Child's Nervous System (2025) 41:199
https://doi.org/10.1007/s00381-025-06843-z

RESEARCH

Three-dimensional examination of cochlear dimensions in children up to 18 years

Saliha Seda Adanır[1] · Mohammad Al Saadi[2] · İlhan Bahşi[1] · Piraye Kervancıoğlu[1] · Vedat Topsakal[3]

Received: 2 January 2025 / Accepted: 8 May 2025

Abstract

Objective A cochlear implant is the most successful neuroprosthesis in healthcare, and its success is due to firstly the tonotopical orientation of the auditory pathways and of course the brain plasticity. In most etiologies causing sensorineural hearing loss, damage to the inner ear (hair) cells leaves the tonotopical architecture intact. Cochlear variations are key to the performance of cochlear implants surgically placed into the scala tympani. Exact placement of all electrodes, correct lengths of the electrodes with full cochlear coverage, and accurate signal processing strategies will allow sound perceptions closer to natural hearing and minimize frequency shifts. Therefore, knowing the cochlea's dimensions is considered significant, especially in children with congenital hearing loss. Not only in smaller children but also in normally developed adult cochlea there are natural variations in dimensions of the cochlear duct length, the cochlea height, and the cochlea width. Here, we examine the dimensions of the cochlea in children aged 0–18 years in this study and account for their hearing status in our analyses.
Methods Computed tomography (CT) images of patients aged 0–18, who had been consulting our department for various reasons consecutively between 2021 and 2022, were included. Children with a history of previous ear surgery and adults (> 18 years) were excluded from the study. CT images in DICOM format were transferred to a commercially available dedicated image processing software. Anatomical landmarks were determined and studied on CT sections for the 3D reconstruction by experienced anatomists.
Results A total of 69 CT images of patients (9.59 ± 5.19, boy: 34, girl: 35), were analyzed. Thirty-five of the children had bilateral hearing loss, and 15 had unilateral hearing loss. The other 19 patients have normal hearing. All parameters except cochlear height were statistically greater in boys than girls. The cochlear height was found to be significantly lower in patients with sensorineural hearing loss than in the normal hearing control group ($p = 0.021$).
Conclusion This study provides reference values for mean cochlear dimensions in children aged 0–18 years. These values may be helpful for designing appropriately sized electrodes for children with hearing loss who have normal cochlear anatomy. Considering the regression equations presented may help surgeons in estimating cochlear dimensions according to age and selecting appropriate electrodes before the surgery.

Keywords Cochlea anatomy · Cochlear variations · Computed tomography · Cochlear implant · Hearing loss

Introduction

Hearing loss is of two types: sensorineural hearing loss (SNHL), which occurs as a result of damage to the cochlea and cochlear nerve, and conductive hearing loss (HL), which occurs as a result of damage to the structures that transmit sound to the cochlea. Among the congenital anomalies, SNHL is a condition that occurs in 1–2 infants per 1000 births [1–3]. Congenital sensorineural hearing loss is usually bilateral, and most cases have severe to profound hearing loss [4]. Compared to children with normal hearing, children with hearing loss have more difficulty developing verbal skills, language, learning, and speech [2]. Therefore, early treatment of hearing loss is very essential.

The inner ear originates embryologically from the ectoderm. Its development begins around the 22nd day of embryonic life. The otic pit occurs when the otic placode rapidly invaginates into the surface ectoderm. The edges of the otic pit

✉ Saliha Seda Adanır
seda.adnr93@gmail.com

1 Department of Anatomy, Faculty of Medicine, Gaziantep University, Gaziantep, Türkiye

2 Department of Otorhinolaryngology Head and Neck Surgery, University Hospital UZ, Vrije Universiteit Brussel, Brussels, Belgium

3 Brussels Health Center, Vrije Universiteit Brussel, Brussels, Belgium

Published online: 02 June 2025

come together to form the otic vesicle. The cochlea develops from the ventral saccular part of the otic vesicle. The spiral organ is formed by the differentiation of epithelial cells in the wall of the cochlear duct. Thus, the human cochlea reaches its adult size and shape by 20–22 weeks of the fetal period [5–7].

It is reported that the anatomy of the cochlea can vary significantly between individuals. Importance variability, particularly in cochlear duct length, has been demonstrated in past studies using modern imaging techniques [8–10]. It is known that cochlear diameter, cochlear height, and cochlear width, as well as variability in cochlear duct length, vary significantly between individuals [11–14]. All of these anatomical variations play a significant role in the cochlear implantation surgery in terms of designing and selecting the appropriate implant for the patient and to minimize intracochlear damage during the surgery [7, 12, 15]. Cochlear implants (CI) are considered to be one of the most successful neural prostheses in otology that restore hearing in people with hearing loss [16]. It has been stated that cochlear diameter and width have a significant correlation with the electrode insertion angle. [17]. Also, surgeons should pay attention to cochlear duct length for maximum cochlear coverage by electrode arrays. So, trauma to electrode insertion and preservation of residual hearing are closely related to cochlear dimensions [17, 18].

There have been publications reporting better auditory performance when implant arrays are correctly and to the highest accuracy well placed [17, 19–21]. With advances in surgical techniques, infants younger than 12 months can be treated with CI [22]. Early hearing rehabilitation through CI has been reported to facilitate developmental outcomes consistent with their normal hearing peers [23]. Hay-McCutcheon et al. [24] reported that a pediatric patient treated with a cochlear implant showed statistical and practical improvement in receptive language development with each subsequent year.

