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Inner ear anatomy in Waardenburg syndrome: Radiological assessment and comparison with normative data

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ABSTRACT

Objective: As patients with Waardenburg syndrome (WS) represent potential candidates for cochlear implantation, their inner ear anatomy is of high significance. There is an ongoing debate whether WS is related to any inner ear dysplasias. Our objective was to evaluate radiologically the inner ear anatomy in patients with WS and identify any temporal bone malformations.
Methods: A retrospective case review was carried out in a tertiary, referral center. The high resolution computed tomography (HRCT) scans of the temporal bone from 20 patients (40 ears) with WS who were managed for deafness in a tertiary referral center from 1995 to 2012 were retrospectively examined. Measurements of 15 different inner ear dimensions, involving the cochlea, the vestibule, the semicircular canals and the internal auditory meatus, as well as measurements of the vestibular aqueduct, were performed independently by two neuroradiologists. Finally, we compared the results from the WS group with a control group consisting of 50 normal hearing subjects (100 ears) and with previously reported normative values.
Results: Inner ear malformations were not found in any of the patients with WS. All measured inner ear dimensions were within the normative values compiled by our study group as well as by others.
Conclusions: Inner ear malformations are not characteristic for all types of WS; however, certain rare subtypes might be related to inner ear deformities. Normative cochleovestibular dimensions that can help in assessing the temporal bone anatomy are provided.

1. Introduction

Waardenburg syndrome (WS) is an autosomal dominant disease, characterised by dystopia canthorum, hyperplasia of the eyebrows, heterochromia iridis, white forelock and congenital sensorineural hearing loss [1,2]. Although WS was initially linked to genetic mutations in the gene PAX3, nowadays, six different genes, including MITF (microphthalmia-associated transcription factor), EDN3 (endothelin 3), EDNRB (endothelin receptor type B), SOX10 (encoding the Sry bOX10 transcription factor), and SNAI2 have been involved [1,2]. Based on the genetic background and the clinical characteristics, WS has been divided into four types. The characteristic feature for type I is dystopia canthorum, while in type II dystopia canthorum is missing. In type III patients additionally have upper limp anomalies and more coarse facial characteristics and, finally, type IV involves Hirschsprung disease [1–4]. Despite the differences between the four types, sensorineural hearing loss represents a common feature of all patients with WS [2–4]. Hearing loss may vary in severity; most patients with WS, however, suffer from profound sensorineural deafness and therefore are candidates for cochlear implantation [5–10].

As the inner ear anatomy is of high significance for cochlear implantation, imaging studies of the temporal bones are crucial for the preoperative assessment of patients with WS [11–13]. There is an ongoing debate whether WS is related to any anatomical inner ear anomalies. The results from previous studies are very heterogeneous with the incidence of temporal bone anomalies varying from 0 to 100% among patients with WS [9,14–16]. In particular, two studies focusing explicit on the temporal bone imaging and involving six and eight patients showed inner ear

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malformations in 50% and 17% of the cases, respectively [15,16]. However, the number of temporal bones evaluated in both studies was small. On the other hand, recent work on the outcome of cochlear implantation, involving 25 patients with WS did not note any inner ear anomalies, which could affect the implantation, without, however, having performed any detailed radiological measurements of the inner ear dimensions [5].

As sufficient evidence on the inner ear malformations in cases with WS is missing, our objective was to evaluate the temporal bone anatomy of such patients using appropriate imaging studies and measurements and comparing the obtained data with normative cochlear and vestibular dimensions.

2. Materials and methods

2.1. Study settings and patients

This retrospective study was carried out in a tertiary referral center. Approval from the Ethical Committee of the University was obtained.

Patients with WS who had been referred to our department from 1995 to 2012 for hearing loss assessment and management were identified through the electronic patients database and the coding system used by the medical staff. The notes of all patients with WS were found and retrospectively reviewed; the severity of hearing loss was documented.

2.2. HRCT settings

The CT scans were performed with three different types of scanners over the lengthy period covered by our study:

Two patients were examined using a HiSpeed Advantage RP CT scanner (GE, Milwaukee, WI, USA): helical CT examinations were performed at 140 kV and 80 mA s, with a section thickness of 1 mm and a pitch of 1.

Six patients were examined using a HiSpeed Advantage CT scanner (GE, Milwaukee, WI, USA): helical CT examinations were performed at 120 kV and 80 mA s, with a section thickness of 1 mm and a pitch of 1. The field of view was 16 cm using a 512 × 512 matrix.

Twelve patients were examined using a Light–Speed16 CT scanner (GE, Milwaukee, WI, USA): helical CT examinations were performed at 120 kV, auto mA s with a maximum up to 100 mA s, a speed of 5.62 s, a thickness of 0.625 mm, and a pitch of 0.562:1.

