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Original Article

The Relationship Between the Third Window Abnormalities and Inner Ear Malformations in Children with Hearing Loss

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OBJECTIVE: To evaluate the relationship between the third window abnormalities and congenital inner ear malformations in pediatric patients with different types of hearing loss. If such a relationship should exist, it would be important to take it into account, in order to diagnose and treat pediatric hearing loss cases more accurately.

METHODS: Two hundred twenty-one children with hearing loss who had temporal bone computed tomography (CT) examination and were identified from 2013 to 2018 were retrospectively evaluated. The types of hearing loss were grouped as sensorineural hearing loss (SNHL), conductive hearing loss (CHL), and mixed hearing loss (MHL). Third window abnormalities included superior semicircular canal (SC) dehiscence, posterior SC dehiscence, enlarged vestibular aqueduct (EVA), X-linked stapes gusher, perilymph fistula, and bone dyscrasias. Congenital inner ear malformations included cochleovestibular, SC, and internal acoustic canal malformations. The relationships were analyzed with chi-square and Fisher's exact tests.

RESULTS: In the study, 40 patients had unilateral hearing loss and 181 had bilateral hearing loss. In 402 ears, the rates of SNHL, CHL, and MHL were 88.5%, 6.9%, and 4.4%, respectively. EVA was the most common third window abnormality (41/402; 9.7%), and SC malformations were the most common inner ear malformations (53/402; 13.2%). In the SNHL group, superior and posterior SC dehiscence were associated with cochleovestibular malformations ($P = .035$ and.020, respectively). In the CHL group, there was a relationship between EVA and SC malformations ($P = .041$). No relationships were found in the MHL group.

CONCLUSION: Third window abnormalities and congenital inner ear malformations may be encountered simultaneously in children with SNHL and CHL.

KEYWORDS: Computed tomography, hearing loss, inner ear, malformation, temporal bone, third window

INTRODUCTION

Third window abnormalities are a group of disorders which result in abnormal communications between the inner and the middle ear, as well as cerebrospinal fluid and vascular structures.[1] They cause a reduction in bone conduction hearing thresholds and an elevation in air conduction thresholds, resulting in a conductive hearing loss (CHL), characterized by abnormally low bone conduction thresholds with an air-bone gap in the audiogram.[1]

Superior semicircular canal (SC) dehiscence (SSCD), posterior SC canal dehiscence (PSCD), enlarged vestibular aqueduct (EVA), X-linked stapes gusher, perilymph fistula (PLF), and bone dyscrasias of the temporal bone comprise the third window abnormalities.[2] The etiology of third window abnormalities is often unknown, even though some of these anomalies, such as PLF, may be secondary to infectious, iatrogenic, or traumatic causes.[2] Clinically, auditory and vestibular symptoms may be present alone or in

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combination. CHL and mixed hearing loss (MHL) are well-described findings which are associated with third window abnormalities. Sensorineural hearing loss (SNHL) may also be present, especially in cases with EVA.[1,3] Although the mechanisms of CHL and MHL can be explained with the air-bone gap, the cause of SNHL in third window abnormalities has not been clarified yet.

Inner ear structures are developed from the otic vesicles. The saccule and the cochlear duct are derived from the ventral or saccular component of the otic vesicle, whereas the dorsal or utricular component is the origin of the utricle, SCs, and the vestibular aqueduct.[4] Sennaroglu et al.[5] have classified inner ear malformations based on this embryological development.

Although there were several previous studies on inner ear malformations and third window abnormalities in pediatric patients,[6-8] to the best of our knowledge, the relationships between them have not been reported before. The main purpose of this study is to reveal any association between the third window abnormalities and inner ear malformations in pediatric patients. The secondary goal is to determine the incidence of these findings in different types of pediatric hearing loss.

