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Association between morphological features in the cochlear promontory and mastoid Process: Implications for Identifying middle ear diseases in human skeletal remains

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ABSTRACT

Infectious Middle Ear Disease (IMED) is a group of infections that frequently afflict individuals across all age groups worldwide. Although in today's clinical practice IMED is efficiently managed, in the past it probably caused severe complications (e.g., hearing loss, balance problems, and facial nerve paralysis), heavily impacting the everyday life of many people. However, despite the valuable insights that studying ear infections in the past can bring, bioarcheology presently lacks a standardized methodology to assess their prevalence in skeletal populations. This can lead to several issues, including incomparability of results, difficulties in replications, and methodological biases.

Recently, straightforward and accessible criteria for the observation of the cochlear promontory were presented to successfully assess IMED on skeletal remains. Yet, as otologists rarely examine the impact of ear infections on the bony structures of the middle ear, the results were not supported clinically, and could therefore not be validated. To fill this gap, we propose a study in which computed tomography (CT) of the mastoid process was utilized on the skulls of 50 individuals to verify the results obtained through gross observation of the cochlear promontory. Statistical analysis revealed significant correlation between hypopneumatization (indicative of childhood IMED) and bony changes of the promontory at the level of the individual. This suggests a potential correlation that warrants further investigation to determine whether the observation of the cochlear promontory should be used as a method for IMED assessment. Overall, our study contributes to the study of IMED in past populations, and underscores the importance of clear, standardized scoring criteria in paleopathology.

1. Introduction

Infectious Middle Ear Disease (IMED) is a group of infections (i.e. chronic otitis media, recurrent acute otitis media, and chronic tubal dysfunction) occurring in the middle ear, the air-filled space behind the eardrum that contains the auditory ossicles. Clinically, IMED may occur as a result of a malfunction of the Eustachian tube, a duct that connects the middle ear with the nasofarynx and helps to equalize the pressure between the middle and the outer ear, as well as to facilitate the drainage of fluids (Rijk et al., 2021; Schilder et al., 2016). In cases when the drainage is impeded, the fluid can build up behind the eardrum and create an environment conducive to bacterial and viral proliferation, potentially leading to tissue inflammation (Schilder et al., 2016). IMED is among the most common diseases occurring during childhood, with approximately 80 % of children having experienced at least one episode by 10 years of age (Schilder et al., 2016).

Today, IMED is efficiently clinically managed and does not commonly result in complications thanks to the accessibility of antibiotics, advancements in screening techniques, and surgical interventions. However, clinical evidence suggests that untreated IMED could have significantly disrupted the lives of past populations by causing enduring and incapacitating complications such as hearing loss, balance problems, and facial nerve paralysis (Jamal et al., 2022). Identifying the prevalence of IMED in ancient populations provides valuable insights into their health and lifestyle challenges (e.g., Díaz-Navarro et al., 2022; Floreanova et al., 2020; Krenz-Niedbała & Łukasik, 2020). Yet, to date

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middle ear diseases have only been sporadically addressed by bioarcheologists, potentially due to limited sample preservation, the difficulty of accessing the middle ear, and more importantly the general lack of explicit and standardized scoring criteria.

One of the first bioarcheological studies on IMED was published by McKenzie and Brothwell (1967) and described several case studies based on the observation of different bony features, such as perforation of the temporal squama and presence of mastoid lesions. Since this initial study, a several diverse approaches (such as endoscopy, radiology, and scanning electron microscopy) have been proposed to identify IMED in past populations (e.g., Collins, 2019; Floreanova et al., 2020; Goycoolea et al., 2019; Purchase et al., 2019; Qvist & Grøntved, 2001). Currently, research conducted on archaeological populations shows significant diversity both in the geographical origins of sampled data (e.g., Northern Europe, Asia, South America, etc.) and in observed prevalence rates (between 1.2 % and 94.6 %) (e.g., Floreanova et al., 2020; Goycoolea et al., 2019; Krenz-Niedbała & Łukasik, 2017, 2020; Purchase et al., 2019; Qvist & Grøntved, 2001; Roumelis, 2007). Most studies focused on the observation of pathological lesions on either the mastoid process or ear ossicles (e.g., Flohr & Schultz, 2009b; Krenz-Niedbała & Łukasik, 2017; Qvist & Grøntved, 2001), while others focused on the presence of rare complications of IMED, such as ossicular fixation and mastoiditis (e.g., Dalby et al., 1993; Flohr et al., 2014; Flohr & Schultz, 2009a).