Although the anatomy and variations of the cochlea have been examined by various methods in the previous studies [7, 11, 14, 25–28], to our current knowledge, there is no study examining the variation of cochlea sizes and variations from newborn to 18 years of age. Therefore, knowing the cochlea's dimensions is considered significant, especially in childhood hearing loss. It aimed to examine the dimensions of the cochlea in children aged 0–18 years with hearing loss in this study.

Methods

Study design

For the retrospective study, approval was obtained from the ethics committee of UZ Brussel with the number 1432021000377 dated 17 February 2021.

Study population

Computed tomography (CT) images of patients aged 1–18 years who applied to the University Hospital UZ Brussel Department of Otorhinolaryngology Head and Neck Surgery between 2021 and 2022 for any reason were included in the study. The patient images with abnormal findings in the radiology report were excluded from the study. In addition, images with low quality that would prevent anatomical landmarks from being visible were excluded from the study.

3D reconstruction of the cochlea

CT images in DICOM format were transferred to OTOPLAN (CASCINATION AG, Bern, Switzerland). Anatomical landmarks were determined on CT sections for the 3D reconstruction of cochlea.

- *Anatomical landmarks for cochlear length (CL):* Distance between the center of the round window and the furthest point on the opposite wall of the cochlea on coronal view (Fig. 1).

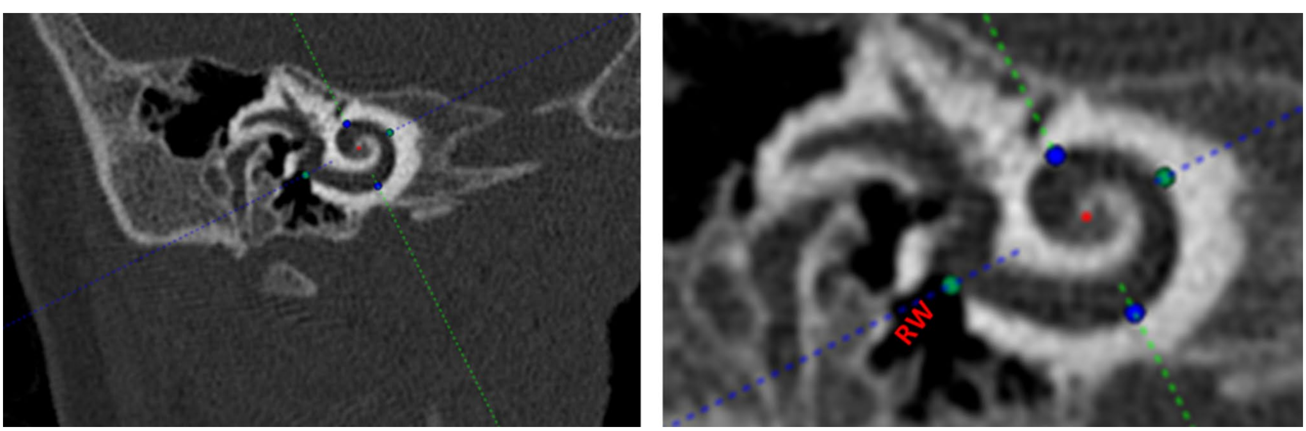

Fig. 1 Measurement of the cochlear length and cochlear width on the coronal view of the cochlea. RW: round window. Green points are landmarks for measurements of cochlear length and blue points are landmarks for measurements of cochlear width

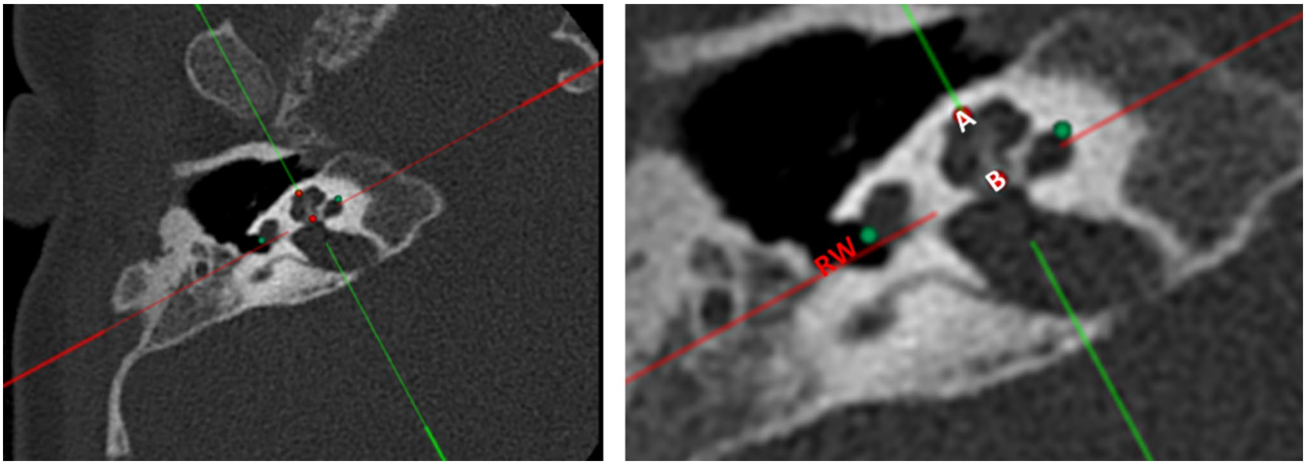

Fig. 2 Measurement of the cochlear height on the axial view of the cochlea. RW: round window. A: apex of the cochlea and B: center of the base of the cochlea

- *Anatomical landmarks for cochlear width (CW):* Distance between inferior and superior point of the lateral wall on coronal view (Fig. 1).
- *Anatomical landmarks for cochlear height (CH):* Distance between the center of the cochlear base and apex of the cochlea on the axial view (Fig. 2).