MATERIALS AND METHODS

Study Population

The retrospective study was approved by our institutional review board. The parents of the children provided informed consent for imaging. We retrospectively identified all pediatric patients (age 0-18 years) admitted to the otorhinolaryngology department for hearing loss, who had a temporal bone computed tomography (CT) evaluation between November 2013 and November 2018. The inclusion criteria were children between 0 and 18 years old with hearing loss. The exclusion criteria were as follows: children with a tumor that infiltrated the inner ear, traumatic PLF, images with severe motion artifacts, and slice thickness greater than 0.67 mm. Subjects who had a syndrome which was related to hearing loss, prenatal causes, or postnatal causes such as otomastoiditis, were not excluded, because identifying the exact cause of the hearing loss was not our main purpose. Additionally, patients with congenital external and middle ear anomalies were not excluded by reason of the different embryological origin of the external and middle ear from the inner ear. In total, 221 children with hearing loss (40 unilateral, 181 bilateral hearing loss) fulfilled the inclusion and exclusion criteria. After determining the study subjects, ears without hearing impairment were also excluded based on their results of a complete audiological assessment battery, including the results of pure-tone audiometry, auditory brainstem response, 226 Hz tympanometry, and distortion product otoacoustic emissions. All patients' audiometric data were analyzed by evaluating each ear separately, and the types of hearing loss were categorized as SNHL, CHL, and MHL.[9] Finally, 402 ears with hearing loss (in 221 patients) were enrolled in the study. The flow chart of the study participants is given in Figure 1.

CT Acquisition

Temporal bone CT exams were performed on a multidetector CT scanner (Brilliance 64 Philips; Philips Medical Systems©, Eindhoven, The Netherlands). Patients were examined with a temporal bone protocol with slices obtained from the arcuate eminence to the mastoid tip. CT images were acquired with the following parameters: routine slice thickness, 0.67 mm; slice interval, 0.33; pitch, 0.348; rotation time, 0.75 seconds; matrix, 768 × 768; field of view, 14 × 14 cm; collimator, 20 × 0.625; 120 kV; 150 mA; and bone algorithm reconstruction. The axial source images and multiplanar reformations including coronal, axial, sagittal, Stenvers's and Poschl's views were used for the evaluations. The Stenvers's view (oblique coronal reconstruction parallel to the petrous bone) and the Poschl's view (oblique coronal reconstruction perpendicular to the petrous bone) were reformatted from the axial source data on a separate postprocessing workstation (Sectra Myrian, Expert 2.0/0502) to assess the SCs.

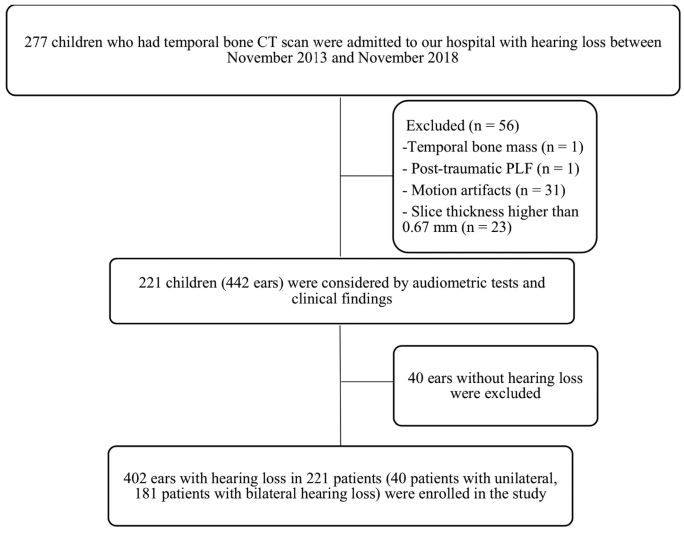

Figure 1. Flow chart of the study group. CT, computed tomography.

Image Interpretation

All the images were reviewed together in consensus by 2 pediatric radiologists, who had 7 and 25 years of radiology experience. All images were reviewed to determine the presence of third window abnormalities (SSCD, PSCD, EVA, X-linked stapes gusher, PLF, bone dyscrasia) and/or inner ear malformations according to the literature.[1,2,5,10-13] The diagnostic criteria to determine the third window abnormalities and inner ear malformations are shown in Table 1.

Although EVA was reported as an inner ear malformation according to Sennaroglu's classification,[5] we considered EVA as a third window abnormality, as mentioned in many articles in the literature.[1,2,14]

Statistical Analysis

Statistical analyses were made using IBM SPSS ver. 22.0 (IBM Corp., Armonk, NY, USA). Categorical variables were summarized with frequency counts and percentages, and the continuous features were summarized with means and standard deviations. The most frequent abnormal findings were taken into account while evaluating the relationships of the third window abnormalities with inner ear malformations. Chi-square and Fisher's exact tests were used in each type of hearing loss. A *P* value less than .05 was considered as statistically significant.