The CT scans were uploaded directly to our current picture archiving and communications system (PACS) (GE, Milwaukee, WI, USA): except for the eight patients in whom only the plain films were available. These were scanned in order to perform the measurements at the workstation. Reconstructions in the coronal plane were available in 12 cases uploaded primarily to the PACS.

2.3. Measurements

All measurements were performed using PACS and the electronic calipers and were taken in millimeters. A modified measurement system of the ones mainly proposed by Purcell et al. [17] as well as by Krombach et al. [18] was employed. In particular, 15 different inner ear dimensions were measured on the coronal and axial plane. These dimensions involved:

- Vestibule (axial): width and height (Fig. 1).
- Cochlea (axial): length of basal turn, width of the basal turn lumen, length of the apical turn and height of the apical turn (Fig. 2).
- Cochlea (coronal): height of the cochlea (Fig. 2).
- Semicircular canals: the width of the superior and the posterior semicircular canals, the width of the bony island (Fig. 3) and the ampulla (Fig. 4) of all three semicircular canals. Canal lumen and bony island measured at maximum diameter of the turn, most often two sections below the first view of the superior semicircular canal. Ampulla identified at sections between canal lumen and vestibule, most often one section below the section used for the lumen measurements. Regarding the posterior semicircular canal, it was measured one to two sections above the inferior limb.
- Internal auditory meatus: length was measured at the longest section and width close to the cochlear aperture (Fig. 5).

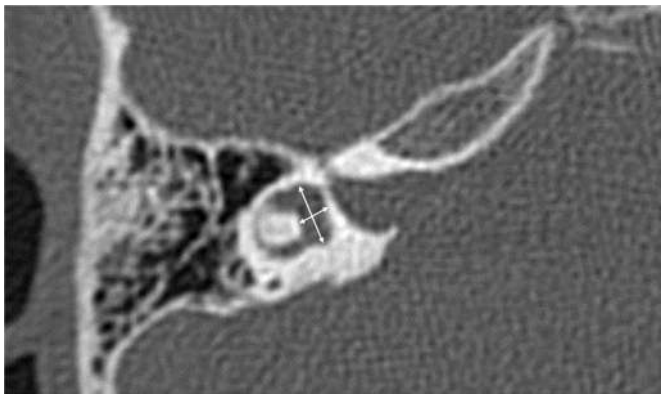

Fig. 1. Measurements of the vestibule in axial HRCT scans.

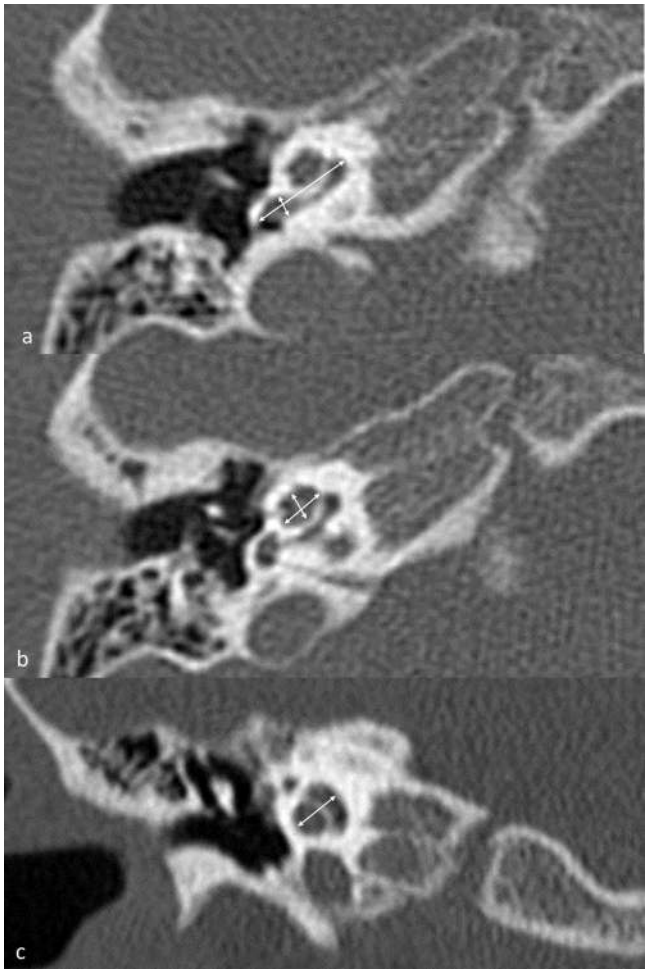

Fig. 2. Measurements of the cochlea on the axial plane: length of basal turn (a), width of the basal turn lumen (a), length of the apical turn (b) and height of the apical turn (b) and on the coronal plane (height of the cochlea, (c).

