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The air we breathe: a study into the impact of historical socioeconomic changes on the respiratory health of past Dutch populations (ca. 470-1850 CE)

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The air we breathe

**A study into the impact of historical socioeconomic changes
on the respiratory health of past Dutch populations (ca. 470-1850 CE)**

Maia Casna

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The air we breathe

A study into the impact of historical socioeconomic changes
on the respiratory health of past Dutch populations (ca. 470-1850 CE)

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CHAPTER 1

Introduction

Today, respiratory disease represents a substantial worldwide health burden: almost 545 million people presently live with a chronic respiratory condition, of which at least 4 million die annually (Soriano et al., 2020). These diseases, which primarily affect the lungs and airways, encompass a broad spectrum of conditions, from common ailments such as seasonal colds to life-threatening diseases (e.g., chronic obstructive pulmonary disease, lung cancer) that today represent the third leading cause of death worldwide (Figure 1.1) (WHO, 2023).

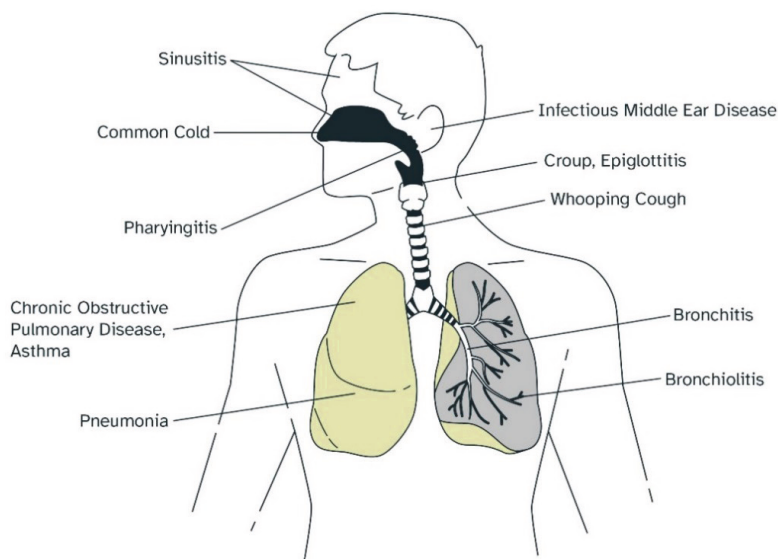


Figure 1.1. Diagram of the human respiratory system, highlighting a selection of associated respiratory conditions. Diagram adapted from storyset / Freepik.

While recent advancements in medical science have improved our understanding of respiratory disease, new challenges continue to emerge, reflecting the evolving nature of respiratory health threats in response to ever-transforming living and working environments (Eguiluz-Gracia et al., 2020; Soriano et al., 2020). In the past decade, the World Health Organization has striven to bring attention to the link between respiratory disease and poor air quality, as rising emissions associated with urbanization and industrialization have been proven to contribute significantly to the global prevalence and incidence of most respiratory conditions (Almetwally et al., 2020; Doiron et al., 2019; Tiotiu et al., 2020; WHO, 2016). However, while the correlation between air pollution and respiratory disease is today well-established, additional factors have clinically been recognized to play a significant role in the spread of these conditions, including socioeconomic inequalities, access to healthcare, and exposure to tobacco smoke (i.e., Badley et al., 1973; Kjaergaard et al., 1989; Soriano et al., 2020). These multifaceted etiologies underscore the complex responsiveness of respiratory disease to environmental factors, highlighting an intricate interplay between external conditions and the prevalence, severity, and spread of these health challenges.

1.1. Respiratory diseases in the past

Because of its link to air pollution, the high burden of respiratory disease is often considered to be a product of the modern world. However, chronic respiratory disorders have been historically documented since the emergence of the first medical science, suggesting these conditions were a recurring issue in the past as well (Brimblecombe, 1987; 2018). One of the earliest pieces of historical evidence of respiratory diseases in ancient populations can be traced back to Hippocrates in the 5th century BCE (Stefanakis et al., 2020). Hippocrates classified respiratory infections as either acute or chronic and emphasized the importance of medical intervention for patients with severe symptoms (Stefanakis et al., 2020). Five hundred years later, the Roman philosopher and statesman Lucius Annaeus Seneca observed a conspicuous connection between air pollution and respiratory health, highlighting the adverse impact of Rome's "infamous air"¹ on his own respiratory system (Brimblecombe, 1987). In the 13th century, a surge of grievances about pervasive smoke and its detrimental effects on residents' health led to the establishment of several commissions to investigate air pollution in London and in other European cities (Brimblecombe, 1987). However, despite efforts to regulate air quality, the rapid urbanization that swept across the European continent in the late- and post-medieval eras posed considerable challenges to any form of control, and air pollution remained an important issue throughout the 17th and 18th centuries (Brimblecombe, 2003; Fowler et al., 2020; Heidorn, 1978).

Contemporary historical data from diverse geographical and temporal contexts provide a comprehensive account of the concerns our ancestors held regarding air pollution (e.g., Brimblecombe, 1987; Fowler et al., 2020; Huisman, 2018; Pancino, 2015). However, while these documents offer valuable insights into historical health challenges, they often lack information on various aspects of respiratory disease, such as variation in occurrence patterns among populations, the impact of socioeconomic inequalities on health, as well as individual embodied experiences (Roberts, 2016). According to clinical research, the risk for respiratory disease can vary significantly based on one's living circumstances (e.g., sex, age, pre-existing conditions) or habits, suggesting that even individuals sharing the same environment may have experienced these conditions in remarkably different ways (Bush et al., 2024; DeBolt & Harris, 2021; WHO, 2010). Previous bioarchaeological research focusing on respiratory disease and its link to socioeconomic changes typically supports the results of clinical research, highlighting a higher historical prevalence of respiratory disease in heavily industrialized, impoverished populations compared to those from less industrialized, wealthier contexts (e.g., Bernofsky, 2010; Lewis, 2002; Lewis et al., 1995; Western & Bekvalac, 2019). However, while these studies have contributed to shaping the trope of how life dramatically worsened with urban development, it should be noted that they have only sporadically considered scenarios outside of England,

1 In the first century BCE, Rome residents referred to their city's smoke cloud as *infamis aer* ("infamous air"). The problem of air pollution in Ancient Rome was a recurring theme in the works of local poets and writers, who frequently highlighted its role in darkening the city's temples and monuments (Brimblecombe, 2018).

whose urban and industrial histories are among the most impactful in the European continent (Lee et al., 2024).

Recent, more diverse bioarchaeological analyses of diverse urban contexts across different time periods and regions suggest that the impacts of medieval and post-medieval developments on human health varied throughout Europe, likely reflecting the specific time, place, and population rather than responding to a uniform pattern (Betsinger & DeWitte, 2021). This is especially relevant when studying Dutch urbanization, as the Netherlands developed much more quickly than other European realities, but with considerable variation among cities (Blockmans, 2011). Due to the political and economic disconnection that persisted until the 19th century, Dutch towns experienced growth and decline asynchronously, achieving different levels of commercialization, specialization, and industrialization at different times (Blockmans, 2011; Brusse & Mijndhardt, 2011; de Vries, 1984). As a consequence, issues commonly associated with urbanization and industrialization, such as health risk factors and social inequalities, varied greatly from city to city, likely leading to significantly different life experiences and health challenges (Blockmans, 2011; Hoppenbrouwers, 2001).

Building on these unique historical perspectives, this study investigates the impact of changes through time and space of respiratory disease in historic Netherlands. Through the analysis of archaeological human skeletal remains, it examines how various demographic and socioeconomic factors influenced the occurrence of respiratory disease among 13 historical Dutch populations (ca. 470-1850 CE).