RESULTS

A total of 221 patients (mean age: 63.59 ± 50.88 months, age range: 3 months-16 years, 109 boys and 112 girls) were enrolled in the study. A total of 40 patients had unilateral, and 181 patients had bilateral hearing loss. Totally, 402 ears (362 ears of 181 patients with bilateral

Table 1. Diagnostic Criteria for Third Window Abnormalities and Inner Ear Malformations

Third Window Abnormalities	Inner Ear Malformations
1. SC dehiscence; focal loss of the bony wall of the SCs.[1] 2. EVA; transverse dimension of the vestibular aqueduct ≥1 mm at the midpoint or ≥2 mm at the operculum).[10] 3. X-linked stapes gusher; the absence of the bone plate that separates the basal turn of the cochlea and the internal auditory canal.[11] 4. PLF; an abnormal connection between the middle ear, and SCs, vestibule and/or scala vestibuli of the cochlea.[2] 5. Bone dyscrasia; the changes in the density of the bony labyrinth.	1. The cochleovestibular malformations; described according to Sennaroglu classification.[5] 2. The SC malformations; agenesis or dysplasia of a SC. SC dysplasia was defined when the diameter of the lateral side of a SC bone island was less than 3 mm.[12] or the irregular wall of the SCs had a cystic or non-cystic appearance. 3. The IAC malformation; stenosis (<2 mm) of the IAC.[13]

EVA, enlarged vestibular aqueduct; IAC, internal acoustic canal; PLF, perilymph fistula; SC, semicircular canal.

hearing loss and 40 ears of 40 patients with unilateral hearing loss) with different types of hearing loss were considered for third window abnormalities and inner ear malformations.

The rates of hearing loss types in all ears were as follows: 356 of 402 (88.5%) were SNHL, 28 (6.9%) were CHL, and 18 (4.4%) were MHL. Children with specific clinical conditions were as follows: CHARGE syndrome (n=3), achondroplasia (n=1), external auditory canal atresia (n=1), isolated congenital ossicular anomaly (n=1), oval window atresia (n=1), and otomastoiditis confirmed clinically (n=4).

The distribution of the inner ear malformations is given in Figure 2.

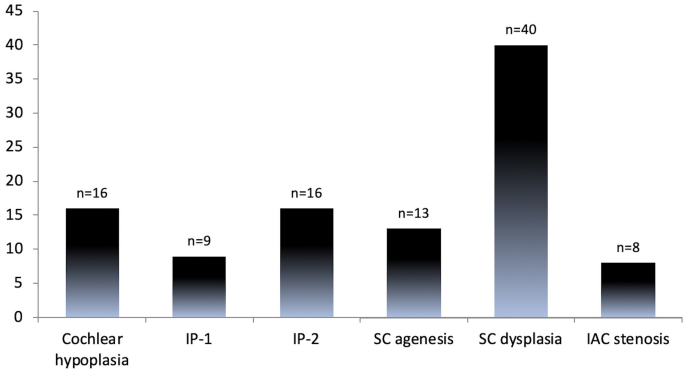

Figure 2. The distribution of inner ear malformations in patients with hearing loss. SC, semicircular canal; IAC, internal acoustic canal, IP-1; incomplete partition type 1; IP-2, incomplete partition type 2.

EVA was the most common third window abnormality (41/402; 9.7%), followed by SSCD (17/402; 4.2%), PSCD (17/402; 4.2%), X-linked stapes gusher (2/402; 0.5%), and PLF (2/402; 0.5%). There were no patients with temporal bone dyscrasias. SC malformations were the most common inner ear malformation (53/402; 13.2%), followed by cochleovestibular malformations (41/402; 10.2%), and IAC malformation (8/402; 1.9%) in all ears.

