, Schell B, Bratzke H, Stöver T, Helbig M. Scalar Localization by Computed Tomography of Cochlear Implant Electrode Carriers Designed for Deep Insertion. Otology & Neurotology. 2012;33(5):745-50. PubMed PMID: 00129492-201207000-00012.

9. Verbist BM, Joemai RM, Teeuwisse WM, Veldkamp WJ, Geleijns J, Frijns JH. Evaluation of 4 multisection CT systems in postoperative imaging of a cochlear implant: a human cadaver and phantom study. AJNR American journal of neuroradiology. 2008 Aug;29(7):1382-8. PubMed PMID: 18483188. Epub 2008/05/17. eng.

10. Arweiler-Harbeck D, Mönninghoff C, Greve J, Hoffmann T, Göricke S, Arnolds J, *et al*. Imaging of Electrode Position after Cochlear Implantation with Flat Panel CT. ISRN Otolaryngol. 2012 2012;2012:728205. PubMed PMID: 23762618. eng.

11. Penninger RT, Tavassolie TS, Carey JP. Cone-Beam Volumetric Tomography for Applications in the Temporal Bone. Otology & Neurotology. 2011;32(3):453-60. PubMed PMID: 00129492-201104000-00017.

12. Husstedt HW, Aschendorff A, Richter B, Laszig R, Schumacher M. Nondestructive three-dimensional analysis of electrode to modiolus proximity. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2002 Jan;23(1):49-52. PubMed PMID: 11773846.

13. Holden LK, Finley CC, Firszt JB, Holden TA, Brenner C, Potts LG, *et al*. Factors affecting open-set word recognition in adults with cochlear implants. Ear and hearing. 2013 May-Jun;34(3):342-60. PubMed PMID: 23348845. Pubmed Central PMCID: 3636188.

14. Nadol JB, Jr., Young YS, Glynn RJ. Survival of spiral ganglion cells in profound sensorineural hearing loss: implications for cochlear implantation. The Annals of otology, rhinology, and laryngology. 1989 Jun;98(6):411-6. PubMed PMID: 2729822.

15. Chakravorti S, Noble JH, Gifford RH, Dawant BM, O'Connell BP, Wang J, *et al*. Further Evidence of the Relationship Between Cochlear Implant Electrode Positioning and Hearing Outcomes. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2019 Jun;40(5):617-24. PubMed PMID: 31083083. Pubmed Central PMCID: 6788798.

16. Finley CC, Holden TA, Holden LK, Whiting BR, Chole RA, Neely GJ, *et al*. Role of electrode placement as a contributor to variability in cochlear implant outcomes. Otology & neurotology:official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2008 Oct;29(7):920-8. PubMed PMID: 18667935. Pubmed Central PMCID: 2663852.

17. O'Connell BP, Cakir A, Hunter JB, Francis DO, Noble JH, Labadie RF, *et al*. Electrode Location and Angular Insertion Depth Are Predictors of Audiologic Outcomes in Cochlear Implantation. Otology & neurotology:official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2016 Sep;37(8):1016-23. PubMed PMID: 27348391. Pubmed Central PMCID: 4983244.

18. Simmons FB, Glattke TJ. Comparison of electrical and acoustical stimulation of the cat ear. The Annals of otology, rhinology, and laryngology. 1972 Oct;81(5):731-7. PubMed PMID: 4651115.

19. Walloch RA, Cowden DA. Placement of electrodes for excitation of the eighth nerve. Archives of otolaryngology. 1974 Jul;100(1):19-23. PubMed PMID: 4842610.

20. Marsh RR, Yamane H, Potsic WP. Effect of site of stimulation on the guinea pig's electrically evoked brain stem response. Otolaryngology--head and neck surgery : official journal of American Academy of Otolaryngology-Head and Neck Surgery. 1981 Jan-Feb;89(1):125-30. PubMed PMID: 6784070.

21. Shepherd RK, Hatsushika S, Clark GM. Electrical stimulation of the auditory nerve: the effect of electrode position on neural excitation. Hearing research. 1993 Mar;66(1):108-20. PubMed PMID: 8473242.

22. Davis TJ, Zhang D, Gifford RH, Dawant BM, Labadie RF, Noble JH. Relationship Between Electrode-to-Modiolus Distance and Current Levels for Adults With Cochlear Implants. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2016 Jan;37(1):31-7. PubMed PMID: 26649603. Pubmed Central PMCID: PMC4675044. Epub 2015/12/10. eng.