1.2. Research questions and objectives

The purpose of this study is to enhance current bioarchaeological knowledge on respiratory health by investigating the prevalence rates of different respiratory diseases (i.e., chronic maxillary sinusitis, infectious middle ear disease, and pleural inflammation) across the early, late, and post-medieval periods in the Netherlands. These conditions were specifically selected because they are commonly observed macroscopically in skeletal remains and have been widely studied in bioarchaeology as they provide valuable insights into the effects of respiratory infections and environmental stressors (e.g., Bernofsky, 2010; Boyd, 2020; Davies-Barrett et al., 2023; Krenz-Niedbała & Łukasik, 2020; Roberts, 2007). By examining these conditions, the present study aims to analyze how their prevalence varied in relation to risk factors commonly associated with urbanization, such as air pollution, overcrowding, tobacco smoke, and socioeconomic status.

To date, most bioarchaeological studies on respiratory disease have focused on differences in prevalence rates across various environments, often highlighting how, within a given time period, urban populations typically exhibit higher rates of respiratory conditions compared to their rural counterparts (e.g., Krenz-Niedbała & Łukasik, 2020; Lee et al., 2024). The present study aims to better frame results within a wider archaeological context, achieving a more complete understanding of the Netherlands' social past by not only taking into account different living

environments, but also including individuals from various different time periods. In doing so, the following research questions will be addressed:

Research Question 1: *How did increasing urbanization in the Netherlands influence rates of respiratory diseases in different environments (e.g., rural, urban) in the time period under study?*

This question aims to examine how the progression of urbanization over time affected respiratory disease rates in various environments. By investigating diachronic differences in urbanization, I aim to understand how changes in urban development were reflected in the prevalence of respiratory diseases in both rural and urban settings.

Research Question 2: *What are the differences in the prevalence, risk factors, and outcomes of respiratory diseases among urban populations of differing socioeconomic status?*

Socioeconomic status is widely acknowledged as a major risk factor for respiratory disease (e.g., Rocha et al., 2019). In the Dutch post-medieval period, lifestyles were significantly shaped by wealth and socioeconomic class (van der Vlis, 2001; Wintle, 2000). With this research question, I aim to test the hypothesis that individuals from the lower socioeconomic strata were more severely impacted by respiratory disease than their wealthier counterparts.

Research Question 3: *To what extent did urbanization and socioeconomic developments affect the respiratory health of children in the Northern Low Countries?*

According to clinical research, children can be more susceptible to respiratory disease due to several physiological, behavioral, and cultural factors (Carraro et al., 2014). In addition, poor living conditions and exploitative working environments in the past are likely to have negatively influenced the (respiratory) health of younger populations (Hendrick, 2009; Kirby, 2013). However, until recently non-adults have been somewhat overlooked in bioarchaeological research on respiratory disease, resulting in a gap in our understanding of how these factors may have affected their health. By including this research question, I aim to obtain a comprehensive overview of the populations under study (i.e., both adults and non-adults) and to address demographic variations in susceptibility to respiratory disease.

Research Question 4: *To what extent did tobacco consumption contribute to the burden of respiratory disease in past Dutch populations?*

Today, tobacco smoking is considered among the main risk factors for chronic respiratory disease (Salvi, 2014). In the Netherlands, tobacco was introduced in the 1600s and immediately became popular among all socioeconomic groups (Brongers, 1964). My aim is to investigate how

tobacco consumption specifically influenced respiratory disease rates in urban environments. By examining this relationship, my aim is to enhance our understanding of how tobacco consumption fits within the broader context of urbanization and socioeconomic changes, and how these factors collectively impacted past health.

1.3. Dissertation outline and structure

In this chapter, I have provided a comprehensive introduction to this dissertation, presenting the significance and objectives of this study, as well as the research questions it aims to answer. I laid the foundations for the subsequent chapters by discussing the prominent role that respiratory disease has had throughout human history, and how they have been addressed by (bio) archaeological research so far. **Chapter 2** provides a clinical overview of the respiratory diseases under investigation in this study (i.e., chronic maxillary sinusitis, infectious middle ear disease, and pleural inflammation). Additionally, it offers useful information on the various factors that trigger respiratory tract inflammation, and discusses how the human skeleton responds to such inflammation, ultimately leading to the development of lesions that are interpreted as indicators of respiratory disease in bioarchaeological research.

Chapters 3 to 8 present several published papers that address the sub-questions outlined earlier. Specifically, **Chapter 3** is a research article that examines the impact of urbanization and industrialization on respiratory diseases over time, offering a comprehensive diachronic overview of respiratory health in the Netherlands from the early Middle Ages to the post-medieval period. The findings presented in this chapter suggest that factors such as increased interaction between urban and rural areas, higher population densities, and the intensification of agricultural production significantly influenced the respiratory health of the studied populations in both rural and urban settings.

Chapter 4 examines socioeconomic disparities during the post-medieval period and their impact on the wellbeing of four populations with varying levels of wealth, focusing on patterns of respiratory health and non-specific stress markers. The results are surprising, revealing no consistent or significant variations in respiratory health or the prevalence rates of stress markers across the different socioeconomic groups. This suggests that, despite differences in wealth leading to varied life experiences, health challenges (especially those related to respiratory diseases) remained relatively consistent across all socioeconomic strata.

Chapter 5 presents data on differences in sinusitis and non-specific stress markers over time in a previously understudied setting (i.e., maritime cities). By analyzing prevalence rates in relation to the development of the sea industry associated with the Dutch West and East India Companies, we observed that de-urbanization and economic decline of maritime cities in the post-medieval period adversely affected the respiratory health of the populations under study, possibly influenced by factors such as working conditions and food availability.

While data presented up until Chapter 5 only consider adults, **Chapter 6** analyses how the aforementioned risk factors impacted respiratory health among non-adults. Similar to the results presented in Chapters 3 and 4, rates of sinusitis increased over time, suggesting that urbanization and industrialization impacted the respiratory wellbeing of both adults and non-adults alike.

Finally, **Chapter 7** and **Chapter 8** present data on tobacco consumption in four diachronic populations and examine its impact on their respiratory health. These chapters highlight the challenges of identifying specific risk factors within the osteoarchaeological record and suggest that tobacco's effects on respiratory health likely varied according to environmental conditions and differing levels of exposure to air pollution.

Chapter 9 concludes this dissertation offering a thorough discussion of the findings presented in the previous chapters. It reflects on how methodological and archaeological limitations have influenced the overall conclusions and identifies areas where further research is needed. This chapter also explores potential future directions for bioarchaeological research on respiratory diseases, offering recommendations to refine methodological approaches and to enhance our understanding of the historical impact of environmental and socioeconomic factors on human respiratory health.

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CHAPTER 2

Clinical background and paleopathology of
respiratory disease

Building on previous paleopathological research on respiratory disease, this study centers on three specific conditions: chronic maxillary sinusitis, infectious middle ear disease, and pleural inflammation. To better understand differences in respiratory disease prevalence rates in archaeological populations, a thorough understanding of modern clinical data on each of these conditions is essential. Thus, the next three sections provide a clinical background on sinusitis, infectious middle ear disease, and pleural inflammation, respectively. Each section covers the anatomy of the organs and tissues affected by inflammation, the pathogenesis and etiology of each disease, as well as the clinical evidence for inflammation-related bone changes. Finally, this chapter concludes with a concise overview of existing bioarchaeological research on respiratory diseases, establishing the foundation for the analytical framework of this dissertation.

2.1. Chronic maxillary sinusitis

In the clinical practice, maxillary sinusitis is defined as the inflammation of the mucous membrane lining the maxillary sinuses (Slavin et al., 2005, S21). Symptoms are varied, but typically include nasal congestion, headache, cough, and purulent nasal discharge. However, depending on the etiology and complications, they may also include fever, fatigue, dental pain, facial pressure, and/or earache (Brook, 2009). Epidemiological studies currently report a global prevalence of chronic sinusitis (defined as symptoms lasting 8 weeks or longer) ranging from 5% to 12% (de Loos et al., 2019; Slavin et al., 2005). In the Netherlands specifically, approximately 500,000 individuals are diagnosed with chronic sinusitis each year, making it one of the most prevalent health conditions among the Dutch population (KNO, 2010).