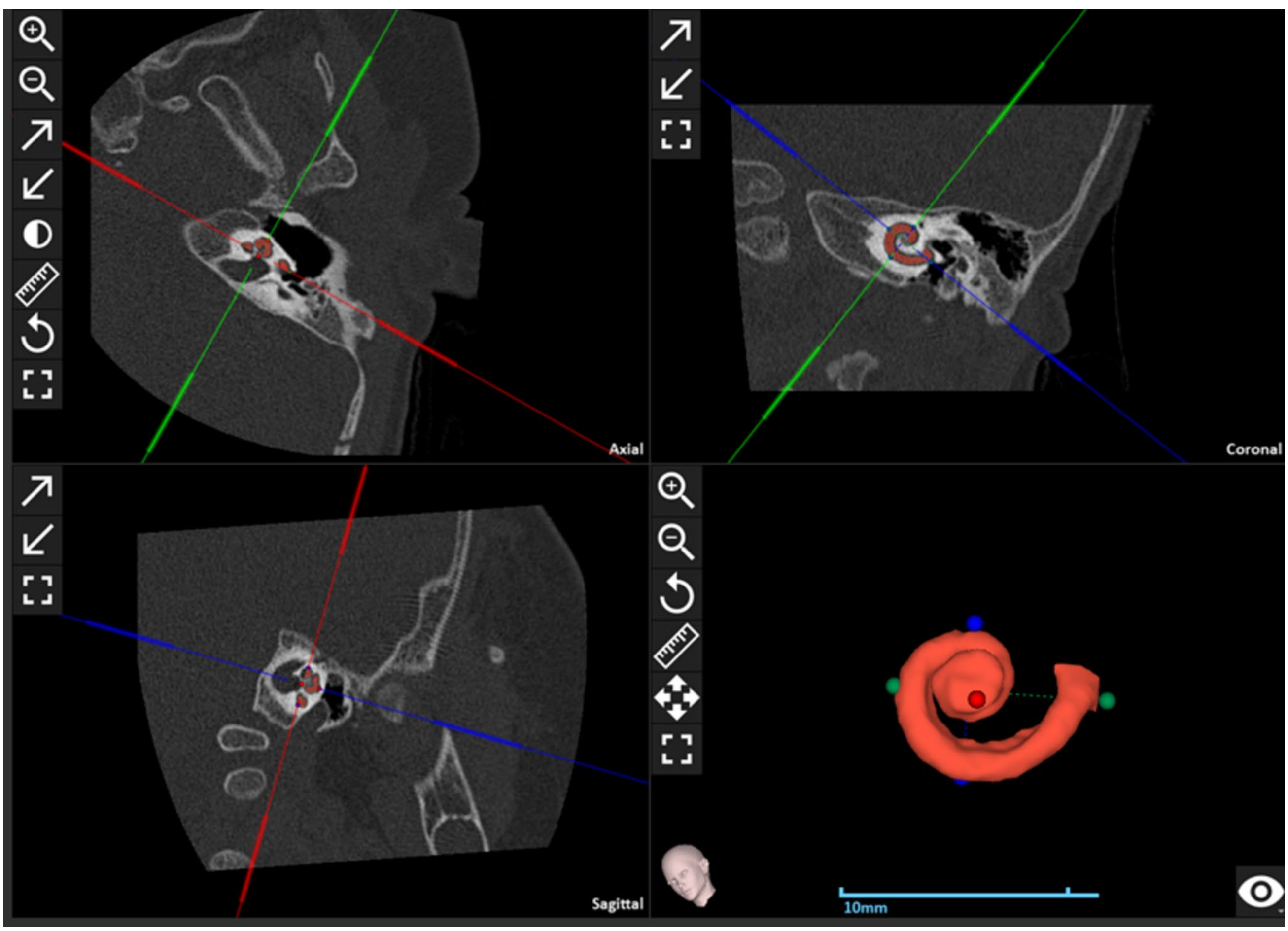

Fig. 3 Measurement of the cochlear duct length and 3D reconstruction of the cochlea according to the cochlear length and cochlear width

Table 1 Etiological data of patients with hearing loss

Etiology	*N*	Boy	Girl	Mean age (years)
Genetic	8	2	6	4.63 ± 2.56
Otitis media	14	6	8	6 ± 4.78
Cholesteatoma	2	–	2	8.50 ± 0.70
Otosclerosis	4	3	1	9.75 ± 3.20
Tympanic membrane degeneration	3	3	–	9 ± 8.54
Trauma	2	1	1	16.50 ± 0.70
Unknown	16	8	8	10.81 ± 4.50
Mastoiditis	1	1	–	6
Total	50	24	26	8.32 ± 5.06

- *Cochlear duct length (CDL):* was measured with OTOPLAN according to CD and CW (Fig. 3).