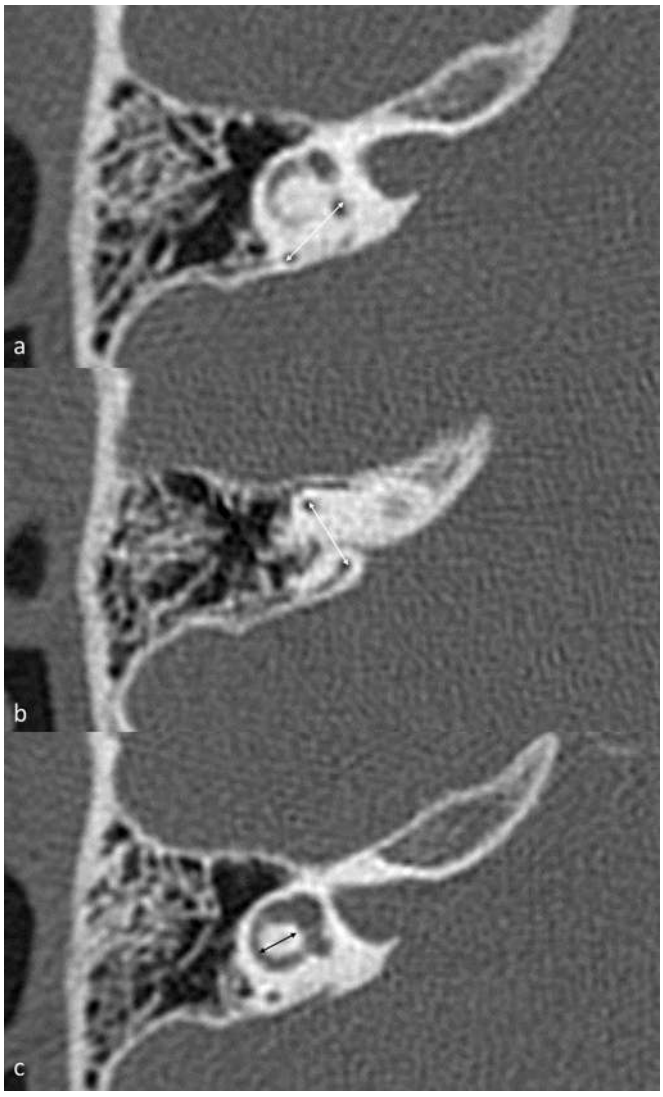

Fig. 3. Measurements of the semicircular canals: width of the posterior (a) and the superior (b) semicircular canals, the width of the bony island (c).

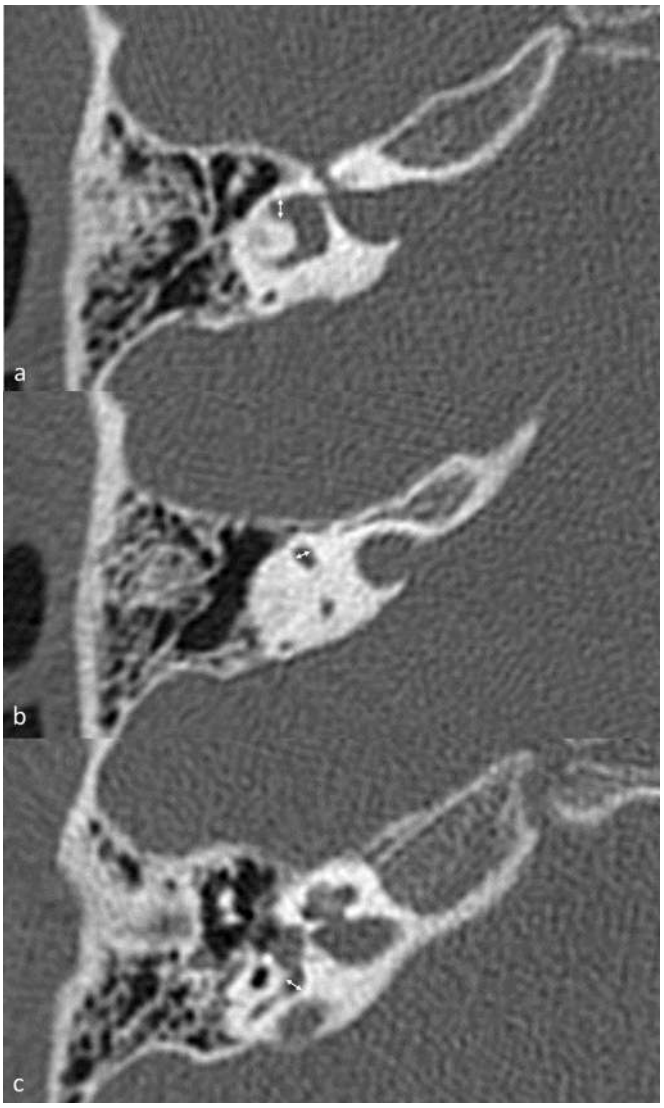

Fig. 4. Measurements of the ampulla of all three semicircular canals (a–c).