2.1.1. Anatomy of the sinuses

The paranasal sinuses consist of eight air-filled cavities located on both sides of the facial region of the skull whose primary function is to act as the first line of defense against potential pathogens (Figure 2.1) (Rosen & Pletcher, 2016). The inner surface of each sinus is lined with the mucosa (or mucous membrane), a layer of ciliated soft tissue interspersed by goblet cells producing mucus (Brook, 2009; Mularczyk & Welch, 2024). The main function of mucus (a thin liquid consisting of water, salts, and immune cells) is to trap pathogens and particulate matter inhaled during breathing. If the paranasal sinus system functions properly, both mucus and any trapped particles are then effectively drained into the nasal cavity through a small, tubular opening known as the ostium (Brook, 2009).

The maxillary sinus, the largest of the paranasal sinuses, is situated bilaterally within the maxillary bone. The maxillary bone forms the majority of the sinus cavity, with the exception of the roof, which is formed by the orbit floor (Mularczyk & Welch, 2024). Unlike the frontal and sphenoid sinuses, the maxillary sinus is present at birth and keeps increasing in size until approximately the age of 18 years, expanding vertically, horizontally, and anteroposteriorly (Lorkiewicz-Muszyńska et al., 2015).

The growth of the maxillary sinus occurs unevenly during childhood. The first phase of rapid development lasts for 2–3 years after birth, followed by a slower growth phase that extends until approximately 7–8 years of age and into puberty (Lorkiewicz-Muszyńska et al., 2015). Once the maxillary sinus is fully formed (i.e., it has reached a volume of ca. 15–20mL), remodeling and expansion of the sinus floor into the alveolar bone of the maxilla may continue, particularly in response to tooth loss (Brook, 2009).

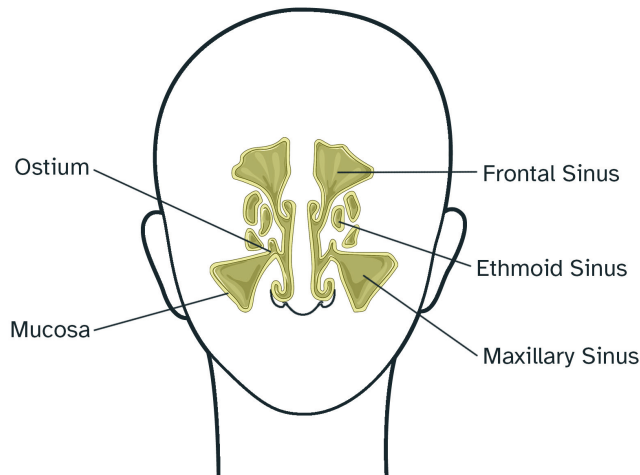


Figure 2.1. Diagram showing the coronal view of the paranasal sinuses. Aspects of diagrams adapted from Servier Medical Art library. Licensed for use by CC BY 4.0.

2.1.2. Pathogenesis and etiology

From a physiological standpoint, sinusitis develops when the ostium becomes blocked, hindering the proper drainage of mucus. The ostium of the maxillary sinus is particularly susceptible to blockage, as its position high on the sinus medial wall hinders gravitational drainage (Ah-See & Evans, 2007; Wald, 1995). The accumulation of mucus creates an ideal environment for the proliferation of bacteria and viruses, which in turn exacerbates inflammation of the mucosa and, consequently, the underlying bone surface (Dykewicz & Hamilos, 2010; Kocak et al., 2002; Slavin et al., 2005).

Inflammation of the mucosa (commonly triggered by a viral or bacterial upper respiratory tract infection or an allergic reaction) is one of the most common causes of ostial blockage, as the swollen tissue resulting from inflammation can lead to a narrowing of the ostium (Brook, 2009; Dykewicz & Hamilos, 2010; Slavin et al., 2005). Various other factors can predispose an individual to mucosal inflammation or ostium obstruction, such as craniofacial anomalies (e.g., cleft palate), physiological variations, nasal blockages (e.g., polyps and tumors), nasal injuries or fractures, cystic fibrosis, inherited and/or acquired immune deficiencies, specific infectious diseases

(e.g., leprosy and tuberculosis), and asthma (Choi et al., 2012; Kaya et al., 2017; Le et al., 2016). While determining the impact of most of these factors on historical sinusitis prevalence rates is challenging, according to Lewis and colleagues (1995) many of these factors (e.g., congenital disease, tumors, immune deficiencies) are expected to have had minimal influence, as individuals suffering from such conditions were unlikely to survive into adulthood. Conversely, it is likely that pre-existing upper respiratory infections, allergies, and poor air quality may have been among the greatest contributors to sinusitis in certain time periods (Davies-Barrett, 2018).

In the case of poor air quality, it is well established today that airborne particulates and pollutants can irritate the mucosa and, subsequently, trigger inflammation (e.g., Leland et al., 2022; Trevino, 1996). This not only includes chemicals from industrial activities, but also tobacco smoke and the domestic burning of biomass fuels, both of which have been associated with chronic sinusitis (Hoover et al., 1997; Lieu & Feinstein, 2000). Additionally, environmental factors such as inadequate ventilation of living and/or working spaces, overcrowding, low humidity, and poor hygienic conditions increase the risk of sinusitis due to heightened exposure to viral and bacterial pathogens (e.g., Dykewicz & Hamilos, 2010; Hoover et al., 1997).

Another common cause of sinusitis is the invasion of the sinus by pathogens originating from dental infections (i.e., odontogenic sinusitis) (Patel & Ferguson, 2012). The roots of the permanent maxillary molars lie just beneath the floor of the maxillary sinus, separated by only a thin layer of bone. This close proximity allows dental infections to easily spread into the sinus cavity, leading to maxillary sinusitis (Patel & Ferguson, 2012). Nowadays, most odontogenic sinusitis cases are attributed to complications arising from modern dental healthcare procedures (Arias-Irimia et al., 2010). However, dental caries can still result in sinusitis by infecting the dental pulp and causing inflammation of the surrounding tissues (Mehra & Jeong, 2009). Chronic abscesses may also lead to resorption of the maxillary bone between the tooth apex and the sinus, forming a direct pathway for infection known as oroantral fistula (Mehra & Jeong, 2009).

2.1.3. Bone involvement

The first clinical evidence of bone involvement in maxillary sinusitis in humans was presented by Tovi and colleagues (1992), who documented a series of histological case studies highlighting a significant periosteal reaction and bone formation within some of the sinuses they analyzed. Most recently, several reports of bone involvement in chronic sinusitis have come from observations of sinus wall thickening through computed tomography, leading to the development of clinical scoring systems which evaluate the extent of bone involvement (Georgalas, 2013; Leung et al., 2016; Snidvongs et al., 2013).

Table 2.1. Skeletal changes categories considered as evidence of chronic sinusitis, as presented by Boocock and colleagues (1995, denoted by *) and Merrett and Pfeiffer (2000, denoted by †). Adapted from Davies-Barrett (2018, Table 3.1; 3.2).

Skeletal change category	Description
Pitting*	Fine clusters of pits (i.e., bone resorption) often found in association with other types of bone change.
Spicules*	Small outgrowths of bone (2-4 mm) located on top of the periosteal surface of the sinus. Clusters of spicules are common and often observed in the form of stellate plates of bone of varying dimensions. These are among the most frequently observed bone changes in previously published bioarchaeological studies on sinusitis.
Remodeled spicules*	Remodeling of spicules into the sinus walls.
White pitted bone*	Localized areas of bone exhibiting extensive pitting, characterized by a white coloration.
Plaque†	Layers of smooth or dense, yet porous bone, with varying thickness.
Lobules†	Smooth, rounded masses of bone located on the periosteal surfaces of the sinus.
Cysts†	Hemispherical depressions in the bone presenting a smooth interior surface and a smooth rim of bone deposition.