Results

CT scans of two boys, aged 3 and 15, and a girl, aged 4, were excluded from the study due to poor image quality CT images of a total of 69 patients; 34 boys (9.53 ± 5.20) and 35 girls (9.66 ± 5.25), were analyzed by OTOPLAN. There was no statistically significant difference between the genders in terms of age ($p > 0.05$). Eleven of the patients were of Asian origin, and 58 were of European origin. Twenty-four patients had SNHL (bilateral), and 26 patients (11 bilateral, 15 unilateral) had HL. Etiological data of 50 patients with unilateral or bilateral hearing loss are given in Table 1. The other 19 patients had normal hearing, who presented with complaints such as adenoids, sinusitis, concha hypertrophy, tinnitus, and dizziness. Comparison of cochlear sizes between genders is given in Table 2. All parameters except cochlear height were statistically greater in boys than girls ($p = 0.001$).

The dimensions have been compared between the sides and there was no significant differences on the measurements (Table 3) ($p > 0.05$).

When the healthy ears of the patients with unilateral HL and both ears of the 19 patients without hearing loss were compared with the affected ears of the patients with unilateral HL and the patients with bilateral HL, the cochlear height was found to be significantly greater in the healthy sides ($p = 0.021$). In other measurements, no statistically significant difference was found between healthy and HL sides (Table 4).

Linear function was calculated as $y = -9.164 + 0.20 \times \text{ages}$ (p = 0.001) for CL in girls and $y = -9.314 + 0.013 \times \text{ages}$ ($p = 0.001$) for CL in boys; as $y = -6.510 + 0.12 \times \text{ages}$ ($p = 0.001$) for CW in girls and $y = -6.735 + 0.012 \times \text{ages}$ ($p = 0.001$) for CW in boys; as $y = 3.022 + 0.33 \times \text{ages}$ ($p < 0.001$) for CH in girls and as $y = 3.392 + 0.003 \times \text{ages}$ ($p < 0.001$) for CH in

Table 3 Comparison of cochlear sizes between the sides

Cochlear sizes	Right (*N*: 69)	Left (*N*: 69)	*p*
CL	9.04 ± 0.47	9.08 ± 0.41	0.396
CW	6.50 ± 0.43	6.50 ± 0.40	0.874
CH	3.36 ± 0.32	3.38 ± 0.31	0.561
CDL	34.56 ± 1.98	34.66 ± 1.81	0.591

CL cochlear length, *CW* cochlear width, *CH* cochlear height, *CDL* cochlear duct length, *N* number of sides

Table 4 Comparison of cochlear sizes between the healthy and affected sides

Cochlear sizes	Sides (*N/S*)	Mean ± SD	*p*
CL	SNHL (24/48)	9.08 ± 0.45	0.481
	HL (26/37)	8.99 ± 0.35	
	Normal hearing (19/53)§	9.25 ± 0.47	
CW	SNHL (24/48)	6.50 ± 0.40	0.128
	HL (26/37)	6.56 ± 0.52	
	Normal hearing (19/53)§	6.60 ± 0.49	
CH	SNHL (24/48)	3.29 ± 0.31	**0.021**
	HL (26/37)	3.47 ± 0.16	
	Normal hearing (19/53)§	3.45 ± 0.36	
CDL	SNHL (24/48)	34.65 ± 1.88	0.362
	HL (26/37)	34.71 ± 2.04	
	Normal hearing (19/53)§	35.34 ± 2.20	

CDL cochlear duct length, *CH* cochlear height, *CL* cochlear length, *CW* cochlear width, *HL* conductive hearing loss, *N* number of patients, *S* number of sides, *SD* standard deviation, *SNHL* sensorineural hearing loss.§The healthy sides of patients with unilateral conductive hearing loss (HL) were also included in the control group with normal hearing

Table 2 Comparison of cochlear sizes between the genders

Cochlear Sizes	Total (*N*: 69; 138 sides)	Girl (*N*: 34, 68 sides)	Boy (*N*: 35, 70 sides)	*p*
Cochlear length (CL)	9.08 ± 0.45	8.94 ± 0.37	9.53 ± 0.51	**0.001***
Cochlear width (CW)	6.50 ± 0.41	6.39 ± 0.42	6.61 ± 0.39	**0.001***
Cochlear height (CH)	3.36 ± 0.31	3.33 ± 0.33	3.41 ± 0.29	0.652
Cochlear duct length (CDL)	34.66 ± 1.89	34.05 ± 1.84	35.19 ± 1.78	**0.001***

N number of patients

boys; and as $y = -34.784 + 0.76 \times \text{ages}$ ($p = 0.001$) for CDL in girls and as $y = -35.836 + 0.68 \times \text{ages}$ ($p = 0.001$) for CDL in boys (Fig. 4).

Discussion

It is known that the anatomy of the cochlea varies from person to person [15]. In the present study, cochlear dimensions were examined in patients aged 0–18 years with and without hearing loss. Although it is known that the cochlea reaches its normal adult size during the fetal period, this study investigated whether the cochlear sizes were different in children with hearing loss compared to healthy subjects.

It is seen in the literature that cochlear dimensions have been examined by various methods (Table 5) [4, 11, 12, 17, 20, 25–27, 29–52]. OTOPLAN provides 3D reconstruction with tomography images of patients, allowing reliable evaluation of human cochlear anatomy [4]. It also provides significant support to the surgeon by helping to determine the safe trajectory for access to the cochlea prior to both conventional and robotic CI surgery. In addition, the determination of postoperative electrode placement angles can be easily evaluated via OTOPLAN.