Third Window Abnormalities and Inner Ear Malformations in SNHL

Among 221 patients, 193 (87.3%) (mean age: 59.22 ± 51.2 months, age range: 3-192 months, 93 boys and 100 girls) had SNHL. The number of ears with SNHL was 356 (326 ears with SNHL in 163 patients who had bilateral findings and 30 patients with unilateral findings). The rates of third window abnormalities and inner ear malformations in SNHL ears are given in Table 2. The most common third window abnormality was EVA in the SNHL group (8.7%). SSCD and PSCD followed EVA with percentages of 3.9% and 3.4%, respectively. SC malformations were found as the most common inner ear malformation (10.4%). Totally 9 of the 37 SC malformations were SC agenesis, and 3 patients with bilateral SC agenesis. Cochleovestibular malformations were also common in this group (9.6%). Cochleovestibular malformations included cochlear hypoplasia (n=13), incomplete partition type 1 (IP-1) (n=7), and incomplete partition type 2 (IP-2) (n=14) in the CHL group.

In the SNHL group, when considering the relationship between the third window abnormalities and inner ear malformations, both SSCD and PSCD had significant relationships with cochleovestibular

Table 2. The Frequencies of Third Window Abnormalities and Inner Ear Malformations According to Each Type of Hearing Loss

	SNHL, n (%)	CHL, n (%)	MHL, n (%)
Third window abnormality, n (%)			
SSCD (17/402; 4.2%)	14/356 (3.9)	2/28 (7.1)	1/18 (5.6)
PSCD (17/402; 4.2%)	12/356 (3.4)	4/28 (14.2)	1/18 (5.6)
EVA (41/402; 10.1%)	31/356 (8.7)	5/28 (17.8)	5/18 (27.7)
X-linked stapes gusher (2/402; 0.4%)	0	1/28 (3.5)	1/18 (5.5)
Perilabyrinthine fistula (2/402; 0.4%)	1/356 (0.2)	0	0
Bone dyscrasia (0/402; 0%)	0	0	0
Inner ear malformation			
Cochleovestibular malformations (41/402; 10.1%)	34/356 (9.6)	3/28 (10.7)	4/18 (22.2)
SC malformations (53/402; 13.1%)	37/356 (10.4)	10/28 (35.7)	6/18 (33.3)
IAC malformation (8/402; 1.9%)	7/356 (2)	0	1/18 (5.5)

CHL, conductive hearing loss; EVA, enlarged vestibular aqueduct; IAC, internal acoustic canal; MHL, mixed hearing loss; PSCD, posterior semicircular canal dehiscence; SC, semicircular canal; SNHL, sensorineural hearing loss; SSCD, superior semicircular canal dehiscence.

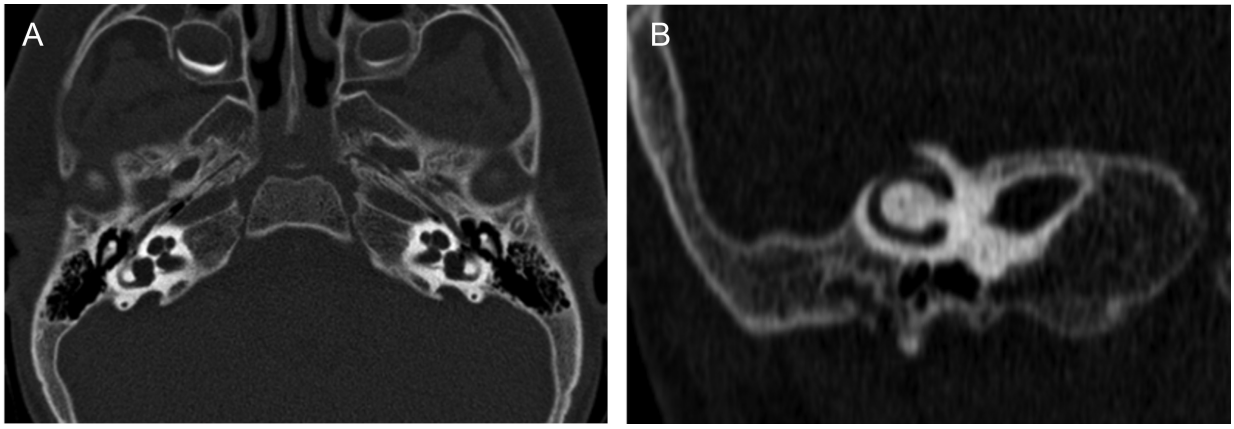

Figure 3. A 7-year-old boy with SNHL. Axial (a) and reformatted (b) images showed IP-2 malformation and PSCD in the right temporal bone. SNHL, sensorineural hearing loss; IP-2, incomplete partition type 2; PSCD, posterior semicircular canal dehiscence.

malformations ($P = .035$ and $P = .020$, respectively) (Figure 3). There was no association between EVA and inner ear malformations. Table 3 presents the relationships between the third window abnormalities and inner ear malformations according to each type of hearing loss.