Paleopathologists, on the other hand, have examined a broader spectrum of skeletal evidence, including bone resorption, minor bone formations on the sinus surface, and more pronounced alterations in sinus wall morphology (Table 2.1) (Boocock et al., 1995; Merrett & Pfeiffer, 2000). While most of these criteria lack a solid clinical foundation, the presence of spicule bone formations (Figure 2.2, B) has been recently identified as a possible evidence of heterotopic mucosal ossification² (Ahn et al., 2017; Meyers et al., 2019). Moreover, it is likely that the pronounced periosteal reaction identified by Tovi and colleagues (1992) is a primary factor contributing to the thickening of the sinus walls noted in various radiographic studies (e.g., Georgalas, 2013; Leung et al., 2016). This type of bone formation (encompassing the bioarchaeological categories of ‘white pitted bone’ and ‘plaque’) (Figure 2.2, C) is possibly indicative of a subperiosteal reaction stemming from inflammation, a phenomenon commonly observed in other regions of the skeleton in paleopathology (Ortner, 2003).

2 Heterotopic ossification is a pathological process with varying levels of morbidity, characterized by the abnormal formation of bone in muscle and soft tissues. In clinical settings, the term heterotopic ossification refers to bone development at any location outside the skeletal system, including sites such as muscles, tendons, ligaments, subcutaneous tissue, skin, vascular walls, or any other connective tissues (Ahn et al, 2017; Meyers et al., 2019).

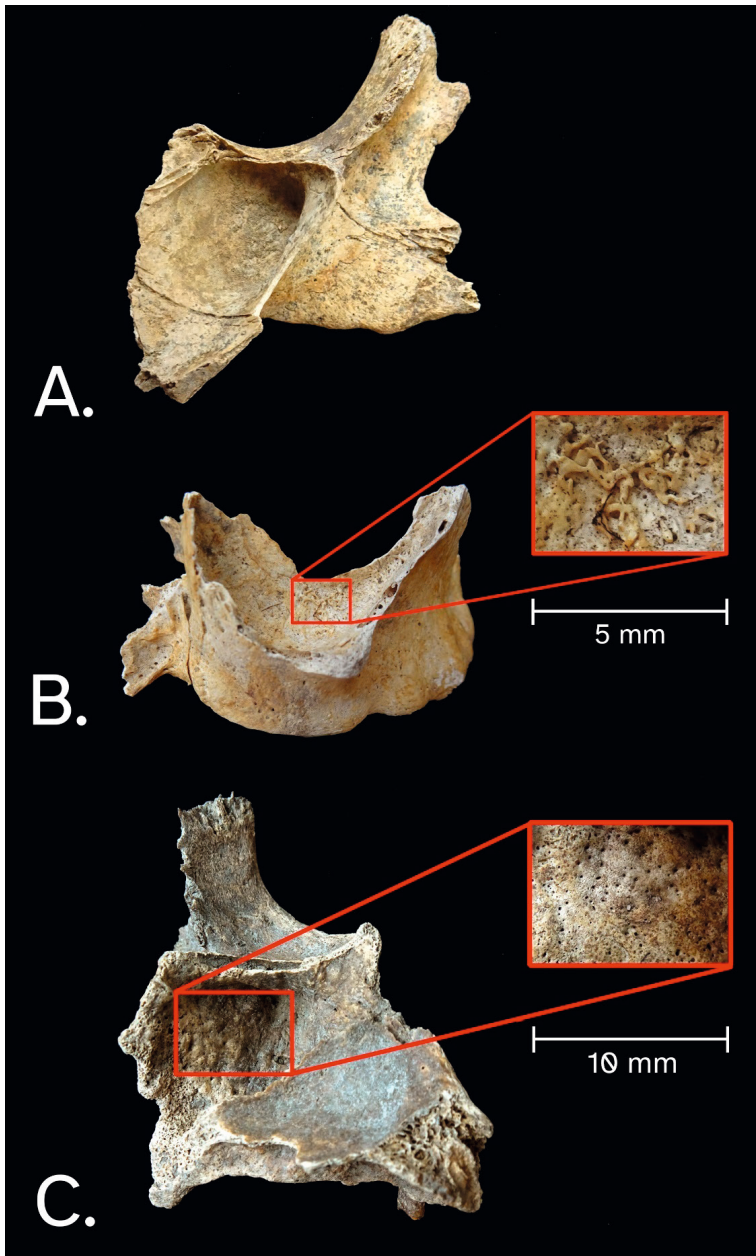


Figure 2.2. Maxillary sinus walls, viewed macroscopically. A: Sinus showing no pathological alteration. Note the smooth walls and the presence of a vascular channel impression on the inferior portion; B: Bone spicules on the medial wall; and C: Thick lamellar bone formation on the distal and anterior sinus walls. Photographs by M. Casna.

2.2. Infectious middle ear disease

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. Today, ear infections are among the most prevalent pediatric conditions, with approximately 80% of children experiencing at least one episode by the age of ten (Schilder et al., 2016). Although primarily considered a childhood condition, IMED is also prevalent in adults. For example, in the Netherlands, acute otitis media alone has an overall incidence of 5.3 cases per 1,000 person-years among individuals aged 15 and older (Rijk et al., 2021). IMED typically manifests with symptoms such as ear pain, fever, fluid drainage from the ears, reduced hearing, and, in some instances, temporary deafness (Briddell et al., 2018; Rettig & Tunkel, 2018). While these infections often resolve without medical intervention, they can result in various complications, including permanent hearing loss, speech delays, and an increased susceptibility to further respiratory infections (Aslam & Al-Qahtani, 2021).

2.2.1. Anatomy of the middle ear

The middle ear, a partially air-filled structure housed within the temporal bone, is one of three main sections of the ear, along with the outer and inner ear (Figure 2.3). It extends from the tympanic membrane to the lateral wall of the inner ear, with its primary function being the transmission of sound vibrations to the cochlea (Mansour et al., 2019).

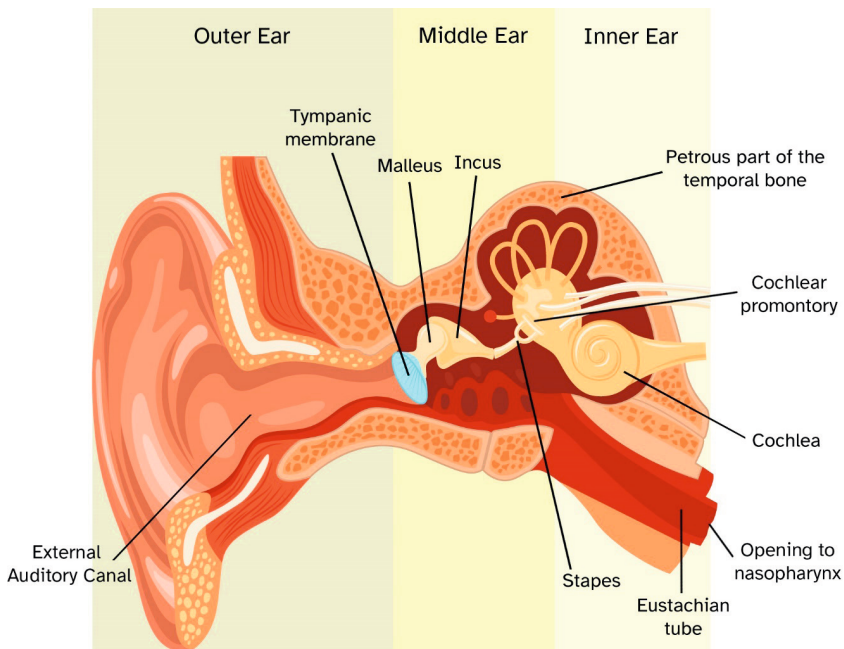


Figure 2.3. Simplified anatomy of the ear. Diagram adapted from macrovector / Freepik.

The middle ear mainly consists of the tympanic cavity, located medially to the tympanic membrane and distally to the cochlea. The tympanic cavity contains the ear ossicles (malleus, incus, and stapes) which, oscillating with the vibration of the tympanic membrane, help transmit sound waves to the inner ear (Mansour et al., 2019). Extending from the anterior wall of the middle ear towards the lateral wall of the nasopharynx there is the Eustachian tube, a fibrocartilaginous duct with the function to help equalizing the pressure between the atmosphere and the middle ear, as well as to facilitate fluid drainage (Proctor, 1967). Similar to the sinus walls, the Eustachian tube is lined with a ciliated mucous membrane, which helps to clear mucus from the middle ear by sweeping it toward the nasopharynx (Mansour et al., 2019).