Finally, the maximum anterior–posterior width of vestibular aqueduct was also measured on axial CT scans; values greater than 1.5 mm were considered as abnormal, showing enlarged vestibular aqueduct, as defined by Valvasori and Clemis [19].

The measurements were performed independently by two experienced neuroradiologists (5 and 10 years of experience) to minimize interobserver error. In cases of discrepancy, values were set by consensus.

2.4. Normative data-control group

The temporal bone HRCT scans of 50 patients (100 ears) with normal hearing thresholds, without any known, persistent inner ear symptoms, were used to establish the normative cochleovestibular dimensions. The mean age of the control group was 38, 68 years and the range was 2–74 years. These patients were identified through the medical electronic database and PACS. Syndromic patients were excluded from the control group using the medical electronic database. The reasons for the temporal bone scans were as follows: suspected chronic mastoiditis (26), suspected cholesteotoma (6), paraganglioma (6), vertigo (8) and suspected trauma (no visible fracture within the inner ear) (4). Despite some middle ear pathologies, all patients who were included in the control group had normal bone conduction (no sensorineural component). The same HRCT protocols as mentioned above were employed for the control group too. The measurement of the same 15 dimensions was performed using the same workstation and electronic caliper by the same two neuroradiologists. These data have been previously used by our group [20].

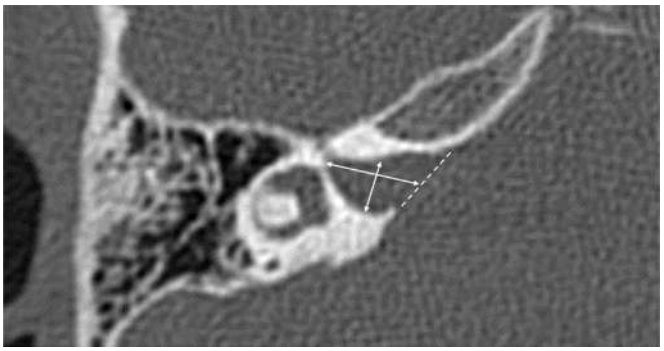

Fig. 5. Measurement of the length of the internal auditory meatus at its maximum length and width. The width was measured in approximately 90° to the measurement of the length.

2.5. Data analysis

Collected data from the HRCT scans of patients with WS and the control group were entered into a Microsoft Excel® Version 10 spreadsheet. Detailed measurements were documented and average values and standard deviations (SD) were obtained. Measurements were compared with the values of our control group and the values obtained by Purcell et al. (measurements from 15 patients-30 temporal bones with normal hearing) [17].

Grossly, measurements were considered normal if they were within 2 SD of the average measurements [17]. However, more detailed statistical analysis was also performed. The measurements form the WS group were compared with the ones from the control group using Mann–Whitney *U* test. *P*-values <0.05 indicated statistical significance.

3. Results

3.1. Patients

Twenty-five patients with WS were identified. The HRCT scans of the temporal bones were, however, available in digital form in 20 patients with WS (40 temporal bones). Hearing loss was severe to profound in all cases and patients were cochlear implant recipients or candidates at the time of the study. Nine of the patients with WS were males and 11 females. Seven patients had been diagnosed with WS type I, six with WS type II, two with WS type III, while in five patients the WS type was not defined at the time of this study. The mean age at the time of the HRCT scan was 9.1 years (range 7 month–24 years).

3.2. Measurements from patients with WS, the control group and previous study

The average values for the WS group were: vestibule's width 6.05 mm, vestibule's length 3.07 mm, length of the cochlear basal turn 9.61 mm, width of the basal turn lumen 1.89 mm, length of the apical turn 3.95 mm, width of the apical turn 3.27 mm, height of the cochlea 4.84 mm, posterior semicircular canal 7.52 mm, superior semicircular canal 7.78 mm, bony island 4.23 mm, ampulla of the lateral semicircular canal 1.76 mm, of the posterior canal 1.47 mm and the superior canal 1.51 mm, internal auditory meatus length 12.08 mm and internal auditory meatus width 4.82 mm (Tables 1 and 2).

The obtained values from our control group with their standard deviations and the measurements from the Purcell et al. study (from 15 patients, 30 temporal bones) are presented in Table 2.