While the number of approaches utilized in the investigation of IMED in archaeological populations is noteworthy, it is important to note that such diversity could lead to incomparability and/or difficulties in reproducibility of results, as well as operational biases. Another limiting factor in the study of IMED in past populations is that most of the presented archaeological strategies to score IMED are currently not clinically supported. As otologists hardly examine the impact of IMED on the bony structures of the middle ear, validating results using clinical sources is in most cases impossible (Floreanova et al., 2020). However, as bioarcheologists often make inferences about the health and lifestyle of past populations solely based on skeletal evidence, clinical validation can refine these interpretations by providing insights into the range of possible causes for observed skeletal markers, which may not be evident from the archaeological context alone.

An exception to what presented above is the observation of mastoid air cells development, which has been widely investigated today by clinicians (Ilea et al., 2014; Roy et al., 2015; Sethi et al., 2006) as well as by archaeologists (e.g., Flohr et al., 2009; Homøe & Lynnerup, 2009; Primeau et al., 2018). Mastoid cells (small air-filled spaces within the mastoid part of the temporal bone) are assumed to help protecting the ear during life, regulating air pressure inside the skull, and potentially preventing injuries on the temporal bone in case of trauma (Magnuson, 2003). The development of mastoid cells (i.e., mastoid pneumatization) occurs in the 33rd week of gestation and lasts until the age of eight or nine (Mansour et al., 2019). During this time of growth, prolonged IMED episodes may interfere with normal development, resulting in a permanently reduced presence of air cells in the mastoid process (i.e., hypopneumatization) (Aoki et al., 2010). Because changes to the mastoid air cell system mainly occur during its development, the presence of hypopneumatization in archaeological specimens has occasionally been used to identify episodes of childhood IMED (Homøe et al., 2009; Homøe & Lynnerup, 2009; Primeau et al., 2019). However, as mastoid pneumatization is observable exclusively through radiographic imaging, the limited availability of X-ray and/or computed tomography (CT) equipment and their associated prohibitive costs have impeded its consistent examination in larger samples.

In a recent publication, Floreanova and colleagues (2020) highlighted the need for paleopathology to develop a consistent methodology for scoring IMED in comparative and accessible way, pinpointing the promontory of the tympanic cavity as a structure potentially impacted during IMED inflammatory processes.

The promontory of the tympanic cavity (or cochlear promontory) is a bony prominence placed between the oval window and the round window niche of the middle ear. Because of its precise location at the site where inflammation and fluid buildup occur during IMED, bony changes on the cochlear promontory have archaeologically been regarded as indicative of inflammatory processes within the middle ear (Collins, 2019; Floreanova et al., 2020; Roumelis, 2007). In their call for more standardized, comparable, and accessible scoring system for IMED, Floreanova and colleagues (2020) applied the criteria set forth by Boocock and colleagues (1995) for chronic maxillary sinusitis (namely, spicules, remodeled spicules, pitting, and new bone formation) to observations of the cochlear promontory, justifying this approach by viewing sinusitis as a condition closely linked to IMED (i.e., shared origin in infections and the common feature of fluid accumulation within a confined space). According to Floreanova and colleagues (2020), the observation of the cochlear promontory is especially useful when studying IMED because: 1) the promontory is enclosed within the middle ear cavity and therefore rarely affected by taphonomic factors (unlike other structures such as ear ossicles which often fall out) (Pinhasi et al., 2015); 2) its observation does not require the use of sophisticated and/or expensive technology (can be performed with an endoscope/microscope); and 3) most bioarchaeologists are already familiar with observing changes associated with inflammation and infections and could therefore apply the method consistently.