Third Window Abnormalities and Inner Ear Malformations in CHL

A total of 20 (9%) patients (mean age: 94.6 ± 35.67 months, age range: 47-168 months, 12 boys and 8 girls) had CHL. The number of ears with CHL was 28 (16 ears with CHL in 8 patients who had bilateral findings and 12 patients with unilateral findings). The rates of third window abnormalities and inner ear malformations in patients with CHL are given in Table 2. EVA (17.8%) was the most common third window abnormality, and SC malformations (35.7%) were the most common inner ear malformations in the CHL group, similarly to the SNHL group. PSCD was the second most frequent finding in the CHL group (14.2%).

When considering the relationship between third window abnormalities and inner ear malformations in the CHL group, there was a significant relationship between EVA and SC malformations ($P = .041$) (Figure 4). No additional relationships were found in the other third window abnormalities and inner ear malformations in the CHL group. The cochleovestibular malformations included cochlear hypoplasia (n = 2) and IP-2 (n = 1) in the CHL group.

Table 3. The Relationships Between the Third Window Abnormalities and Inner Ear Malformations

	SNHL	CHL	MHL
The Findings	*P**	*P**	*P**
SSCD and cochleovestibular malformations	**.035**		
SSCD and SC malformations	1		
SSCD and IAC malformations	.896		
PSCD and cochleovestibular malformations	**.020**	.382	
PSCD and SC malformations	.360	.116	
PSCD and IAC malformation	1	N/A	
EVA and cochleovestibular malformations	.689	.459	1
EVA and SC malformations	.547	**.041**	.268
EVA and IAC malformation	1	N/A	1

*Chi-square test and Fisher's exact tests were used to determine the relationship of between the findings.
CHL, conductive hearing loss; EVA, enlarged vestibular aqueduct; IAC: internal acoustic canal; MHL, mixed hearing loss; N/A, not applicable; PSCD, posterior semicircular canal dehiscence; SC, semicircular canal; SNHL, sensorineural hearing loss; SSCD, superior semicircular canal dehiscence.
Bold values indicate statistically significant.

Third Window Abnormalities and Inner Ear Malformations in MHL

Totally 12 (5%) patients (mean age: 93.42 ± 43.46 months, age range: 36-180 months, 5 boys and 7 girls) had MHL. The number of ears with MHL was 18 (12 ears with MHL in 6 patients who had bilateral