With regards to the vestibular aqueduct, all values were smaller than 1.5 mm, showing normal size.

3.3. Comparison

All values from the WS group were within the average values ± 2 SD from our control group and the Purcell et al. one, showing that patients with WS have normal inner ear anatomy (Table 2, Fig. 6). Moreover, *p*-values were all higher than 0.05, indicating no statistically significant difference between the control group (normative) and patients with WS.

Also a comparison of the three subgroups WS type I, type II and type III revealed no significant differences between the subtypes, when regarded separately they were all within the normal range of our control group. There was, however, a large SD for the internal auditory meatus dimensions. This variability was common for all three groups (Table 2). Based on our measurements, hearing loss in patients with WS is not related to anatomical inner ear malformations.

4. Discussion

Since 1951, when WS was first described [2], new knowledge has been obtained and important relevant aspects have been better understood. Among others, hearing loss and its treatment attracted the interest of many working groups. Due to its usually bilateral, profound character, previous case series have already reported cochlear implantation as the suitable method for hearing rehabilitation in patients with WS, focusing mainly on the post-implantation outcome [5–10]. Simultaneously, some studies evaluated the inner ear anatomy in WS and how this could affect cochlear implantation [5,9,14–16]. The results, however, ranged widely, from 0% to 100% [5,9,14–16], mainly because of the limited number of enrolled patients and the fact that the evaluation of the HRCT scans was solely based on visual inspection and not on accurate measurements.

We examined the inner ear anatomy in a large series of patients with WS (40 temporal bones) performing accurate, repeatable measurements on HRCT scans and detailed comparisons with normative inner ear dimensions obtained from past study and from our own extended database. We showed that WS is not related to any inner ear malformations. In general, inner ear dysplasias can underlie in 20% of patients with congenital sensorineural hearing loss [21,22]; such malformations might be present in patients with WS because of their congenital deafness but not because of the syndrome.

4.1. Temporal bone abnormalities in WS

Many previous studies have shown inner ear malformations in some of the patients with WS who had been enrolled in their surveys. Internal auditory meatus anomalies were found in 11% of patients with WS type I (eight patients) [15]. The same study compared the findings from eight patients with WS type I with 28 patients with WS, which have been previously described in the literature (at the time of that study). Inner ear malformations were found in 17% of the described cases with the absence of the semicircular canals to be the most common, followed by the hypoplastic cochlea (8%) [15].

On the other hand, recent study involving 25 patients with WS who have received a cochlear implant did not reveal any inner ear malformation which could affect cochlear implantation in any of the cases [5]; a questionably dilated vestibule was, though, reported. Interestingly, the above mentioned works concluded in completely different outcomes. However, neither of these studies used any radiological measurements of the inner ear dimensions but only visual inspection. Although visual inspection is used in everyday radiological practice as the standard technique to evaluate HRCT scans, it may be misleading when examining the temporal bone in detail. While sufficient for detecting severe inner ear malformations, visual inspection is often inadequate in the diagnosis of subtle abnormalities as this approach is greatly dependent on the experience of the examiner [23]. This might have affected the results of previous studies and can well be considered as one of the reasons for the noteworthy, existing discrepancy.

It seems that inner malformations in patients with WS have been a matter of interest for many years. In particular, the largest case series dates back to 1975 involving 24 patients with WS (48 temporal bones) [24]. That study did not identify any inner ear malformations in any of the enrolled patients, which was in contrast with the existing knowledge, at that time, as it was believed that patients with WS had semicircular canal malformations [24]. However, detailed radiological evaluation of the temporal bones in 1975, because of the limited existing technology, was not possible. Nemansky and Hageman had used Stenver's

Table 1
Inner ear dimensions for the patients with WS.