Recently, the work of Floreanova and colleagues (2020) was criticized by Flohr and colleagues (2023) in a study analyzing the microscopic features of the cochlear promontories of two individuals from medieval Germany. Their analysis revealed no discernible differences in the osseous architecture of the promontory wall, despite one of the individuals being purportedly diagnosed with IMED while the other did not exhibit the condition. Based on this evidence, Flohr and colleagues (2023) concluded that bony overgrowth of the promontory surface should therefore be seen as a normal anatomical variant. Yet, as highlighted by both Floreanova and colleagues (2020) and Flohr and colleagues (2023), there is a lack of clinical evidence indicating whether IMED actually affects the cochlear promontory, thus complicating the validation or dismissal of their results. To contribute to this body of literature concerning IMED in the past, we conducted a study in which computed tomography (CT) of the mastoid process is utilized to verify the results obtained through gross observation of the cochlear promontory as described by Floreanova and colleagues (2020) in a post-medieval population from the Netherlands. By comparing and analyzing the data obtained from the observation of both mastoid pneumatization and changes of the cochlear promontory, we aim to provide further insights into the potential limitations and benefits of both approaches to study IMED in the past.

Table 1
Demographic composition of the sample included in this study.

		Age-at-Death			Total
		Young adult (18–34 years)	Middle adult (35–49 years)	Old adult (50 + years)	
Sex	Male	9	8	13	30
	Female	11	4	5	20
Total		20	12	18	50

2. Materials

2.1. Post-Medieval Arnhem

The Dutch post-medieval skeletal population of Arnhem was chosen for its excellent preservation and skeletal completeness, as well as for its well-understood historical and bioarcheological context. Dating between 1626 and 1829 CE, this skeletal assemblage is likely representative of the Arnhem's poorest socioeconomic class, possibly workers in the small scale industries (e.g., tobacco production, shoemaking, typography) that thrived in the city at that time (Baetsen et al., 2018;

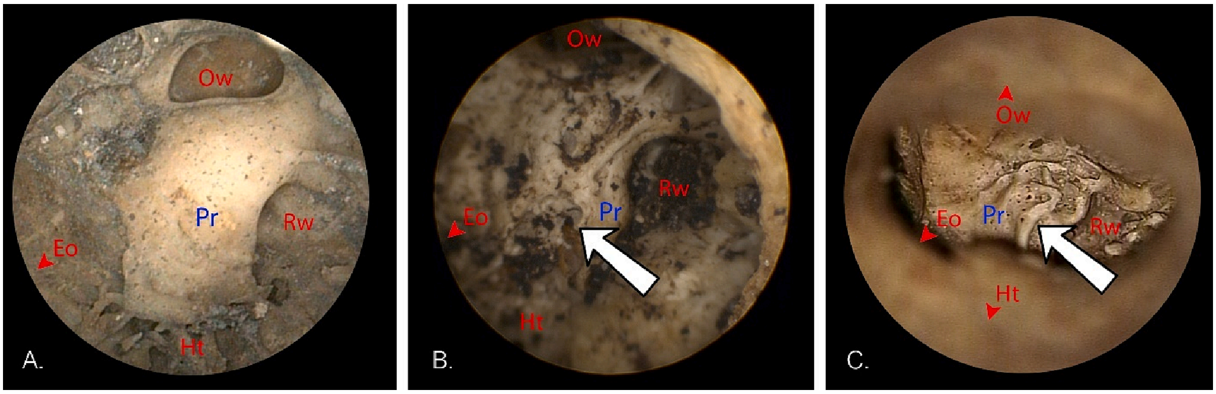

Fig. 1. Endoscopic view of the cochlear promontory (Pr). Surrounding structures have been labeled for anatomical reference: Ht = Hypotympanum; Eo = Eustachian orifice; Rw = Round window niche; Ow = Oval window. (A) No remodeling is present; the surface is smooth therefore suggesting absence of IMED. (B) Disruption of the promontory surface integrity (here considered as indicative of IMED). The white arrows emphasize substantial resorption of the inferior portion of the promontory, contrasting with Fig. 1-A where the smooth promontorial surface extends towards the hypotympanum between the round window niche and the eustachian orifice. Sharp margins on the inferior surface (indicated by the arrow) suggest limited remodeling of the lesion. (C) Bone growth in the form of 'spicule formation' superiorly from the round window. The white arrow highlights distinct bone formation on top of the otherwise smooth cochlear promontory surface. Pictures taken by M. Casna and T. D. Bruintjes.