The development of the middle ear starts as early as the fourth week of intrauterine life (Mansour et al., 2019). Most structures within the middle ear (e.g., the ossicles and the tympanic cavity) cease to grow at around 20 weeks in-utero, when full adult proportions are attained (Mansour et al., 2019). The Eustachian tube, in contrast, continues to grow after birth up until early adolescence, extending in length and gradually shifting diagonally to accommodate craniofacial development (Magro et al., 2021; Proctor, 1967).

2.2.2. Pathogenesis and etiology

According to clinical literature, IMED is closely linked to upper respiratory tract infections (e.g., common colds, sinusitis, and pharyngitis), with the latter being necessary for the initial onset of the former (Thornton et al., 2020). In fact, infections of the upper respiratory tract can lead to swelling of the Eustachian tube and/or the surrounding membranes, impeding fluid drainage and providing a favorable environment for viral and bacterial growth, leading to tissue inflammation (Rijk et al., 2021; Schilder et al., 2016).

The etiology of IMED is highly similar to that of sinusitis (Wald, 2011). Predisposing factors may include Eustachian tube dysfunction, immunodeficiencies, anatomical abnormalities of the palate, and chronic vitamin deficiencies (Cetinkaya & Topsakal, 2023). Furthermore, in children specifically, a shorter, horizontally-oriented Eustachian tube can impede fluid drainage in case of swelling, contributing to a higher incidence of ear infections among pediatric populations (Massa et al., 2015). The living environment is also considered to be a major impacting factors on the development of IMED. Chronic exposure to air pollution, particularly nitrogen dioxide produced by the combustion of fuels such as coal, can alter the middle ear mucosa and cause the widening of vascular spaces (i.e., swelling of the Eustachian tube walls), potentially obstructing normal fluid drainage (Lee et al., 2023). Additionally, air pollutants have been observed to decrease ciliary action, further impairing fluid clearance in the middle ear (Park et al., 2014).

2.2.3. Bone involvement

In IMED, bone involvement is primarily linked to inflammation in the tympanic cavity and to the accumulation of fluid following episodes of infection and inflammation (e.g., Floreanova et al., 2020; Friedmann, 1957; Wiatr et al., 2020). In past osteoarchaeological studies, these changes have often been referred to as otitis media (e.g., Casna et al., 2023; Goycoolea et al.,

2019; Krenz-Niedbała & Łukasik, 2017; Qvist & Grøntved, 2001). However, because any observed changes within the ear canal are inherently non-specific, it should be noted that it is not possible to identify the exact type of ear infection that affected an archaeological individual. Therefore, the term IMED is more appropriate in this context.

Bone involvement in IMED has been extensively studied in both clinical and archaeological contexts, with various studies focusing on different bony structures (e.g., ear ossicles, mastoid cells, tympanic canal, cochlear promontory) (e.g., Casna et al., 2024; Friedmann, 1957; Krenz-Niedbała & Łukasik, 2017; Primeau et al., 2018). The majority of these studies focus on the tympanic cavity, and are clinically associated with the formation of cholesteatoma, a destructive, non-cancerous yet expansive growth in the middle ear, linked to chronic episodes of IMED (e.g., Jung & Chole, 2002; Kärjä et al., 1976; Wiatr et al., 2020). The chronic inflammation associated with cholesteatoma triggers the release of both cytokines (signaling proteins that help control inflammation) and osteoclasts, ultimately leading to bone resorption within the tympanic cavity (Jung & Chole, 2002). This process has been observed to actively impact the ear ossicles, resulting in a range of consequences that can significantly influence the patient's symptoms and clinical outcomes (Kärjä et al., 1976; Wiatr et al., 2020).

In palaeopathology, the erosion of the ear ossicles has been the primary focus of most studies investigating ear infections (e.g., Collins, 2019; Krenz-Niedbała & Łukasik, 2017, 2020; Qvist & Grøntved, 2000). Bone changes have been observed to vary, ranging from small pits affecting less than 25% of the bone surface to extensive pathological alterations covering the majority of the ossicular surface (Figure 2.4).

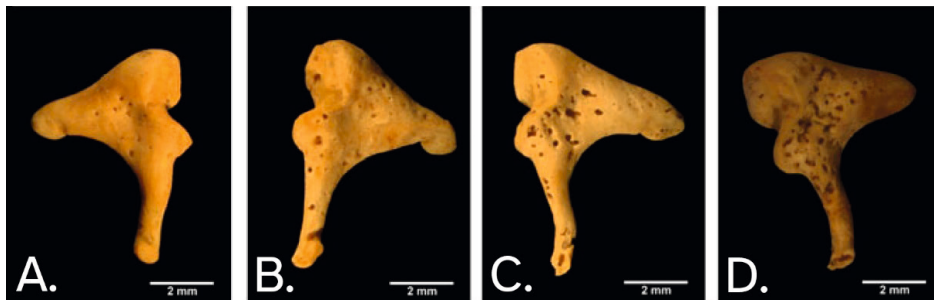


Figure 2.4. Classification of severity of ear bones erosion as presented by Krenz-Niedbała and Łukasik (2017, Figure 2). A: No erosion present; B: Small pits affecting less than 25% of the bone surface; C: Pits present in 25–50% of the affected bone area; and D: More than half of the bone surface pathologically altered. Adapted from Krenz-Niedbała and Łukasik (2017). License Number 1532926-1.

Although the observation of ear ossicle erosion has proven to be a reliable and straightforward method for analyzing IMED in past populations, it is important to acknowledge that ossicles are frequently absent from archaeological skeletal remains. Additionally, their delicate nature makes them highly susceptible to taphonomic damage, further complicating their preservation and

analysis (Bruitjes, 1990; Ortner, 2003). For this reason, recent bioarchaeological research has shifted focus towards changes to other bony structures within the tympanic cavity as potential indicators of IMED. One such structure is the cochlear promontory, located on the medial wall of the tympanic cavity, which has been increasingly recognized for its diagnostic potential in the study of ear infections in past populations (Figure 2.5) (Casna, et al., 2024; Collins, 2019; Floreanova et al., 2020; Roumelis, 2007). Although clinical data on the involvement of the cochlear promontory during chronic episodes of IMED remains limited, some evidence suggests that bone changes in this region may be associated with the presence of cholesteatoma, in a manner similar to the pathological alterations observed in ear ossicles (e.g., McGinn & Chole, 1991). Most recently, bony alterations of the cochlear promontory as presented by Floreanova and colleagues (2020) were recently analyzed in relation to hypopneumatization of the mastoid process (an indicator of childhood IMED)³ in 50 archaeological individuals (Casna et al., 2024). The findings revealed a significant correlation between mastoid hypopneumatization and promontory bone changes, further reinforcing the role of the cochlear promontory in chronic IMED episodes (Casna et al, 2024).

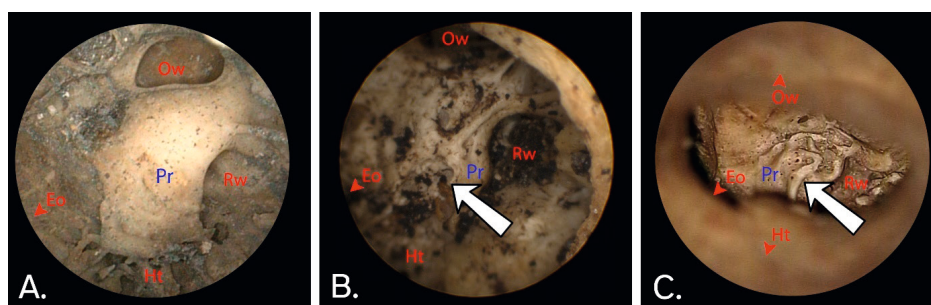


Figure 2.5. Endoscopic view of the cochlear promontory (Pr) as seen by Casna and colleagues (2024, Figure 1). Surrounding structures were labelled for anatomical reference: Ht = Hypotympanum; Eo = Eustachian orifice; Rw = Round window niche; Ow = Oval window. A: No remodeling is present; B: Disruption of the promontory surface integrity in the form of bone erosion (white arrow); and C: Bone growth in the form of bony spicules formation located superiorly from the round window. Licensed for use by CC BY 4.0.