P	WS	Side	Cochlea					Vestibule		SCC						IAM	
			H	Basal L	Basal W	Apic. L	Apic. H	W	H	BI	Sup SCC	Post SCC	Ampulla			L	W
													Hor	Sup	Post		
1	1	Right	na	10.8	1.8	3.6	2.8	5.3	2.6	4.4	7.3	8.3	1.8	2.3	1.3	9.3	4.1
		Left	na	10.2	1.8	3.3	2.4	5.5	2.7	5	7.5	7.9	1.4	2.2	1.8	10.3	3.7
2	1	Right	na	9.9	1.9	4.1	3.5	6	3	4.7	7.2	7.1	1.3	1.2	1.2	12.6	4.5
		Left	na	9.4	2.1	3.8	3.2	5.8	2.8	4.2	7.2	7.3	1.5	1.1	1.2	13.9	4.6
3	1	Right	na	9.2	1.9	3.9	3.3	5.2	2.8	4.8	7.5	6.8	1.4	1.5	1.5	11.1	3.3
		Left	na	8.8	1.9	4.1	3.6	5.5	2.6	4.5	7.6	6.7	1.7	1.5	1.6	10.7	3.6
4	1	Right	na	9.2	1.9	3.6	3.2	5.8	3.3	4.5	6.9	6.7	1.4	1.3	1.8	10.8	4.2
		Left	na	8.9	1.7	3.9	3.1	5.9	3.3	4.2	7.2	7.3	1.6	1.2	1.6	12.5	4.8
5	1	Right	4.1	9.6	2.2	4.1	3.2	6.1	3.3	4	7.7	6.9	1.7	1.2	1.3	10.1	7.1
		Left	5.1	9.3	1.9	3.2	3.4	5.3	3.1	4.3	7.5	7	1.4	1.8	1.4	10.4	7.8
6	1	Right	4.4	10.2	1.7	4	3.6	6.7	3	3.8	7.4	7.1	2	1.6	1.1	10.4	6.1
		Left	4.9	10.1	1.9	4	3.4	6.5	3	3.8	6.9	6.9	1.9	1.3	1.2	10.3	6.4
7	1	Right	na	9.8	1.7	3.6	3.8	6.3	2.9	3.8	7.9	7.1	2	1.3	1.8	12.6	4.4
		Left	na	9.5	1.7	3.9	3.3	6.2	3.1	4.6	8.1	6.7	1.8	1.4	1.9	12.8	4.5
8	2	Right	4.4	10	1.9	4.2	3.3	7.4	3.6	4.8	8.1	7.7	1.6	1.1	1.6	14.9	5
		Left	4.5	9.3	1.6	3.8	3.3	6.5	2.9	4.9	7.8	7.6	1.9	1.1	1.6	13.2	5.9
9	2	Right	4.9	10	2	4	3.5	6.3	3	4.6	7.5	7.3	2	2.1	1.2	10.6	4.9
		Left	5.1	9.6	2	4.2	2.9	5.8	3.3	4.6	6.9	6.9	2.1	1.9	1.4	10.5	4.9
10	2	Right	4.6	10.6	2.2	4	3.6	7.1	3.4	4.4	8.9	9.1	2.2	1.1	1.8	12.9	5.1
		Left	4.6	10.2	2.2	4.6	3.8	5.9	3.8	4.4	8.8	9.1	1.9	1.3	1.6	13.1	6
11	2	Right	na	8.5	1.7	3.3	3.1	5.3	2.5	3.3	7.9	6.7	1.4	1	1.5	12.2	5.6
		Left	na	8.5	1.8	3.3	3.1	5.7	3.3	3.4	7.9	7.3	1.5	1.1	1.3	13.9	5
12	2	Right	na	8.9	1.7	3.6	3	5.7	3.4	3.2	7.6	8.3	1.5	1.2	1.2	7.9	5.5
		Left	na	8.7	1.7	3.3	2.6	5.8	3	3.9	7.6	8.6	1.6	1.1	1.3	8.3	5.8
13	2	Right	na	9.9	1.7	3.9	2.9	6.3	2.9	4.6	7.3	7.1	1.9	1.6	1.4	13.8	5
		Left	na	10	1.9	3.6	3	5	3.1	3.8	7.9	7.7	1.4	1.2	1.8	13.4	4.7
14	3	Right	4.9	10.3	1.8	4.3	2.9	6.4	3	3.8	8.3	6.9	1.6	1.3	1.8	11.6	3.7
		Left	4.9	9.7	2	3.8	3.1	5.8	2.7	4.1	7.9	7.5	1.6	1.6	1.8	11.9	4.2
15	3	Right	5.1	10	1.7	3.8	3.1	6.5	2.9	4.4	8.6	7.1	2	1.4	1.6	13.2	4.1
		Left	4.9	9.6	1.6	4	3.5	6.7	3.5	3.8	8.8	7.5	1.6	1.3	1.4	12.9	4.1
16	n.d.	Right	5.6	8.7	2.2	4.3	3.5	5.4	3.3	3.8	7.8	8.3	2.1	1.7	1.2	11.7	3.8
		Left	5	8.8	2.2	4.3	3.6	5.7	3.5	4.2	7.7	8.3	1.8	1.6	1.2	11.3	4.9
17	n.d.	Right	5.2	9.4	1.9	4.5	3.4	5.7	2.6	4.2	7.8	7.3	1.7	1.6	1.3	11.6	3
		Left	5.1	9.6	1.9	4.2	3.6	5.9	2.6	4.1	8.1	7.5	1.9	1.6	1.6	11	3.8
18	n.d.	Right	na	9.5	1.8	3.7	3.3	6.3	3.3	5.1	7.5	8.1	1.5	1.5	1.1	12.9	4.7
		Left	na	9.9	1.7	4.2	3.4	6.3	3.6	5.1	7.9	8.6	1.8	1.3	1.4	13.8	5.6
19	n.d.	Right	4.4	9.3	1.6	4.1	3.4	6.5	2.6	4.1	8.4	8.5	2.3	1.1	1.8	14.4	4.8
		Left	4.5	9.4	1.9	4.5	3.2	6.6	2.6	4.4	8.6	7.8	2	1.2	2	16.3	3.8
20	n.d.	Right	5.1	10.5	2.3	4.9	3.3	6.6	3.4	3.5	8	6.9	2.6	2.4	2	13.4	4.4
		Left	5.1	10.4	2.4	4.4	3.6	6.8	3.6	4.1	7.5	7.4	2.1	2.5	1.8	14.7	5.3
Av			4.84	9.61	1.89	3.95	3.27	6.05	3.07	4.23	7.78	7.52	1.76	1.47	1.51	12.08	4.82
SD			0.35	0.59	0.2	0.39	0.31	0.55	0.35	0.48	0.51	0.68	0.29	0.39	0.26	1.8	1