23. Lathuilliere M, Merklen F, Piron JP, Sicard M, Villemus F, Menjot de Champfleur N, *et al*. Cone-beam computed tomography in children with cochlear implants: The effect of electrode array position on ECAP. International journal of pediatric otorhinolaryngology. 2017 Jan;92:27-31. PubMed PMID: 28012529.

24. Wurfel W, Lanfermann H, Lenarz T, Majdani O. Cochlear length determination using Cone Beam Computed Tomography in a clinical setting. Hearing research. 2014 Oct;316:65-72. PubMed PMID: 25124151.

25. Trieger A, Schulze A, Schneider M, Zahnert T, Murbe D. In vivo measurements of the insertion depth of cochlear implant arrays using flat-panel volume computed tomography. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2011 Jan;32(1):152-7. PubMed PMID: 20962701. Epub 2010/10/22. eng.

26. Bartling SH, Gupta R, Torkos A, Dullin C, Eckhardt G, Lenarz T, *et al*. Flat-panel volume computed tomography for cochlear implant electrode array examination in isolated temporal bone specimens. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2006 Jun;27(4):491-8. PubMed PMID: 16791040. Epub 2006/06/23. eng.

27. Aschendorff A, Kubalek R, Turowski B, Zanella F, Hochmuth A, Schumacher M, *et al*. Quality control after cochlear implant surgery by means of rotational tomography. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2005 Jan;26(1):34-7. PubMed PMID: 15699717. Epub 2005/02/09. eng.

28. Schuman TA, Noble JH, Wright CG, Wanna GB, Dawant B, Labadie RF. Anatomic verification of a novel method for precise intrascalar localization of cochlear implant electrodes in adult temporal bones using clinically available computed tomography. The Laryngoscope. 2010 Nov;120(11):2277-83. PubMed PMID: 20939074. Pubmed Central PMCID: PMC4445845. Epub 2010/10/13. eng.

29. Aschendorff A, Kromeier J, Klenzner T, Laszig R. Quality control after insertion of the nucleus contour and contour advance electrode in adults. Ear and hearing. 2007 Apr;28(2 Suppl):75s-9s. PubMed PMID: 17496653. Epub 2007/05/15. eng.

30. Kurzweg T, Dalchow CV, Bremke M, Majdani O, Kureck I, Knecht R, *et al*. The value of digital volume tomography in assessing the position of cochlear implant arrays in temporal bone specimens. Ear and hearing. 2010 2010/06//;31(3):413-9. PubMed PMID: 20440115. eng.

31. Zeitler DM, Wang KH, Prasad RS, Wang EY, Roland JT. Flat-panel computed tomography versus multislice computed tomography to evaluate cochlear implant positioning. Cochlear implants international. 2011 Nov;12(4):216-22. PubMed PMID: 22251809. Epub 2012/01/19. eng.

32. Struffert T, Hertel V, Kyriakou Y, Krause J, Engelhorn T, Schick B, *et al*. Imaging of cochlear implant electrode array with flat-detector CT and conventional multislice CT: comparison of image quality and radiation dose. Acta oto-laryngologica. 2010 Apr;130(4):443-52. PubMed PMID: 19883180. Epub 2009/11/04. eng.

33. Cushing SL, Daly MJ, Treaba CG, Chan H, Irish JC, Blaser S, *et al*. High-resolution cone-beam computed tomography: a potential tool to improve atraumatic electrode design and position. Acta oto-laryngologica. 2012 Apr;132(4):361-8. PubMed PMID: 22235960. Epub 2012/01/13. eng.

34. Casselman JW, Gieraerts K, Volders D, Delanote J, Mermuys K, De Foer B, *et al*. Cone beam CT: non-dental applications. JBR-BTR : organe de la Societe royale belge de radiologie (SRBR) = orgaan van de Koninklijke Belgische Vereniging voor Radiologie (KBVR). 2013 Nov-Dec;96(6):333-53. PubMed PMID: 24617175. Epub 2014/03/13. eng.

35. Zou J, Lahelma J, Koivisto J, Dhanasingh A, Jolly C, Aarnisalo A, *et al*. Imaging cochlear implantation with round window insertion in human temporal bones and cochlear morphological variation using high-resolution cone beam CT. Acta oto-laryngologica. 2015 May;135(5):466-72. PubMed PMID: 25675836. Pubmed Central PMCID: 4487572.

36. Zou J, Hannula M, Lehto K, Feng H, Lahelma J, Aula AS, *et al*. X-ray microtomographic confirmation of the reliability of CBCT in identifying the scalar location of cochlear implant electrode after round window insertion. Hearing research. 2015 Aug;326:59-65. PubMed PMID: 25922206.