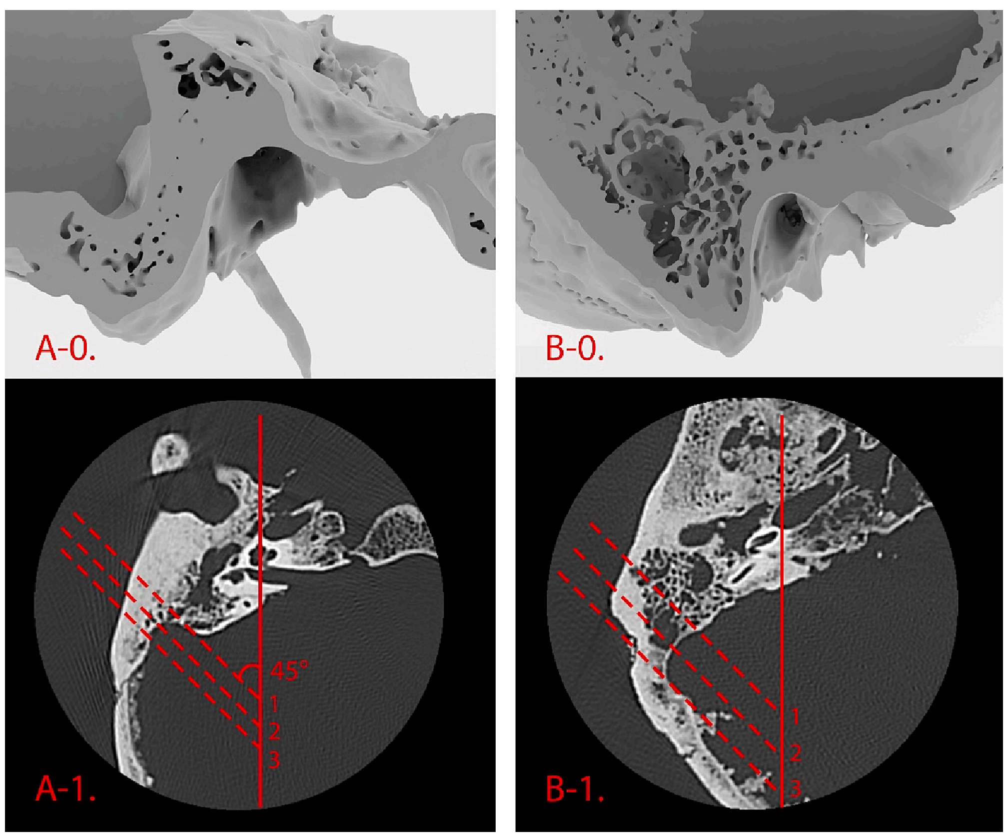

Fig. 2. Comparison of mastoid pneumatization examples, showcasing rendered (A-0 and B-0) and radiographical (A-1 and B-1) representations. (A): Hypopneumatization: air cells are confined to the anteromedial region of the arbitrary line passing through the most anterior point of the sigmoid sinus (Line 1). (B): Pneumatization extends towards the most posterior point of the sigmoid sinus. Figure by M. Casna and M. Lucca.

Wintle, 2000).

The Dutch post-medieval period is particularly fitting to our analysis as, despite differences in approaches, previous bioarcheological studies observed that IMED prevalence rates are usually higher in contexts associated with urbanization, low quality of housing and/or working environments, and lower levels of hygienic conditions (e.g., Krenz-Niedbała & Łukasik, 2020; Qvist & Grøntved, 2001), suggesting that it was the poorer sections of society who were the ones burdened by ear health problems the most (Roberts, 2016). Previous bioarcheological research demonstrated that infectious diseases such as syphilis, osteomyelitis, and chronic sinusitis were indeed common among this skeletal population (Casna & Schrader, 2022; Zielman & Baetsen, 2020). Additionally, otitis media (assessed through the presence of changes on the cochlear promontory according to the criteria set by Floreanova et al., 2020) was identified in 20 % of the 125 analyzed adult individuals in a recent study by Casna and colleagues (2023).