2.3. Pleural inflammation

Pleural inflammation is clinically defined as the inflammation of the pleurae, the membranes that surround the lungs and line the chest cavity (Broaddus, 2022). It is among the most common complications of lower respiratory tract infections, and typically manifest as sharp chest pain while breathing, with associated shortness of breath, cough, and possibly fever (Wrightson &

³ Mastoid pneumatization refers to the process by which air cells develop within the mastoid portion of the temporal bone, creating a system of air-filled spaces connected to the middle ear. This process only occurs during childhood and stops permanently in cases of chronic middle ear infections, resulting in the permanently incomplete development of these air cells (Aoki et al., 2010; Mansour et al., 2019).

Maskell, 2012). Other causes include pneumonia, pulmonary embolism, autoimmune disorders, and lung cancer (Fenster et al., 2022).

2.3.1. Anatomy of the lower respiratory tract

The lower respiratory tract begins at the larynx and continues through the trachea, which divides into the left and right bronchi to supply air to the lungs (Figure 2.6) (Gibson, 2003). The main bronchi branch into smaller divisions, which extends to the bronchioles, leading into the lung parenchyma, where the alveolar ducts are housed (Gibson, 2003). Aside from the mediastinum (which contains structures like the heart and esophagus), the lungs occupy most of the thoracic cavity (Marieb & Hoehn, 2008). The apex of each lung is located beneath the clavicle, while the base rests on the diaphragm (Gibson, 2003).

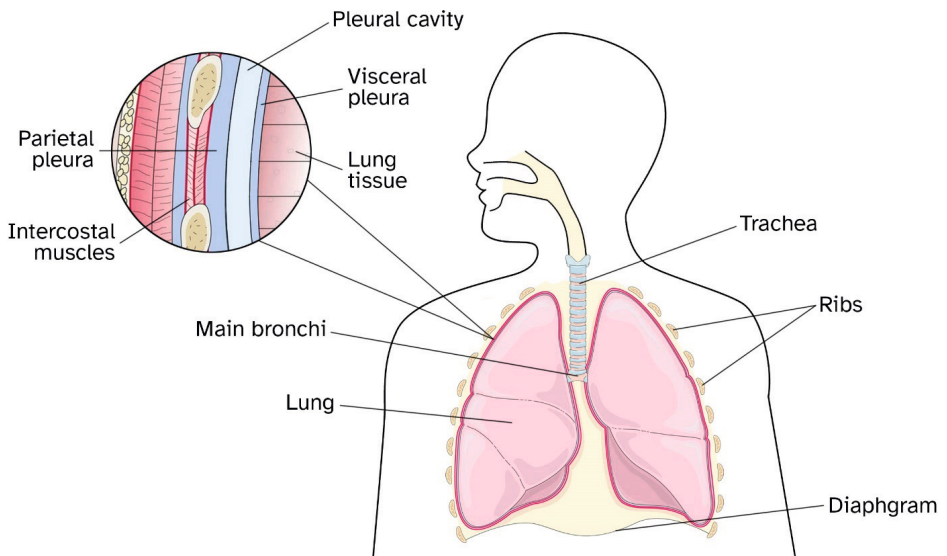


Figure 2.6. Simplified diagram of the lower respiratory tract, featuring a cross-sectional view of the thoracic wall (upper-left corner) that highlights the relevant anatomical relationships between the ribs, pleural membranes, and lungs. Aspects of the diagram adapted from Freepik and Servier Medical Art library. Licensed for use by CC BY 4.0. Cross-sectional anatomy of the thoracic wall reproduced from Hicks (2000, Figure 9.4). License Number 1537985-1.

In living individuals, the lungs are encased in a serous membrane known as the visceral pleura, which closely adheres to their surface. This is paralleled by the parietal pleura, a corresponding membrane that lines the inner chest wall (Broaddus, 2022). Between these two layers lies the pleural cavity, a fluid-filled space that facilitates smooth movement, enabling the lungs to expand and contract seamlessly within the chest during breathing (Broaddus, 2022). Overlaying the parietal pleura are the visceral surfaces of the ribs and portions of the intercostal muscles, which play a crucial role in expanding and contracting the chest cavity during breathing (Marieb & Hoehn, 2008).

2.3.2. Pathogenesis

As previously discussed, pleural inflammation can arise from various pathological processes. When linked to infections in the lungs (e.g., pneumonia, bronchitis), pleural inflammation occurs due to the accumulation of inflammatory cells and fluid within the alveoli, which mobilize to neutralize pathogens (Wilkinson & Woodhead, 2004). The spread of pathogens and inflammatory cells from the lung tissue to the pleura initiates inflammation, often resulting in pleural effusion (i.e., an abnormal accumulation of fluid within the pleural cavity) (Kroegel & Antony, 1997).

Pleural effusion and pleural inflammation are clinically closely linked, as inflammation of the pleural membranes often leads to the accumulation of excess fluid in the pleural cavity, with the effusion further exacerbating the inflammatory response by creating pressure and impairing lung function (Broaddus, 2022). In fact, pleural effusion is a frequent complication of various lung infections, particularly in pneumonia (where it occurs in about 50% of cases), and tuberculosis (Broaddus & Light, 2022; Roy et al., 2021). In tuberculosis specifically, the effusion and inflammation are thought to result from the rupture of a subpleural granuloma,⁴ releasing tuberculous proteins into the pleural cavity and provoking an immune response (Kroegel & Antony, 1997). Among non-infectious causes, congestive heart failure is a common contributor, as increased pulmonary capillary pressure forces pulmonary fluid into the pleural space, typically affecting both sides of the chest (Broaddus & Light, 2022). Similarly, pleural effusion (and subsequent inflammation) can develop in up to 50% of patients with pulmonary embolism due to the heightened permeability of lung capillaries, leading to fluid migration into the pleural space (Light, 2013). Neoplastic-related pleural effusions are also prevalent, accounting for 22% of cases, often originating from metastases of cancers such as lung, breast, gastrointestinal, genitourinary, or lymphoma (Gonnelli et al., 2024). In cases of malignant pleural effusion, fluid accumulation and associated inflammation result from cancerous obstruction of parietal lymphatic channels, which impairs lymphatic drainage and increases pleural fluid production (Fashoyin-Aje & Brahmer, 2020; Gonnelli et al., 2024).

2.3.3. Etiology

As pleural inflammation can result from a wide range of diseases, its etiology is complex and multifactorial. Factors such as age, infectious disease prevalence rates, access to prior healthcare, and the geographic or demographic context of the population significantly influence its underlying causes (Fashoyin-Aje & Brahmer, 2020; Light, 2013; Wrightson et al., 2012). However, similarly to sinusitis and IMED, exposure to particulate air pollution, both indoor and outdoor smoke, and overcrowded living conditions have been shown to increase the likelihood of developing infectious diseases commonly associated with pleural inflammation, such as

4 The human body's typical immune response to tuberculosis infection involves the recruitment of macrophages and other immune cells to encapsulate the mycobacterial foci that have adhered to alveolar cells. This process leads to the formation of granulomas, i.e. cellular masses that serve to isolate, rather than eliminate, the bacteria from the rest of the system (Guirado & Schlesinger, 2013; Walter & Daley, 2012).

pneumonia, tuberculosis, and cancer (Kyung & Jeong, 2020; van der Poll & Opal, 2009; Wilkinson & Woodhead, 2004).