The electrodes must offer a high level of flexibility and adaptability due to the highly individual anatomical characteristics of the cochlea. Reporting of significant differences in cochlear sizes among individuals has made the need to design personalized electrodes even more important. In addition, the variability of cochlear dimensions also affects the technique of approaching the cochlea [4]. All these factors are particularly related to the prevention of damage to the neural structures of the cochlea during

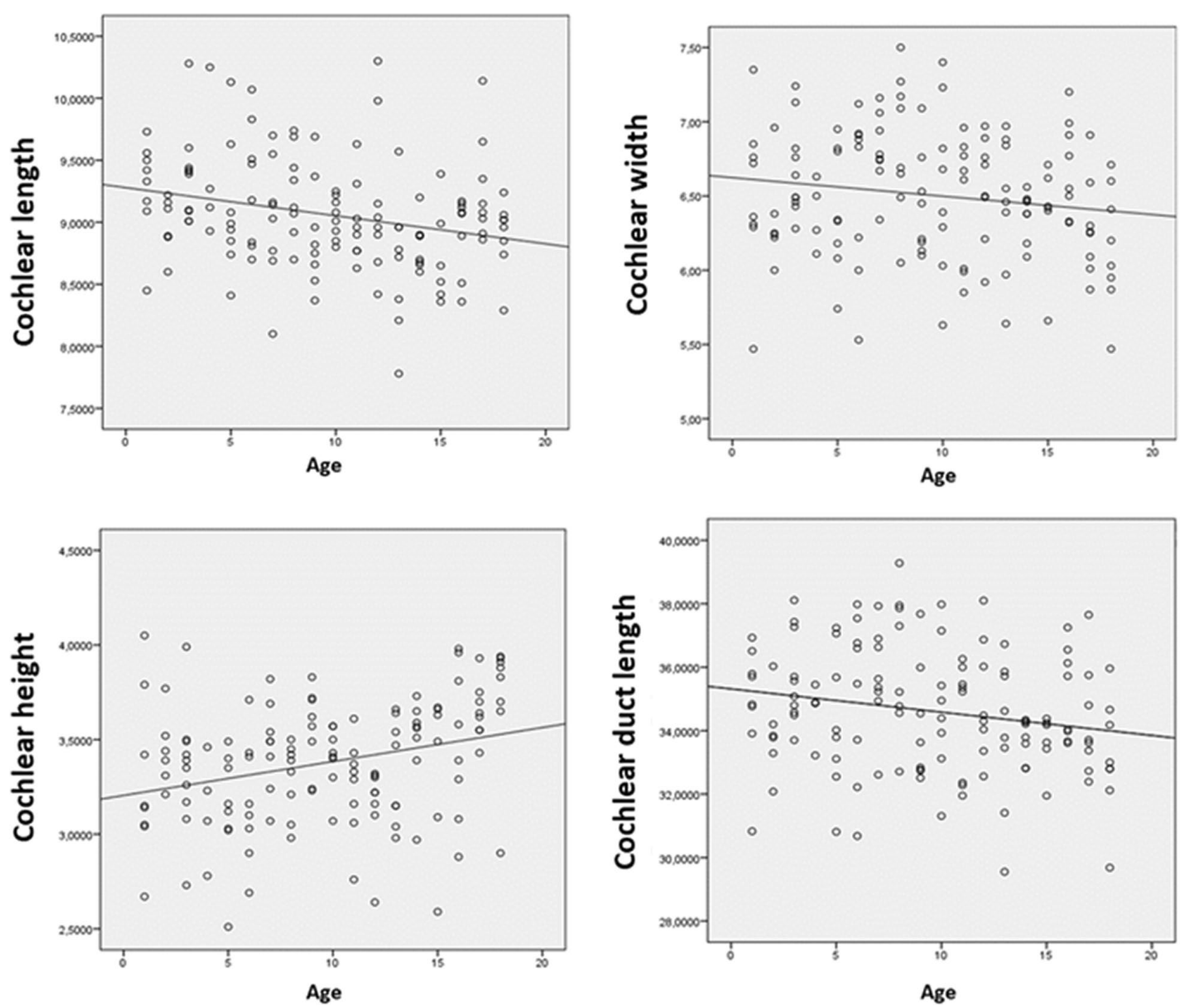

Fig. 4 Regression graphics of the cochlear sizes according to age

surgery, electrode trauma, preservation of residual hearing, and success of postoperative audiological outputs. Escude et al. [25] found in their HRCT study that the mean cochlear length was 9.23 mm and the cochlear width was 6.99 mm. In the current CT study, the mean cochlear length was 9.25 ±0.47 mm on the healthy side and 9.08 ±0.45 mm on the side with SNHL. In addition, no significant difference was found between the healthy and the SNHL side. Cochlear width was 6.60 ±0.49 mm on the healthy side and 6.50 ±0.40 mm on the SNHL side, and similarly, no significant difference was found between the healthy and HL sides. Shin et al. [46] examined the dimensions of the cochlea with 3D reconstruction and found a cochlear length of 9.7 ±0.3 mm, a cochlear width of 7 ± 0.3 mm and a cochlear height of 3.8 ±0.2 mm. In this study, the mean cochlear height was 3.45 ±0.36 mm on the healthy side and 3.29 ±0.31 mm on the hearing loss side. Moreover, it was significantly greater in the healthy side than the hearing loss side ($p = 0.021$). In contrast, Lan et al. [42] found greater cochlear height in children with sensorineural hearing loss than in healthy children. Chen et al. [53] reported that there was no significant difference in cochlear dimensions between children with and without hearing loss. It is seen that the average cochlear duct length reported in the literature is in the range of 29.80–42 mm [12, 26]. The mean cochlear length found in this study was 34.39 ±1.85