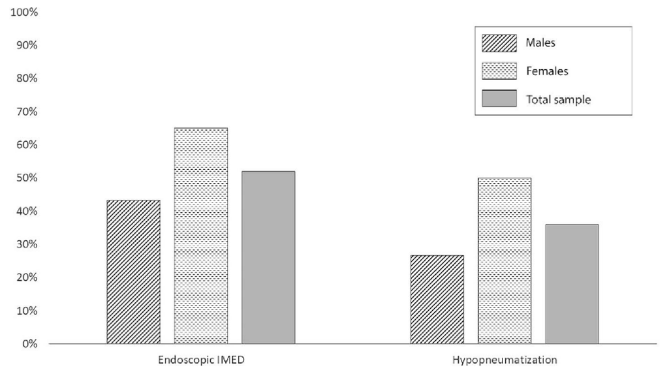

Fig. 3. Prevalence of endoscopically assessed IMED and Hypopneumatization for the sample under study. Correlation between pneumatization and bony changes of the promontory was found to be statistically significant when analyzing data from left middle ears ($p = 0.002$, $\varphi = 0.493$), but not from the right side ($p = 0.085$, $\varphi = 0.272$) (Table 2).

Table 2
Distribution of lesions under study per side within the total sample.

	Left			Right		
	Presence of bony changes on the promontory	Absence of bony changes on the promontory	Total	Presence of bony changes on the promontory	Absence of bony changes on the promontory	Total
Presence of hypopneumatization (%)	7 (14.6)	1 (2.1)	8 (16.7)	7 (14.0)	8 (16.0)	15 (30.0)
Absence of hypopneumatization (%)	10 (20.8)	30 (62.5)	40 (83.3)	7 (14.0)	28 (56.0)	35 (70.0)
Total (%)	17 (35.4)	31 (64.6)	48 (100.0)	14 (28.0)	36 (72.0)	50 (100.0)

3. Methods

3.1. Sample selection

From a database of adult individuals previously analyzed for sex and age-at-death by Casna and colleagues (2023), a specific sample for this study was selected on the basis of 1) at least one observable and intact mastoid process (left or right); and 2) at least one accessible and observable cochlear promontory (left or right). Both features were considered as observable only if they were fully intact, showing minimal to no macroscopic signs of taphonomic alteration. According to these criteria, a sample of 72 adult skeletons of mixed sex and age-at-death was selected. More details on the larger sample and on how sex and age-at-death were estimated can be found in Casna and colleagues (2023).

The presence of IMED was assessed for all 72 individuals. However, due to cost and time constraints, only 50 were chosen for CT analysis. A careful selection process was then undertaken to decide which skeletons among the 72 individuals would be subjected to CT analysis, ensuring a balanced representation among those with positive and negative IMED scores, as well as across skeletal sex and age-at-death categories (Table 1).

3.2. IMED assessment: Endoscopic analysis

For every individual, a flexible medical endoscope (Pentax, model: FNL-10RBS, ø=4mm; view angle = 30°) was inserted in both the external auditory meatuses and kept perpendicular to the skull surface. The medial wall of the middle ear (i.e., the cochlear promontory) was then examined for osseous changes considered as indicative of IMED following the standards set by Floreanova and colleagues (2020). According to Floreanova and colleagues (2020), a promontory without pathological changes presents a smooth surface (Fig. 1-A), with occasionally one or more grooves known as the promontory sulcus. IMED was scored as "present" in cases where observed lesions interrupted the integrity of the promontory surface, either due to 1) bone resorption with possible (significant) erosion (Fig. 1-B); and/or 2) isolated bone formation with clear margins in the forms of spicules or "crests" (Fig. 1-C) (Floreanova et al., 2020). Presence or absence of lesions was recorded both by side and per individual. Within one individual, IMED was scored as "present" whenever at least one cochlear promontory (i.e., left or right) showed one or more of the lesions mentioned above.

3.3. IMED assessment: Image acquisition and CT analysis

The 50 crania were radiologically analyzed through computed tomography at the Radiology Department, Leiden University Medical Center (LUMC). CT scans were obtained with a Canon Aquilion One scanner (Canon Medical Systems), according to the following scanning protocol: voltage on the X-ray tube 120 kV, tube current 150 mA, slice thickness 0.5 mm. To facilitate the scanning of the mastoid process, each skull was laid out in anatomical position on a polystyrene ring. CT scans were saved as DICOM files and later imported into a software for image visualization (3D Slicer for Windows, v.5.0.3).