Both indoor and outdoor air pollution have been extensively studied in the field of respiratory medicine, with sufficient data now available to detail the specific physiological impacts of various pollutants on the respiratory system (e.g., Balmes & Holm, 2022; Kuschner & Blanc, 2022). In most cases, air pollution has been widely observed to exacerbate asthmatic symptoms (Tran et al., 2023). Furthermore, individuals with pre-existing respiratory conditions have been observed to exhibit increased susceptibility to infections, as pollutants can impair both lung development and overall respiratory function (Maung et al., 2022). Chronic exposure to particulate air pollution can also induce cellular changes in the airways, increasing the risk of lung cancer (Almetwally et al., 2020). It is estimated that approximately 16% of lung cancer deaths are attributable to air pollution, making it among the greatest contributors to the global burden of respiratory diseases (WHO, 2016).

2.3.4. Bone involvement

In clinical reports of lower respiratory tract and lung disease, the presence of new bone formation on the visceral surfaces of ribs has been only sporadically linked to pleural inflammation (e.g., Asnis & Niegowska, 1997; Eyler et al., 1996; Guttentag & Salwen, 1999; Simon, 1973). Studies analyzing skeletal remains with known causes of death have revealed a significant correlation between new bone formation on the visceral surfaces of ribs and pulmonary tuberculosis (e.g., Matos & Santos, 2006; Roberts et al., 1994; Santos & Roberts, 2001, 2006). However, similar lesions were also identified in 15–36% of individuals who died from other pulmonary conditions (e.g., pneumonia, bronchitis, and emphysema), suggesting that the bone formation may have a more non-specific origin, rather than being exclusively linked to a single disease (Davies-Barrett et al., 2019). As previously discussed, chronic exposure to particulate pollution can lead to interstitial lung disease, which may trigger ongoing inflammation and fibrosis (i.e., the development of fibrous connective tissue in response to persistent inflammation) in the lungs (Gold et al., 2000; Ross & Murray, 2004; Sirajuddin & Kanne, 2009). According to Davies-Barrett and colleagues (2019) this process may, in return, trigger the formation of new bone on the surface of the ribs in direct contact with the parietal pleura.

Building on this hypothesis, Davies-Barrett and colleagues (2019) conducted a systematic investigation of new bone formation on the visceral surface of ribs in archaeological skeletal remains, developing a method to distinguish inflammatory bone formation from other types of bony alterations (e.g., fracture calluses, soft tissue attachment markers, and normal anatomical variations). Their study identified key characteristics of bone formation associated with pleural inflammation, including irregular, diffuse woven bone patches and porous remodeling of lamellar bone deposited atop the original cortical surface (Figure 2.7) (Davies-Barrett et al., 2019). The criteria established by Davies-Barrett et al. (2019) have since become a standardized method for recording pleural inflammation in archaeological skeletal remains, providing a consistent framework for diagnosing this condition in past populations.



Figure 2.7. Visceral surfaces of ribs, viewed macroscopically. A: Rib showing no pathological alteration.; and B: Inflammatory periosteal reaction in the form of woven bone formation on the rib neck and angle. Photographs by M. Casna.

2.4. The bioarchaeology of respiratory disease

Over the past two decades, the bioarchaeological investigation of respiratory disease has expanded significantly, with an increasing number of publications featuring both case studies and population-level analyses (e.g., Coutinho-Nogueira et al., 2022; Goycoolea et al, 2019; Lee et al., 2024; Riccomi et al., 2021; Vilumets et al., 2024). In archaeological populations, the increased occurrence of the bone changes discussed in this chapter is usually interpreted as a sign of prolonged exposure to irritants, such as particulate matter from indoor fires (e.g., Sundman & Kjellström, 2013), industrial emissions (e.g., Boyd, 2020), or overcrowded living environments (e.g., Casna et al., 2021), all of which are characteristic of urbanized societies. Additionally, respiratory diseases have also been used as proxies to explore the impact of climate change on

human health, further highlighting the multifaceted and complex etiology of these conditions (Davies-Barrett et al., 2023).

Decades of bioarchaeological research into respiratory disease have highlighted their unique role in understanding historical living environments (Lee et al., 2024; Roberts, 2016). However, more recently, concerns have been raised about existing interpretations, as findings often appear contradictory across different studies. For instance, when investigating chronic maxillary sinusitis in medieval Yorkshire, Lewis and colleagues (1995) observed that urban populations exhibited higher prevalence rates than their rural counterparts. Similarly, Davies-Barrett and colleagues (2023) reported higher rates of pleural inflammation in urban populations compared to rural groups in the Middle Nile Valley over an extended time period (2500 BCE–1500 CE). However, several other studies comparing urban and rural settings have identified no significant differences in respiratory diseases, indicating that variations in living and working conditions may not have consistently influenced respiratory health across different historical and environmental contexts (e.g., Bernofsky, 2010; Casna et al., 2021; Krenz-Niedbala & Łukasik, 2016). These discrepancies may suggest that, while the bioarchaeological study of respiratory disease offers valuable insights, our understanding of the complex interactions between environmental, social, and biological factors influencing health currently remains incomplete (Betsinger & DeWitte, 2021). As bioarchaeology and paleopathology gain increasing recognition as essential tools for investigating the past alongside historical and archaeological sources, it becomes imperative to broaden the scope of paleopathological analysis by incorporating a wider diversity of contexts in the study of respiratory disease. To contribute to this effort, the following chapters will analyze prevalence rates of respiratory disease in diverse living conditions, encompassing various geographic regions, time periods, and socioeconomic environments. This approach will provide a comprehensive overview of how diverse risk factors influenced different Dutch populations across time and space, enriching our knowledge of the complex interplay between health and environment throughout human history.

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CHAPTER 3

A Distant City: assessing the impact of Dutch socioeconomic developments on urban and rural health using respiratory disease as a proxy

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5 In this version of the article, references to “AD” have been updated to “CE” to align with the terminology consistently used throughout this dissertation. All other content remains unchanged from the original publication.

Abstract

Objectives: To investigate the prevalence of respiratory disease in several populations from the Netherlands across different time periods and socioeconomic conditions.

Materials: We analyzed 695 adult individuals from six different Dutch contexts of urban and rural settlements dating to different time periods (i.e., early-medieval, late-medieval, post-medieval).

Methods: For each individual, the presence/absence of chronic maxillary sinusitis, otitis media, and inflammatory periosteal reaction on ribs was recorded macroscopically according to accepted methods.

Results: Statistically significant associations were found in the presence of sinusitis diachronically (early-medieval to late-medieval period, and early-medieval to post-medieval period) both in rural and urban environments. Differences in prevalence rates of otitis media were found statistically significant when comparing rural to urban environments in the early-medieval and late-medieval periods.

Conclusion: Our results suggest that factors such as increased contacts between towns and countryside, higher population densities, and intensification of agricultural production impacted the respiratory health of past populations both in rural and urban settings.

Significance: Our study provides new insights into the impact of environmental changes and urbanization on respiratory disease prevalence, shedding light on the relationship between health and changing social and environmental contexts.

Limitations: Research limitations included the complex etiology of respiratory diseases, and the impact of uncontrollable factors such as hidden heterogeneity, selective mortality, and rural-to-urban migration.

Future research: Further research in different contexts is advised in order to continue exploring urbanization and its impact on human health across both time and space.

Keywords: Netherlands; Maxillary Sinusitis; Otitis Media; Rib Lesions; Periosteal Reaction; Medieval

3.1. Introduction

According to historical sources, urbanization dramatically altered Europe's economic, political, and social realities starting already from the 11th century (de Vries, 1984; Schmal, 2018; Scott, 2018). As cities gradually began to increase their economic production, many people migrated from the countryside to the newly formed urban centers in search of new opportunities. With great numbers of people flowing into cities, population densities increased, while necessary infrastructures (e.g., housing facilities, healthcare system, social support networks) failed, in most cases, to accommodate the needs of the growing population (Blockmans, 2010; Wintle, 2000). As a consequence, starting from the 16th century, problems such as overcrowding, precarious working conditions, and limited access to resources (i.e., clean water, nutritious food, healthcare) were common in many European centers (Benevolo, 1996; Clark, 2009; Wintle, 2000). In contrast, rural people lived in comparatively uncrowded communities, much less threatened by these specific factors, albeit likely exposed to several other hazards such as fungal spores, dust, and pollen (Krenz-Niedbala & Łukasik, 2020).