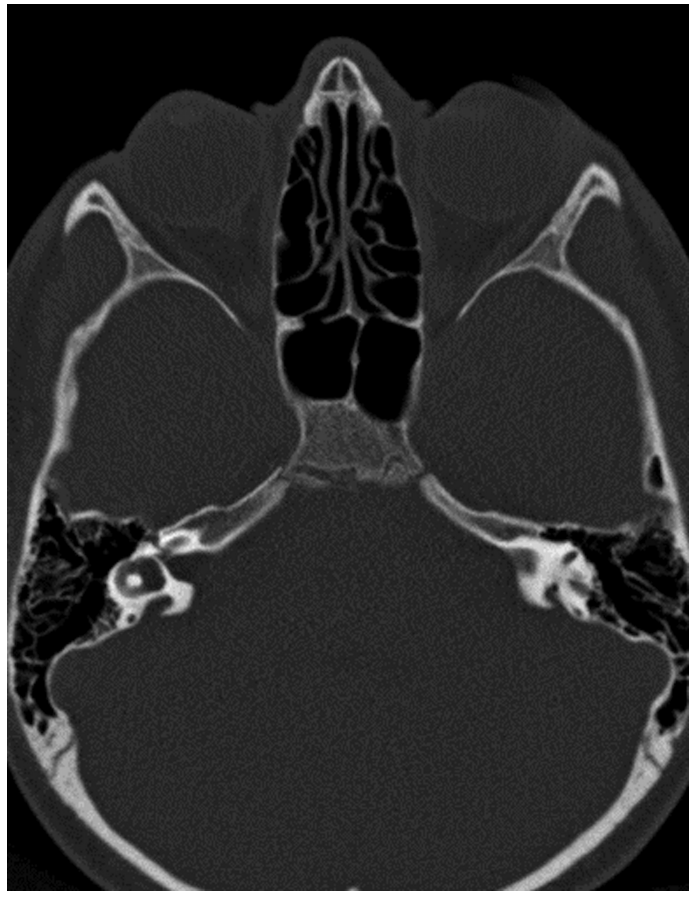

Figure 4. A 7-year-old boy with CHL. EVA and Lateral SC Dysplasia seen together in the right temporal bone. CHL, conductive hearing loss; EVA, enlarged vestibular aqueduct; SC, semicircular canal.

findings and 6 patients with unilateral findings). Table 2 summarizes the frequencies of the third window abnormalities and inner ear malformations in patients with MHL.

In 18 (4.4%) of 402 ears with MHL, EVA (27.7%) and SC malformations (33.3%) were more frequent than the other malformations, similar to other types of hearing loss. There were no relationships between the third window abnormalities and inner ear malformations in this group. Cochlear hypoplasia (n = 1), IP-1 (n = 2), and IP-2 (n = 1) were detected as the cochleovestibular malformations; 1 patient had bilateral SC agenesis, and the rest were SC dysplasia.

DISCUSSION

In our study, we investigated whether there is a relationship between the third window abnormalities and inner ear malformations in different types of hearing loss. In addition, finding out the incidences of each anomaly in a relatively large population was our secondary purpose. We showed that the third window abnormalities and congenital inner ear malformations may accompany each other in children with SNHL and CHL. We demonstrated that both SSCD and PSCD were related to cochleovestibular malformations in the SNHL group. In addition, there was a relationship between the EVA and SC malformations in the CHL group. In all 3 types of hearing loss, EVA was found as the most common third window abnormality, and SC malformations were the most common inner ear malformations. The awareness of these relationships is important, and may contribute to the clinical practice by evaluating them more carefully and specifically in children with hearing loss.

The relationship between SC dehiscence and inner ear malformations was investigated previously.[15,16] Sugihara et al.[15] and Saxby et al.[16] did not observe any relationship between SSCD and inner ear malformations. In contrast to these studies, Wang et al.[17] published a case report that noted bilateral SSCD associated with inner ear anomalies. According to our results, SSCD and PSCD had relationships with the cochleovestibular malformations in the SNHL group ($P = .035$ and $P = .020$, respectively). We speculated that the dehiscence of the SCs may cause an interruption in the development of the cochlea through a change in endolymphatic pressure. In addition, the mechanism of the SNHL may be explained with the increased pressure in the SCs through cerebrospinal fluid, which may lead to damage of the hair cells, resulting in a deterioration in the transfer of acoustic energy from SCs to the cochlea.

In our study, we revealed a significant relationship between EVA and SC malformations in the CHL group. Pyle[18] studied the embryological development of the vestibular aqueduct and suggested that the EVA may not result from an arrest in development early in fetal life. Postnatal and early childhood maldevelopment were associated with the EVA, according to this study.[18] Besides this, the development of SC begins with the emergence of mineralized cartilage at 19 weeks and ends at 27 weeks of gestation.[19] The arrest of the development during these weeks results in the malformation of the SCs.[19] We suggest that the abnormal acoustic energy transmitted to the vestibular aqueduct via dysplastic SCs may induce the development of the EVA.

EVA most commonly manifests as fluctuating and progressive SNHL, but CHL and MHL may also be observed.[20] The causes of the conductive and mixed components of hearing loss in patients with EVA have been explained with stapes fixation[21] and abnormal intracochlear fluid pressure which result from the third window phenomenon.[2,22,23] EVA may also damage sensory cells inside the cochlea due to the reflux of hyperosmolar endolymphatic sac contents.[23] Some authors have suggested that there is an association between SNHL and EVA when a cochlear anomaly accompanies EVA.[24,25] However, Okumura et al.[26] reported that SNHL could be present independently from the cochlear anomaly, as a result of EVA. In our study, EVA was observed in all types of hearing loss.