Scoring criteria for mastoid pneumatization (i.e., presence/absence of childhood IMED) were adapted from the clinical classification system presented by Han and colleagues (2007). Originally, Han and colleagues (2007) arbitrarily based their observations on the section where the malleoincudal complex "*appears as an ice cream-cone shape*" (Han et al., 2007, 1112). Because in archaeological samples the malleus and incus (if present at all) are often not in their natural position, we based our observations on the slice where the external rim of the auditory meatus disappeared from view. Here, for each CT scan three parallel lines angled at 45° in the anterolateral direction were applied at positions in which each line crossed, respectively: 1) the most anterior point of the sigmoid sinus at the junction with the petrous bone; 2) the most lateral aspect along the transverse plane of the sigmoid groove; and 3) the most posterior point of the sigmoid sinus (Han et al., 2007).

Table 3
Distribution of lesions under study per individual within the total sample.

	Presence of bony changes on the promontory	Absence of bony changes on the promontory	Total
Presence of hypopneumatization (%)	16 (32.0)	2 (4.0)	18 (36.0)
Absence of hypopneumatization (%)	9 (18.0)	23 (46.0)	32 (64.0)
Total (%)	25 (50.0)	25 (50.0)	50 (100.0)

Hypopneumatization was considered as present when air cells remained anteromedial to the line that was drawn at the most anterior point of the sigmoid sinus (Fig. 2-A). Whenever the air cells crossed that line, extending towards and/or beyond the most posterior point of the sigmoid sinus, the mastoid process was considered as pneumatized, and hypopneumatization was therefore scored as absent (Fig. 2-B) (Han et al., 2007). Presence or absence of hypopneumatization was recorded both by side and for individual. Within one individual, hypopneumatization was scored as "present" whenever at least one mastoid process (either left or right) showed reduced mastoid air cells size.

3.4. Statistical analysis

To statistically test co-occurrence of skeletal lesions, Pearson's chi-squared test was calculated using IBM SPSS Statistics for Windows, v.29. In the cases where expected cell count was below 5, Fisher's exact test was used instead. In all statistical tests, a p-value ≤ 0.05 was considered to be statistically significant. As multiple tests were conducted on the same samples, significance levels were adjusted using a final Bonferroni corrected p-value of ≤ 0.01 to account for familywise error.

Furthermore, a Phi coefficient (φ) was employed to assess the strength and direction of the relationship between lesions, providing a quantifiable measure ranging from -1 to $+1$ to determine the strength of their association. Values closer to these extremes signify stronger relationships, while values near zero denote weak to no-discernible association (Chan, 2003; Davenport & El-Sanhurry, 1991). In this paper, a Phi coefficient $0.3 \leq \varphi \leq 0.5$ was considered as "fairly strong". Phi coefficients between 0.6 and 0.8 were considered as "moderately strong" according to Chan (2003).

4. Results

In the final sample of 50 crania, 25 individuals showed signs of bony changes of the cochlear promontory, of which there were 13 males and 12 females. CT analysis revealed that 18 of those 50 individuals (36 %) showed hypopneumatization, 8 male individuals and 10 female individuals, respectively (Fig. 3).

At the level of the individual, hypopneumatization and bony changes on the cochlear promontory co-occurred in 16 individuals, while 23 individuals showed no lesions at all (Table 3). Statistical analysis revealed moderately strong positive correlation between pneumatization and bony changes of the cochlear promontory at the level of the individual ($\chi^2 = 17.01$, $p < 0.001$, $\varphi = 0.583$). Furthermore, correlation between hypopneumatization and changes on the cochlear promontory were found to be significant for males ($p = 0.009$, $\varphi = 0.537$) and nearly significant for females ($p = 0.020$, $\varphi = 0.612$) (Table 4).

5. Discussion

In recent years, bioarcheologists have considered erosion and bone formation on the cochlear promontory surface as indicative of infectious processes within the middle ear (Collins, 2019; Floreanova et al., 2020; Roumelis, 2007). The observation of the cochlear promontory is relatively straightforward for bioarcheologists as 1) it is directly accessible with the use of a simple endoscope and/or microscope; and 2) due to its location within the middle ear canal, it is typically well-preserved as it is not subjected to aggressive taphonomic processes, ensuring its integrity for observation (Pinhasi et al., 2015). However, as noted by Floreanova and colleagues (2020), no clinical proof is present to confirm that changes on the cochlear promontory are linked to infectious episodes in the middle ear. At the level of the individual, our results showed moderately strong statistical correlation between changes on the promontory and hypopneumatization of the mastoid process (a strong indicator for childhood IMED), overall suggesting that observation of the cochlear promontory may be a reliable and accessible strategy for diagnosing IMED in past populations. This is further supported by the fact that, while we observed that 16 (32 %) of the 50 analyzed individuals showed both changes on the cochlear promontory and hypopneumatization, 23 (46 %) presented no signs of either.