Table 5 Comparison of cochlear dimensions reported in the literature and present study

Study	Method	CL (mm)	CW (mm)	CH (mm)	CDL (mm)
Retzius (1884) [29]	Histologic				33.5±0.80
Hardy (1938) [30]	Histologic	10.83			31.52
Bredberg (1968) [31]	Histologic				34±1.30
Walby (1985) [32]	Histologic				32.60±2.10
Ulehlova et al. (1987) [34]	Histologic				34.20±2.90
Pollak et al. (1987) [33]	Histologic				28.40±3.40
Wright et al. (1987) [35]	Histologic				32.90±2.60
Takagi and Sando (1989) [36]	Histologic				36.40
Dimopoulos and Muren (1990) [11]	Plastic casts	8.58±0.45	6.77±0.35	3.93±0.40	
Sato et al. (1991) [37]	Histologic				34.73±2.90
Kawano et al. (1996) [38]	Histologic				35.58±1.40
Ketten et al. (1998) [27]	CT		7.91±0.53	1.43±0.26	33.01±2.31
Skinner et al. (2002) [39]	CT	8.01±0.30		1.56±0.22	34.62±1.20
Sridhar et al. (2006) [40]	Histologic				33.31±2.40
Escude et al. (2006) [25]	HRCT	9.23	6.99		
Stakhovskaya et al. (2007) [41]	Histologic				33.13±2.10
Erixon et al. (2009) [12]	Plastic casts		6.80±0.46	3.90±0.37	42±1.96
Lan et al. (2009) [42]	CT		8.71±0.29	4.79±0.45	
Lee et al. (2010) [43]	Histologic				30.80±0.60
Martinez-Monedero et al. (2011) [44]	CT	8.62±0.49	6.55±0.47		
Erixon and Rask-Anderson (2013) [45]	Plastic casts	9.30±0.40			41.20±1.90
Wimmer et al. (2013) [47]	μCT	9.35±0.32			
Shin et al. (2013) [46]	3D reconstruction	9.7±0.30	7±0.30	3.8±0.20	30±1.60
Wurfel et al. (2014) [50]	CBCT				37.90±2.00
van der Marel et al. (2014) [49]	CT	8.85±0.45	6.58±0.40		
Pelliccia et al. (2014) [48]	HRCT	9.12±0.68		6.81±0.50	
Meng et al. (2016) [51]	CT	9.04±0.31	6.33±0.28		35.80±2.00
Rivas et al. (2017) [52]	3D reconstruction	8.91 ± 0.49			32.71±1.80
Grover et al. (2018) [26]	HRCT	8.12			29.80
Ketterer et al. (2018) [20]	HRCT	9.95±0.59	6.54±0.48	3.85±0.34	
Zahara et al. (2019) [4]	HRCT	8.75±0.31	6.53±0.35	3.26±0.24	
Oh et al. (2021) [17]	CT	8.67±0.42	5.73±0.32		36.20±1.57
Present study	CT	9.08±0.45	6.50±0.41	3.36±0.31	34.66±1.89

CBCT cone beam computed tomography, *CDL* cochlear duct length, *CH* cochlear height, *CL* cochlear length, *CT* computed tomography, *CW* cochlear width, HRCT high-resolution computed tomography, *μCT* computed tomography mm on the healthy side and 34.39 ± 1.85 mm on the HL side. The comparison of the cochlear dimensions reported in the current study and the literature is given in Table 4 [4, 11, 12, 17, 20, 25–27, 29–52].

Although it is known that the cochlea reaches adult sizes during the fetal period, significant changes occur in both the skull base and temporal bone after birth. Therefore, age-related differences in the cochlea may occur [11, 27, 54]. Although there are many studies examining the cochlear dimensions, there is more need to investigate the postnatal development of the cochlea. Meng et al. [51] reported that cochlear dimensions did not differ between age groups. In this study, linear function for cochlear length, width, and cochlear duct length were calculated. These formulas may be used to estimate the cochlear size.

Limitations

There are some limitations in our study. Our population is relatively small, and there is a need to study larger populations, especially to examine age-related development.

Conclusion

This study provides reference values for mean cochlear dimensions in children aged 0–18 years. These values may be helpful for designing appropriately sized electrodes for children with normal cochlear anatomy. Considering the regression equations presented may help surgeons in estimating cochlear dimensions according to age and selecting appropriate electrodes before the surgery.