P: patient, WS: type of WS, L: length, H: height, W: width, Apic: apical, BI: bony island, SCC: semicircular canal, hor: horizontal, post: posterior, sup: superior, IAM: internal auditory meatus, Av: average; SD: standard deviation; nd: not defined; all values in mm.

projection for their study; therefore the accuracy of their diagnosis remains open to discussion [24].

Further works on patients with WS involved very small numbers of patients. In particular, radiological measurements of 12 temporal bones of patients with WS has shown some type of inner ear malformation in all cases (100%) [16], while a study involving only five patients with WS and visual inspection of CT scans revealed temporal bone abnormalities in one patient and questionable findings in one more [9]. Additional reports on syndromic cochlear implant recipients labeled the temporal bones of patients with WS malformed, even though these were isolated cases [6,25]. We consider, however, drawing conclusions from

Table 2
The average values for patients with Waardenburg syndrome, for our control group (normative dimensions) and from the study by Purcell et al. [17].

	Cochlea					Vestibule		SCC						IAM	
	H	Basal L	Basal W	Apic. L	Apic. H	W	H	BI	Sup SCC	Post SCC	Ampulla			L	W
											Hor	Sup	Post		
WS	4.84	9.61	1.89	3.95	3.27	6.05	3.07	4.23	7.78	7.52	1.76	1.47	1.51	12.08	4.82
(±SD)	0.35	0.59	0.2	0.39	0.31	0.55	0.35	0.48	0.51	0.68	0.29	0.39	0.26	1.8	1
Normative	4.89	9.43	1.75	4.09	3.31	6.09	2.92	4.65	7.4	6.9	1.96	1.6	1.7	11.96	4.9
(±SD)	0.37	0.33	0.14	0.3	0.32	0.39	0.27	0.65	0.4	0.49	0.20	0.17	0.21	1.23	0.74
Purcell et al. (±SD)	5.31	8.59	2.15	6.24	3.96	5.83	3.4	3.67	Na	7.52	[a]	2.26	[a]	11.1	Na
	0.52	0.41	0.18	0.4	0.38	0.58	0.28	0.35	Na	0.53		0.26		1.72	Na

L: length, H: height; W: width; Apic: apical, BI: bony island, SCC: semicircular canal, hor: horizontal, post: posterior, sup: superior, IAM: internal auditory meatus, SD: standard deviation. The normative values obtained from our control group are highlighted with grey background. Mann–Whitney *U* test was used to compare the values from the WS and the control group; $p > 0.05$ for all measurements. All values in mm.

[a] was not measured by Purcel et al. [17].

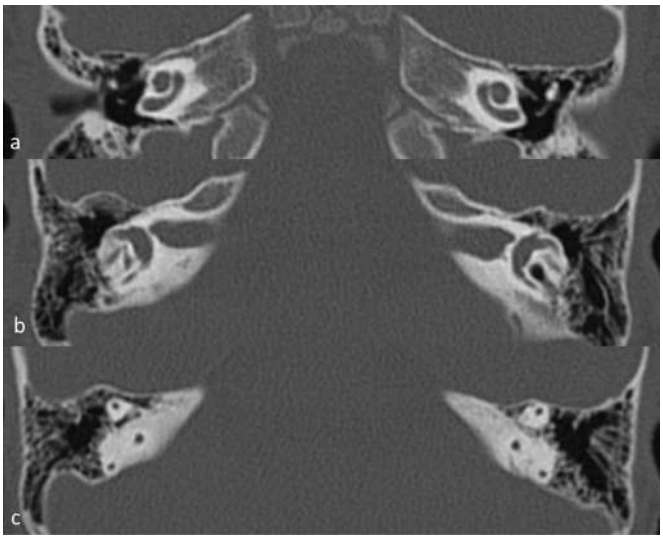

Fig. 6. The inner ear of patients with WS: normal anatomy.