When investigating the association per side (i.e., left and right), it was interesting to note that a statistically significant association was found between changes of the cochlear promontory and mastoid hypopneumatization in left middle ears but not in right ones. While this can be a direct effect of our limited sample size, it is also worth considering that unilateral presentations of IMED exist in clinical settings and are today more common than bilateral manifestations (e.g., Leibovitz et al., 2007). This could potentially contribute to the variations observed in our tests, especially when diagnosis relied on single-sided CT scans (two individuals had unobservable left mastoid processes). Furthermore, mastoid hypocellularity may in some cases be caused by an inflammatory process (i.e., mastoiditis) obliterating fully-pneumatized air cells at any point of the life of an individual (Bluestone, 1998; Fleischer, 1979). However, this is a much rarer occurrence at least in archaeological samples, as evidenced by Flohr and colleagues (2009) in their investigation of 151 temporal bones in which only 1.3 % showed bone proliferation within existing air cells due to mastoiditis. Another possible explanation for the observed difference in significance between left and right sides is that the changes we observed on the cochlear promontory and hypopneumatization are not indicative of the same infectious episode. In fact, a noteworthy number of individuals (left: 20.8 %; right:

Table 4
Distribution of lesions under study per skeletal sex within the total sample.

	Males			Females		
	Presence of bony changes on the promontory	Absence of bony changes on the promontory	Total	Presence of bony changes on the promontory	Absence of bony changes on the promontory	Total
Presence of hypopneumatization (%)	7 (23.3)	1 (3.3)	8 (26.6)	9 (45.0)	1 (5.0)	10 (50.0)
Absence of hypopneumatization (%)	6 (20.0)	16 (53.4)	22 (73.4)	3 (15.0)	7 (35.0)	10 (50.0)
Total (%)	13 (43.3)	17 (56.7)	30 (100.0)	12 (60.0)	8 (40.0)	20 (100.0)

14 %) presented changes on the cochlear promontory in absence of hypopneumatization. While this has undoubtedly affected the results of our statistical analysis, we argue that it does not necessarily contradict our initial hypothesis that observation of the cochlear promontory may be a valid method to test for IMED in past populations. In fact, it must be remembered that mastoid hypopneumatization most commonly attest to childhood recurring episodes of IMED (Aoki et al., 2010), while changes on the cochlear promontory may occur throughout the life of an individual. Although ear infections tend to be more common during childhood, adults can still be affected, even more so in contexts where clinical care is not readily available such as the post-medieval Netherlands (Rijk et al., 2021; van Poppel, 2018). Therefore, it is possible for cochlear promontory changes and hypopneumatization not to be indicative of the same infectious episode. However, we argue that even if these episodes are different, it remains unlikely for them to be entirely unrelated: in fact, within the total sample, hypopneumatization was present in only 2 individuals who did not show promontory alteration, suggesting that some kind of relationship exists between mastoid pneumatization and changes on the cochlear promontory.

While hypopneumatization occurred evenly among males and females, we observed a stronger (albeit not statistically significant) correlation with changes on the cochlear promontory in females (φ = 0.612) than in males (φ = 0.537). Historically, it is possible that in Arnhem a gender-based division of labor may have influenced people's health to some extent. In the post-medieval period in the Netherlands, children were usually employed in small-scale manufacturing regardless of their gender (Wintle, 2000). This likely exposed them to similar risk factors for IMED, hence the even distribution of hypopneumatization across the two skeletal sex categories. Adults, on the other hand, were subjected to a stricter gender-based division of labor: men were more often involved in activities that would expose them to risk factors such as dust, fumes, gases, and vapors (e.g., tobacco toasting, leather processing), while women worked the same amount of hours but were usually involved in activities that would have limited their exposure to environmental risk factors for IMED (e.g., button and pipe making) (van der Woud, 2010; Wintle, 2000). According to the distribution of lesions presented in Table 4, most individuals in the female category (45 %) showed both hypopneumatization and changes on the cochlear promontory. On the other hand, 20 % of male individuals who showed changes on the cochlear promontory also showed a normally-pneumatized mastoid, suggesting that, while IMED episodes in females were more strictly related to their childhood health, in males IMED episodes occurred independently to their childhood experiences, perhaps because their working situation would expose them to a greater amount of risk.