Author contributions SSA and VT: Project development and Manuscript writing. SSA and MA: Data collection. SSA and MA: morphometric measurement and data analysis, SSA, İB, PK, and VT: Manuscript writing and editing. All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

1. Fortnum H (2003) Epidemiology of permanent childhood hearing impairment: implications for neonatal hearing screening. Audiological Medicine 1:155–164
2. Salvago P, Martines E, Martines F (2013) Prevalence and risk factors for sensorineural hearing loss: Western Sicily overview. Eur Arch Otorhinolaryngol 270:3049–3056
3. Morton NE (1991) Genetic epidemiology of hearing impairment. Ann N Y Acad Sci 630:16–31
4. Zahara D, Dewi RD, Aboet A, Putranto FM, Lubis ND, Ashar T (2019) Variations in cochlear size of cochlear implant candidates. Int Arch Otorhinolaryngol 23:184–190
5. Standring S (2016) Gray's anatomy: the anatomical basis of clinical practice. Holland, Elsevier Limited
6. Moore KL, Persaud TVN, Torchia MG (2015) The developing human: clinically oriented embryology. Elsevier
7. Alexiades G, Dhanasingh A, Jolly C (2015) Method to estimate the complete and two-turn cochlear duct length. Otol Neurotol 36:904–907
8. Koch RW, Elfarnawany M, Zhu N, Ladak HM, Agrawal SK (2017) Evaluation of cochlear duct length computations using synchrotron radiation phase-contrast imaging. Otol Neurotol 38:e92–e99
9. Koch RW, Ladak HM, Elfarnawany M, Agrawal SK (2017) Measuring cochlear duct length–a historical analysis of methods and results. J Otolaryngol Head Neck Surg 46:1–11
10. Li H, Schart-Morén N, Rohani SA, Ladak HM, Rask-Andersen H, Agrawal S (2020) Synchrotron radiation-based reconstruction of the human spiral ganglion: implications for cochlear implantation. Ear Hear 41:173–181
11. Dimopoulos P, Muren C (1990) Anatomic variations of the cochlea and relations to other temporal bone structures. Acta Radiol 31:439–444
12. Erixon E, Högstorp H, Wadin K, Rask-Andersen H (2009) Variational anatomy of the human cochlea: implications for cochlear implantation. Otol Neurotol 30:14–22
13. Rask-Andersen H, Erixon E, Kinnefors A, Löwenheim H, Schrott-Fischer A, Liu W (2011) Anatomy of the human cochlea–implications for cochlear implantation. Cochlear Implants Int 12:S13–S18
14. Avci E, Nauwelaers T, Lenarz T, Hamacher V, Kral A (2014) Variations in microanatomy of the human cochlea. J Comp Neurol 522:3245–3261
15. Schurzig D, Timm ME, Majdani O, Lenarz T, Rau TS (2021) The use of clinically measurable cochlear parameters in cochlear implant surgery as indicators for size, shape, and orientation of the scala tympani. Ear Hear 42:1034–1041
16. Topsakal V, Heuninck E, Matulic M, Tekin AM, Mertens G, Van Rompaey V, Galeazzi P, Zoka-Assadi M, van de Heyning P (2022) First study in men evaluating a surgical robotic tool providing autonomous inner ear access for cochlear implantation. Front Neurol 13:804507
17. Oh J, Cheon JE, Park J, Choi YH, Cho YJ, Lee S, Oh SH, Shin SM, Park SW (2021) Cochlear duct length and cochlear distance on preoperative CT: imaging markers for estimating insertion depth angle of cochlear implant electrode. Eur Radiol 31:1260–1267
18. Jagt A, Kalkman RK, Briaire JJ, Verbist BM, Frijns JH (2017) Variations in cochlear duct shape revealed on clinical CT images with an automatic tracing method. Sci Rep 7:1–9
19. Büchner A, Illg A, Majdani O, Lenarz T (2017) Investigation of the effect of cochlear implant electrode length on speech comprehension in quiet and noise compared with the results with users of electro-acoustic-stimulation, a retrospective analysis. PLoS ONE 12:e0174900
20. Ketterer MC, Aschendorff A, Arndt S, Hassepass F, Wesarg T, Laszig R, Beck R (2018) The influence of cochlear morphology on the final electrode array position. Eur Arch Otorhinolaryngol 275:385–394
21. Morrel WG, Holder JT, Dawant BM, Noble JH, Labadie RF (2020) Effect of scala tympani height on insertion depth of