Dehiscence of SC is characterized by loss of bone covering the canal, thus there is a potential communication between the canal and the cranial cavity. The incidence of SC dehiscence is highly associated with age, because the thickness of bone overlying the SCs increase with age.[15,17,27,28] The rate of SSCD was reported as 1.9-6.2% in all age groups,[15,27] while it varied between 2.3% and 36.7% in children younger than 2 years.[2,15,16,27] Our result is compatible with the literature, with a rate of 4.2%. The incidence of PSCD was also 4.2% in our study. Saxby et al.[16] reported the PSCD incidence as 1.7% in their study, which included all children with temporal bone CT regardless of indication. This incompatible result may be explained by the fact that our study group consisted only of children with hearing loss.

SC malformations were found as the most common inner ear malformations in all types of hearing loss in our study. Venkatasamy et al.[29] found an association between SC malformations and different types of hearing loss. They suggested that multiple structures sharing the same embryological origin, such as the footplate of the stapes and labyrinth, derive from ectoderm, and may be affected by interruptions during embryogenesis, leading to various degrees of clinical outcomes.[29]

The first limitation of our study is its retrospective design and the lack of a healthy control group matched for age, assuming that the inner ear findings in children with hearing loss were not comparable with a normal group. Second, the number of ears with CHL and MHL was small due to the reason that CT imaging is not generally requested for such uncomplicated pediatric cases. Third, the image interpretation was done with a consensus of 2 radiologists, omitting intraobserver and interobserver agreements. Fourth, we included patients with hearing loss and did not consider vestibular symptoms that may also be associated with third window abnormalities; the reason was that the vestibular symptoms could not always be reliably evaluated in young children.

CONCLUSIONS

Third window abnormalities and congenital inner ear malformations may accompany each other in children with SNHL and CHL. According to our results, both SSCD and PSCD and cochleovestibular malformations may be commonly detected together in children with SNHL. EVA and SC malformations may also be seen together in children with CHL. Controlled studies with larger sample sizes are required to support our findings and further evaluate the underlying pathogenesis of the different types of hearing loss encountered with inner ear malformations and third window abnormalities.

Ethics Committee Approval: Ethics committee approval was received for this study from Dokuz Eylul University Ethics Committee (2019/03-46).

Informed Consent: Informed consent is not necessary due to the retrospective nature of this study.

Peer Review: Externally peer-reviewed.

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Conflict of Interest: The authors have no conflict of interest to declare.