isolated cases very precarious. Interestingly, Madden et al. [16] reported large vestibular aqueduct in 50% of the enrolled patients with WS. However, only the scans of six patients were examined, which is a limited number of patients [16]. Moreover, their comparison of the vestibular aqueduct measurements of patients with WS with measurements from non-WS individuals (177 temporal bones) did not reach the level of statistical significance [16]; enlarged vestibular aqueduct can be found in both non-syndromic and WS populations, without being typical for WS.

Recently, a multicentre study reported on 15 patients with WS and SOX10 mutations suggesting strong association with hypoplasia or agenesis of the semicircular canals, enlarged vestibule and cochlear deformity [26]. As the authors state, SOX10 mutations are responsible for 15% of patients with WS type II and up to 50% with WS type IV [26]; thus, their findings refer to this certain mutation and not to patients with WS in general. In our study, there were six patients with WS type II and five with unknown genotype but no one with Hirschprung disease (no patients with WS type IV), without any temporal bone abnormalities. It seems that there are subtypes of WS with temporal bone abnormalities, such as individuals with the SOX10 mutation.

Hearing loss in WS has been attributed to atrophy of the organ of Corti and stria vascularis, absence of melanocytes in the inner ear and reduced spiral ganglion counts [9,27,28]. In particular, past histopathological study of a cochlea from a patient with WS showed absence of melanocytes and of stria vascularis, missing hair cells, dysplastic tectorial membrane, and lack of peripheral processes of the spiral ganglion cells [27]. Similar results were reported in 1992 suggesting absence of inner ear pigment as a possible pathogenetic factor for hearing loss in WS [27]. There seems to be a histopathological background explaining hearing loss in WS and not the inner ear malformation itself, when present. Temporal bone malformations, as defined by imaging studies, might co-exist as sporadic findings but should not be necessarily strictly linked to the pathogenesis of hearing loss.

4.2. Normative measurements of the inner ear

Identifying and classifying inner ear malformations are of high significance for cochlear implantation [11–13]. In most cases with severe inner ear malformations visual inspection is adequate for setting the diagnosis. However, in more mild forms visual inspection may be proven insufficient for the precise description of the underlying dysplasia, if any [23]. Therefore, accurate measurements of the inner ear dimensions and comparison with normative values should be employed, at least for the less severely malformed cases.

Previous works have performed detailed measurements on HRCT images of the temporal bones of patients with normal hearing, providing normative values for the cochleovestibular complex [17,18]. Although the aim of these studies was different, they both obtained normative values. We used the values obtained by Purcell et al. (as the measured dimensions were similar to ours) [17] as "normal" values but also used our own normal data from 50 patients (100 temporal bones) without any known ear related pathology [20]. The SD was, however, much higher for the internal auditory meatus measurements; this observation is common in past study [17]. It seems that there is a wider variety regarding the dimensions of the internal auditory meatus, at least based on HRCT scans.

Regarding the basal cochlear turn, it is worth mentioning that its dimensions are repeatable and stable with a SD of 0.66 mm based on our study and 0.41 mm based on Purcell et al. [17]. However, 2 SD make a difference of approximately 1 mm, which may be surgically important when advancing the cochlear implant electrode array into the cochlea. This deviation could well explain the feeling reported by many experienced cochlear implant surgeons that some radiologically normal cochleae are smaller than others (personal communication and unpublished data).

Finally, it is important adding that measurements performed on HRCT images may deviate about 10% from the actual dimensions [29]. In particular, there has been reported a 10% possible increase in size [24]. However, it seems that radiological studies are the most simple and accurate method to perform such measurements to evaluate the inner ear; thorough evaluation of temporal bone HRCT scans may even uncover difficult to identify and assess fine abnormalities [30]. Histological studies, which have been previously used, are not feasible *in vivo* in human and they may also result in inaccurate and not repeatable values because of the fixation process used for the temporal bones and their decalcification [18,31]. HRCT of the temporal bones is an everyday employed method in imaging the bony inner ear, giving us the option to perform measurements and compare with established normative values.

5. Conclusion

Inner ear malformations are not characteristic for all types of WS. However, certain subtypes might be related to inner ear deformities. This study also provides normative cochleovestibular dimensions that can help in assessing in detail the temporal bone anatomy.

Conflict of interest

None to declare.

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