Another possible interpretation of the observed differences among skeletal sex categories is our sample size. While we selected the individuals suitable for this study to the best of our capacities, when breaking down the sample in lesion and sex groups we encountered some imbalance. For example, the number of male individuals not showing hypopneumatization is more than double the number of females. While we believe that the results we presented may contribute to the development of improved diagnostic for IMED in past populations, as well as to the understanding of the impact ear infections had on the life course of people, it must be noted that our small sample size is an obvious drawback of our study, meaning our findings cannot be generalized, and more importantly that research on a bigger sample size is advised to potentially reveal different patterns. Secondly, important to note is that genetic factors may play a role in the development of mastoid air cells. While most clinical studies today associated hypopneumatization to early-life episodes of ear disease (Baklaci et al., 2019; Khan et al., 2022; Roy et al., 2015; Sadé et al., 2009) (i.e., environmental theory), some evidence exists that the pneumatization of the mastoid cells is regulated by genetic factors, and it is an inherited reduced pneumatization to actually predisposes children to IMED (i.e., genetic theory) (Sade & Hadas, 1979; Schulter-Ellis, 1979; Ueda & Eguchi, 1962). Yet, most recent clinical studies investigating mastoid pneumatization predominantly support the environmental theory, thereby indicating that chronic inflammation of the middle ear in children inhibits the pneumatization process within the temporal bone (e.g., Baklaci et al., 2019; Khan et al., 2022; Roy et al., 2015). Therefore, in this study we were confident in considering hypopneumatization as an indicator of childhood ear infection.

Overall, our study holds significance for bioarcheology and paleopathology. It is reasonable to assume that in the past complications stemming from IMED were considerably more prevalent compared to the present era. Investigating the frequency of these conditions within historical and archaeological populations remains a crucial focal point of study for paleopathologists, as the etiologies of IMED are significantly linked not only to physiological and genetic factors (Kvaerner et al., 1997), but also to environmental and cultural behaviors (Kong & Coates, 2009). Our paper underscored the significance of systematically and consistently studying IMED prevalence rates through well-defined and easily applicable criteria, as the investigation of infectious middle ear disease opens new perspectives for understanding past societies and provides insights into the daily lives (as well as into the health challenges) of archaeological populations.

6. Conclusion

The primary objective of this paper was to examine various approaches to studying infectious middle ear disease (IMED) in historical contexts, focusing on the observation of the cochlear promontory and mastoid pneumatization. We observed statistically significant associations between the presence of bony changes on the cochlear promontory and hypopneumatization of the mastoid process at the level of the individual, on the left side, but not on the right side. While our findings hint at a potential correlation between bony changes on the promontory and mastoid hypopneumatization, caution is advised in concluding that this supports the use of the cochlear promontory surface as an evaluation method for IMED. Additional research incorporating a larger sample size is necessary to validate this potential association.

Despite these limitations, our study provides new insights into the impact of infectious ear disease on the health of both children and adults in the Netherlands during the post-medieval period. While previous studies already showed that chronic IMED was common among adults in post-medieval Arnhem (Casna et al., 2023), we observed that it was also likely affecting the health and wellbeing of children. Our findings have implications for the understanding of past health patterns, and possibly on the link between childhood and adult morbidity. Further research on larger samples and with a focus on gender-specific patterns could provide a more comprehensive understanding of the dynamics of infectious ear disease in the past and its impact on population health.

CRediT authorship contribution statement

Maia Casna: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Joost J.H. Roelofs:** Software, Methodology. **Rachel Schats:** Writing – review & editing, Supervision. **Berit Verbist:** Resources. **Tjasse D. Bruintjes:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Dataset was uploaded on an external repository for archaeological data. The complete citation is available in the manuscript, under: "Additional Information"

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Additional Information.

The datasets generated and analyzed during the current study, as well as the original pool from which the total sample was drawn, are available at Casna, Maia, 2023, "*Data for: "Reliability of Cochlear Promontory Surface Observation in Studying Ear Infections in Archaeological Human Skeletal Remains"*", doi: 10.17026/AR/AHC21L, DANS Data Station Archaeology

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