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REFERENCES

1. Merchant SN, Rosowski JJ. Conductive hearing loss caused by third-window lesions of the inner ear. *Otol Neurotol*. 2008;29(3):282-289. [CrossRef]
2. Ho ML, Moonis G, Halpin CF, Curtin HD. Spectrum of third window abnormalities: semicircular canal dehiscence and beyond. *AJNR Am J Neuroradiol*. 2017;38(1):2-9. [CrossRef]
3. Zalzal GH, Tomaski SM, Vezina LG, Bjornsti P, Grundfast KM. Enlarged vestibular aqueduct and sensorineural hearing loss in childhood. *Arch Otolaryngol Head Neck Surg*. 1995;121(1):23-28. [CrossRef]
4. Yiin RS, Tang PH, Tan TY. Review of congenital inner ear abnormalities on CT temporal bone. *Br J Radiol*. 2011;84(1005):859-863. [CrossRef]
5. Sennaroglu L, Saatci I. A new classification for cochleovestibular malformations. *Laryngoscope*. 2002;112(12):2230-2241. [CrossRef]
6. Murray LN, Tanaka GJ, Cameron DS, Gianoli GJ. Coronal computed tomography of the normal vestibular aqueduct in children and young adults. *Arch Otolaryngol Head Neck Surg*. 2000;126(11):1351-1357. [CrossRef]
7. Chen EY, Paladin A, Phillips G, et al. Semicircular canal dehiscence in the pediatric population. *Int J Pediatr Otorhinolaryngol*. 2009;73(2):321-327. [CrossRef]
8. Park AH, Kou B, Hotaling A, et al. Clinical course of pediatric congenital inner ear malformations. *Laryngoscope*. 2000;110(10 Pt 1):1715-1719. [CrossRef]
9. Gurgel RK, Jackler RK, Dobie RA, Popelka GR. A new standardized format for reporting hearing outcome in clinical trials. *Otolaryngol Head Neck Surg*. 2012;147(5):803-807. [CrossRef]
10. Boston M, Halsted M, Meinzen-Derr J, et al. The large vestibular aqueduct: a new definition based on audiologic and computed tomography correlation. *Otolaryngol Head Neck Surg*. 2007;136(6):972-977. [CrossRef]
11. Kumar G, Castillo M, Buchman CA. X-linked stapes gusher: CT findings in one patient. *AJNR Am J Neuroradiol*. 2003;24(6):1130-1132.
12. Blaser S, Propst EJ, Martin D, et al. Inner ear dysplasia is common in children with Down syndrome (trisomy 21). *Laryngoscope*. 2006;116(12):2113-2119. [CrossRef]
13. Baek SK, Chae SW, Jung HH. Congenital internal auditory canal stenosis. *J Laryngol Otol*. 2003;117(10):784-787. [CrossRef]
14. Zhou G, Gopen Q. Characteristics of vestibular evoked myogenic potentials in children with enlarged vestibular aqueduct. *Laryngoscope*. 2011;121(1):220-225. [CrossRef]
15. Sugihara EM, Babu SC, Kitsko DJ, Haupert MS, Thottam PJ. Incidence of pediatric superior semicircular canal dehiscence and inner ear anomalies: a large multicenter review. *Otol Neurotol*. 2016;37(9):1370-1375. [CrossRef]
16. Saxby AJ, Gowdy C, Fandiño M, et al. Radiological prevalence of superior and posterior semicircular canal dehiscence in children. *Int J Pediatr Otorhinolaryngol*. 2015;79(3):411-418. [CrossRef]
17. Wang JR, Parnes LS. Superior semicircular canal dehiscence associated with external, middle, and inner ear abnormalities. *Laryngoscope*. 2010;120(2):390-393. [CrossRef]
18. Pyle GM. Embryological development and large vestibular aqueduct syndrome. *Laryngoscope*. 2000;110(11):1837-1842. [CrossRef]
19. Richard C, Courbon G, Laroche N, et al. Inner ear ossification and mineralization kinetics in human embryonic development-microtomographic and histomorphological study. *Sci Rep*. 2017;7(1):4825. [CrossRef]
20. Jackler RK, De La Cruz A. The large vestibular aqueduct syndrome. *Laryngoscope*. 1989;99(12):1238-1242. [CrossRef]
21. Callison DM, Horn KL. Large vestibular aqueduct syndrome: an overlooked etiology for progressive childhood hearing loss. *J Am Acad Audiol*. 1998;9(4):285-291.
22. Govaerts PJ, Casselman J, Daemers K, et al. Audiological findings in large vestibular aqueduct syndrome. *Int J Pediatr Otorhinolaryngol*. 1999;51(3):157-164. [CrossRef]
23. Levenson MJ, Parisier SC, Jacobs M, Edelstein DR. The large vestibular aqueduct syndrome in children. A review of 12 cases and the description of a new clinical entity. *Arch Otolaryngol Head Neck Surg*. 1989;115(1):54-58. [CrossRef]
24. Arcand P, Desrosiers M, Dubé J, Abela A. The large vestibular aqueduct syndrome and sensorineural hearing loss in the pediatric population. *J Otolaryngol*. 1991;20(4):247-250.
25. Mafee MF, Charletta D, Kumar A, Belmont H. Large vestibular aqueduct and congenital sensorineural hearing loss. *AJNR Am J Neuroradiol*. 1992;13(2):805-819.
26. Okumura T, Takahashi H, Honjo I, Takagi A, Mitamura K. Sensorineural hearing loss in patients with large vestibular aqueduct. *Laryngoscope*. 1995;105(3 Pt 1):289-293. [CrossRef]
27. Jackson NM, Allen LM, Morell B, et al. The relationship of age and radiographic incidence of superior semicircular canal dehiscence in pediatric patients. *Otol Neurotol*. 2015;36(1):99-105. [CrossRef]
28. Meiklejohn DA, Corrales CE, Boldt BM, et al. Pediatric semicircular canal dehiscence: radiographic and histologic prevalence, with clinical correlation. *Otol Neurotol*. 2015;36(8):1383-1389. [CrossRef]
29. Venkatasamy A, Foll DL, Eyermann C, et al. Malformations of the lateral semicircular canal correlated with data from the audiogram. *Eur Arch Otorhinolaryngol*. 2019;276(4):1029-1034. [CrossRef]