straight cochlear implant electrodes. Otolaryngol Head Neck Surg 162:718–724
22. DeSaSouza S (2022) Cochlear implants: new and future directions. Springer Nature Singapore
23. Svirsky MA, Teoh S-W, Neuburger H (2004) Development of language and speech perception in congenitally, profoundly deaf children as a function of age at cochlear implantation. Audiol Neurootol 9:224–233
24. Hay-McCutcheon MJ, Kirk KI, Henning SC, Gao S, Qi R (2008) Using early language outcomes to predict later language ability in children with cochlear implants. Audiol Neurootol 13:370–378
25. Escude B, James C, Deguine O, Cochard N, Eter E, Fraysse B (2006) The size of the cochlea and predictions of insertion depth angles for cochlear implant electrodes. Audiol Neurootol 11(Suppl 1):27–33
26. Grover M, Sharma S, Singh SN, Kataria T, Lakhawat RS, Sharma MP (2018) Measuring cochlear duct length in Asian population: worth giving a thought! Eur Arch Otorhinolaryngol 275:725–728
27. Ketten DR, Skinner MW, Wang G, Vannier MW, Gates GA, Gail Neely J (1998) In vivo measures of cochlear length and insertion depth of nucleus cochlear implant electrode arrays. Ann Otol Rhinol Laryngol Suppl 175:1–16
28. Verbist BM, Ferrarini L, Briaire JJ, Zarowski A, Admiraal-Behloul F, Olofsen H, Reiber JHC, Frijns JHM (2009) Anatomic considerations of cochlear morphology and its implications for insertion trauma in cochlear implant surgery. Otol Neurotol 30:471–477
29. Retzius G (1884) Das Gehörorgan der Wirbelthiere: morphologisch-histologische Studien. 2, Das Gehörorgan der Reptilien, der Vögel und der Säugethiere. Stockholm: Samson & Wallin
30. Hardy M (1938) The length of the organ of Corti in man. Am J Anat 62:291–311
31. Bredberg G (1968) Cellular pattern and nerve supply of the human organ of Corti. Acta Otolaryngol Suppl 236:1
32. Walby A (1985) Scala tympani measurement. Ann Otol Rhinol Laryngol 94:393–397
33. Pollak A, Felix H, Schrott A (1987) Methodological aspects of quantitative study of spiral ganglion cells. Acta Otolaryngol Suppl 436:37–42
34. Ulehlová L, Voldrich L, Janisch R (1987) Correlative study of sensory cell density and cochlear length in humans. Hear Res 28:149–151
35. Wright A, Davis A, Bredberg G, Ulehlova L, Spencer H (1987) Hair cell distributions in the normal human cochlea. Acta Otolaryngol Suppl 444:1–48
36. Takagi A, Sando I (1989) Computer-aided three-dimensional reconstruction: a method of measuring temporal bone structures including the length of the cochlea. Ann Otol Rhinol Laryngol 98:515–522
37. Sato H, Sando I, Takahashi H (1991) Sexual dimorphism and development of the human cochlea. Computer 3-D measurement. Acta Otolaryngol 111:1037–1040
38. Kawano A, Seldon HL, Clark GM (1996) 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. Ann Otol Rhinol Laryngol 105:701–709
39. Skinner MW, Ketten DR, Holden LK, Harding GW, Smith PG, Gates GA, Neely JG, Kletzker GR, Brunsden B, Blocker B (2002) 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 3:332–350
40. Sridhar D, Stakhovskaya O, Leake PA (2006) A frequency-position function for the human cochlear spiral ganglion. Audiol Neurootol 11(Suppl 1):16–20
41. Stakhovskaya O, Sridhar D, Bonham BH, Leake PA (2007) Frequency map for the human cochlear spiral ganglion: implications for cochlear implants. Journal of the Association for Research in Otolaryngology : JARO 8:220–233
42. Lan MY, Shiao JY, Ho CY, Hung HC (2009) Measurements of normal inner ear on computed tomography in children with congenital sensorineural hearing loss. Eur Arch Otorhinolaryngol 266:1361–1364
43. Lee J, Nadol JB Jr, Eddington DK (2010) Depth of electrode insertion and postoperative performance in humans with cochlear implants: a histopathologic study. Audiol Neurootol 15:323–331
44. Martinez-Monedero R, Niparko JK, Aygun N (2011) Cochlear coiling pattern and orientation differences in cochlear implant candidates. Otol Neurotol 32:1086–1093
45. Erixon E, Rask-Andersen H (2013) How to predict cochlear length before cochlear implantation surgery. Acta Otolaryngol 133:1258–1265
46. Shin KJ, Lee JY, Kim JN, Yoo JY, Shin C, Song WC, Koh KS (2013) Quantitative analysis of the cochlea using three-dimensional reconstruction based on microcomputed tomographic images. Anatomical Record (Hoboken, NJ : 2007) 296:1083–1088
47. Wimmer W, Gerber N, Dhanasingh A, Mistrik P, Jolly C, Bell B, Weber S, Kompis M, Caversaccio M (2013) In-vitro micro CT validation of preoperative cochlear duct length estimation. CEUR Workshop Proc 1477:143–146
48. Pelliccia P, Venail F, Bonafé A, Makeieff M, Iannetti G, Bartolomeo M, Mondain M (2014) Cochlea size variability and implications in clinical practice. Acta otorhinolaryngologica Italica : organo ufficiale della Societa italiana di otorinolaringologia e chirurgia cervico-facciale 34:42–49
49. van der Marel KS, Briaire JJ, Wolterbeek R, Snel-Bongers J, Verbist BM, Frijns JH (2014) Diversity in cochlear morphology and its influence on cochlear implant electrode position. Ear Hear 35:e9-20
50. Würfel W, Lanfermann H, Lenarz T, Majdani O (2014) Cochlear length determination using Cone Beam Computed Tomography in a clinical setting. Hear Res 316:65–72
51. Meng J, Li S, Zhang F, Li Q, Qin Z (2016) Cochlear Size and Shape Variability and Implications in Cochlear Implantation Surgery. Otol Neurotol 37:1307–1313
52. Rivas A, Cakir A, Hunter JB, Labadie RF, Zuniga MG, Wanna GB, Dawant BM, Noble JH (2017) Automatic cochlear duct length estimation for selection of cochlear implant electrode arrays. Otol Neurotol 38:339–346
53. Chen JL, Gittleman A, Barnes PD, Chang KW (2008) Utility of temporal bone computed tomographic measurements in the evaluation of inner ear malformations. Archives of otolaryngology–head and neck surgery 134:50–56
54. Jeffery N, Spoor F (2004) Prenatal growth and development of the modern human labyrinth. J Anat 204:71–92