37. Wanna GB, Noble JH, Carlson ML, Gifford RH, Dietrich MS, Haynes DS, *et al*. Impact of electrode design and surgical approach on scalar location and cochlear implant outcomes. The Laryngoscope. 2014 Nov;124 Suppl 6:S1-7. PubMed PMID: 24764083. Pubmed Central PMCID: 4209201.

38. Skinner MW, Holden TA, Whiting BR, Voie AH, Brunsden B, Neely JG, *et al*. In vivo estimates of the position of advanced bionics electrode arrays in the human cochlea. The Annals of otology, rhinology & laryngology Supplement. 2007 Apr;197:2-24. PubMed PMID: 17542465.

39. Parkinson AJ, Arcaroli J, Staller SJ, Arndt PL, Cosgriff A, Ebinger K. The nucleus 24 contour cochlear implant system: adult clinical trial results. Ear and hearing. 2002 Feb;23(1 Suppl):41S-8S. PubMed PMID: 11883766.

40. Jeong J, Kim M, Heo JH, Bang MY, Bae MR, Kim J, *et al*. Intraindividual comparison of psychophysical parameters between perimodiolar and lateral-type electrode arrays in patients with bilateral cochlear implants. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2015 Feb;36(2):228-34. PubMed PMID: 25473955.

41. Wackym PA, Firszt JB, Gaggl W, Runge-Samuelson CL, Reeder RM, Raulie JC. Electrophysiologic effects of placing cochlear implant electrodes in a perimodiolar position in young children. The Laryngoscope. 2004 Jan;114(1):71-6. PubMed PMID: 14709998.

42. Hughes ML, Abbas PJ. Electrophysiologic channel interaction, electrode pitch ranking, and behavioral threshold in straight versus perimodiolar cochlear implant electrode arrays. The Journal of the Acoustical Society of America. 2006 Mar;119(3):1538-47. PubMed PMID: 16583899.

43. van Weert S, Stokroos RJ, Rikers MM, van Dijk P. Effect of peri-modiolar cochlear implant positioning on auditory nerve responses: a neural response telemetry study. Acta oto-laryngologica. 2005 Jul;125(7):725-31. PubMed PMID: 16012034.

44. Esquia Medina GN, Borel S, Nguyen Y, Ambert-Dahan E, Ferrary E, Sterkers O, *et al*. Is electrode-modiolus distance a prognostic factor for hearing performances after cochlear implant surgery? Audiology & neuro-otology. 2013;18(6):406-13. PubMed PMID: 24157488.

45. van der Beek FB, Briaire JJ, van der Marel KS, Verbist BM, Frijns JH. Intracochlear Position of Cochlear Implants Determined Using CT Scanning versus Fitting Levels: Higher Threshold Levels at Basal Turn. Audiology & neuro-otology. 2016;21(1):54-67. PubMed PMID: 26891130.

46. Buchman CA, Dillon MT, King ER, Adunka MC, Adunka OF, Pillsbury HC. Influence of cochlear implant insertion depth on performance: a prospective randomized trial. Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology. 2014 Dec;35(10):1773-9. PubMed PMID: 25122601.

47. Khan AM, Handzel O, Burgess BJ, Damian D, Eddington DK, Nadol JB, Jr. Is word recognition correlated with the number of surviving spiral ganglion cells and electrode insertion depth in human subjects with cochlear implants? The Laryngoscope. 2005 Apr;115(4):672-7. PubMed PMID: 15805879.

48. Lee J, Nadol JB, Jr., Eddington DK. Depth of electrode insertion and postoperative performance in humans with cochlear implants: a histopathologic study. Audiology & neuro-otology. 2010;15(5):323-31. PubMed PMID: 20203481. Pubmed Central PMCID: 2919426.

49. Skinner MW, Ketten DR, Holden LK, Harding GW, Smith PG, Gates GA, et al. CT-derived estimation of cochlear morphology and electrode array position in relation to word recognition in Nucleus-22 recipients. Journal of the Association for Research in Otolaryngology : JARO. 2002 Sep;3(3):332-50. PubMed PMID: 12382107. Pubmed Central PMCID: 3202410.

50. Lee J, Nadol JB, Jr., Eddington DK. Factors associated with incomplete insertion of electrodes in cochlear implant surgery: a histopathologic study. Audiology & neuro-otology. 2011;16(2):69-81. PubMed PMID: 20571258. Pubmed Central PMCID: 2948664.