Because of its complex and varied nature, the urbanization phenomenon has been the center of many bioarchaeological studies aiming to reconstruct its impact on human wellbeing through a variety of methods (e.g., non-specific stress markers, dietary isotopes, stature, respiratory disease) (e.g., Betsinger & DeWitte, 2017; Lewis, 1999; Schats, 2016; Sundman & Kjellström, 2013; Western & Bekvalac, 2019). In most cases, it has been suggested that the challenges associated with the transition to urban life (e.g., inaccessibility to food and clean water, overcrowding, etc.) increased exposure to several risk factors such as malnutrition, sanitary hazards, and air pollution, leading to a general decline in human health and, similarly, to increased exposure to infectious diseases (Betsinger et al., 2020). In this framework, respiratory infections (i.e., chronic maxillary sinusitis, otitis media, and pulmonary diseases) have often been studied in relation to urbanization under the assumption that the general worsening of both living and working conditions would result in increased risk of respiratory stress among urban and later industrial populations, suggesting an association between prevalence rates of respiratory disease and certain risk factors such as air pollution, socioeconomic status, adverse climate conditions, and insufficient ventilation of living and working spaces (e.g., Boyd, 2020; Casna et al., 2021; Sundman & Kjellström, 2013). However, most published studies on the impact of urbanization on human respiratory health so far have focused on a particular point in time, rarely addressing changes in urbanization patterns through history (Betsinger & DeWitte, 2021). To fill this gap, we analyzed patterns of respiratory stress across time, assessing and comparing the presence of chronic maxillary sinusitis, otitis media, and inflammatory periosteal reaction on ribs in a large sample from both rural and urban environments, dating from the early-middle ages (300-1080 CE), the late-middle ages (1080-1500 CE), and the post-medieval era (1500-1850 CE). We aimed to test the hypothesis that the prevalence of respiratory stress markers gradually increased over time together with the transition to urban life in the Netherlands. Furthermore, since many bioarchaeological studies on respiratory disease did not observe significant changes between rural and urban populations (e.g., Bernofsky, 2010; Casna et al., 2021; Panhuysen et al., 1997), we

hypothesized that prevalence rates of respiratory stress markers would progressively increase with time in rural samples as well.

3.1.1. Upper respiratory tract diseases

Upper respiratory tract diseases are a group of illnesses that affect the nose, throat, or larynx, typically caused by viral or bacterial infections. Aiming to produce comparable results, we collected data on those upper respiratory tract infections that are most often addressed in osteoarchaeology: chronic maxillary sinusitis and otitis media. Chronic maxillary sinusitis (CMS) is an inflammation of the lower paranasal sinuses, small air-filled chambers that surround the nasal passages and help protect them from inhaled fine dust and pathogens. CMS is caused by the accumulation of mucus in the sinus, which provides an ideal environment for bacterial growth and contributes to the inflammation of the mucosa and to the involvement of the bone surface in the form of either depositional and/or resorptive lesions (Boocock et al., 1995; Kocak et al., 2002; Slavin et al., 2005; Stannard & O'Callaghan, 2006). The etiology of sinusitis includes both genetic and environmental factors (e.g., viral and bacterial infections, allergies, and pollutants) (Slavin et al., 2005). As air pollutants act as irritants causing inflammation, the role of both indoor and outdoor air pollution is increasingly recognized as a cause of sinusitis, together with overcrowding and tobacco smoke (Behr & Nowak, 2002; Schwarzbach et al., 2020; Wee et al., 2021). Although CMS is generally not considered a life-threatening condition, if the inflammation spreads from the sinuses to the nearby Eustachian tubes (which connect the middle ear to the back of the throat), it can lead to fluid buildup and inflammation in the middle ear, resulting in otitis media.

Otitis media (OM) is a group of inflammatory diseases of the middle ear, differing in both symptoms and complications (Qureishi et al., 2014). The etiology of OM is complex and includes allergy, physiologic features related to the Eustachian tube, infections (viral and bacterial). Despite it being largely considered as a childhood condition, today chronic OM affects more than 4% of the adult population worldwide (Gisselsson-Solen, 2022).

Bone changes associated to OM include bone growth and resorption of the auditory ossicles, the middle ear cavity, the mastoid bone (i.e., mastoiditis), and of the petrous portion of the temporal bone (Estalrich et al., 2020; Flohr & Schultz, 2009; Floreanova et al., 2020; Krenz-Niedbała & Łukasik, 2017; Qvist & Grøntved, 2001). Because of the difficulty in examining the middle ear osteologically and the lack of clear scoring criteria, bioarchaeological studies on OM are scant. The majority of the extant studies employed either radiography or light microscopy and observed prevalence rates varying between 6-83.4% (Flohr & Schultz, 2009; Gregg & Steele, 1982; Krenz-Niedbała & Łukasik, 2016; Qvist & Grøntved, 2001).

Despite differences in approaches and observed prevalence rates, most bioarchaeologists generally agree that in the past both CMS and OM tended to be more frequent in contexts associated with urbanization, low quality of housing and/or working environments, and lower levels of hygiene (e.g., Boyd, 2020; Qvist & Grøntved, 2001; Sundman & Kjellström, 2013). However, many bioarchaeological studies of CMS in both urban and rural environments have

yielded varying results. In fact, while many have shown a higher prevalence of CMS in urban contexts when compared to rural ones (e.g., Fleischer, 2007; Merrett & Pfeiffer, 2000; Sundman & Kjellström, 2013), others have found no statistical differences between the two environments, suggesting that other causes such as climate, smoking, or exposure to animal dander may also have played a significant role in the spread of CMS and possibly of other upper respiratory tract diseases (e.g., Bernofsky, 2010; Casna et al., 2021; Panhuysen et al., 1997).

3.1.2. Lower respiratory tract diseases

Lower respiratory tract diseases are a group of illnesses that affect the lungs, bronchi, and other structures in the lower respiratory system. In bioarchaeology, inflammatory periosteal reaction on the cortical layer of the visceral surface of the ribs (IPR) has often been used as a marker for lower respiratory tract disease (Davies-Barrett et al., 2019; Roberts et al., 1994; Roberts, 2019). Several clinical studies have attested to the association between particulate matter inhalation and chronic lung inflammation, which may produce IPR on the visceral surface of ribs, where the pleura is in direct contact with the rib cage (Kyung & Jeong, 2020; Paulin & Hansel, 2016; Zanobetti et al., 2000). If chronically inflamed, the pleura can thicken and induce new bone formation (Eyler et al., 2013; Guttentag & Salwen, 1999). Despite the non-specific nature of IPR (i.e., it is caused by a variety of conditions, such as tuberculosis, pneumonia, and bronchitis), its presence in archaeological populations has often been considered as an indicator of the impact of environmental factors (e.g., poor air quality) on human respiratory health (Bernofsky, 2010; Boyd, 2020; Davies-Barrett et al., 2019; Lamber, 2002; Santos & Roberts, 2001; Western & Bekvalac, 2019).

3.2. Materials and methods

For this study, the total sample was composed of six different populations from the area today encompassed by the Netherlands (Table 3.1; Figure 3.1). They were selected because they represent a diachronic window into life in the Northern Low Countries in the early-medieval (300-1080 CE), late-medieval (1080-1500 CE) and post-medieval (1500-1850 CE) periods. Here, the traditional tripartition (early Middle Ages, 300-1000 CE; central Middle ages, 1000-1300 CE; and late Middle Ages, 1300-1500 CE) was adapted for the sake of clear arrangement, opting for a periodization in which emphasis is placed on transition from an era of land owners and isolated communities (300-1080 CE), to the rise of the cities in the medieval society (1080-1500 CE) (Blockmans & Hoppenbrouwers, 2007).

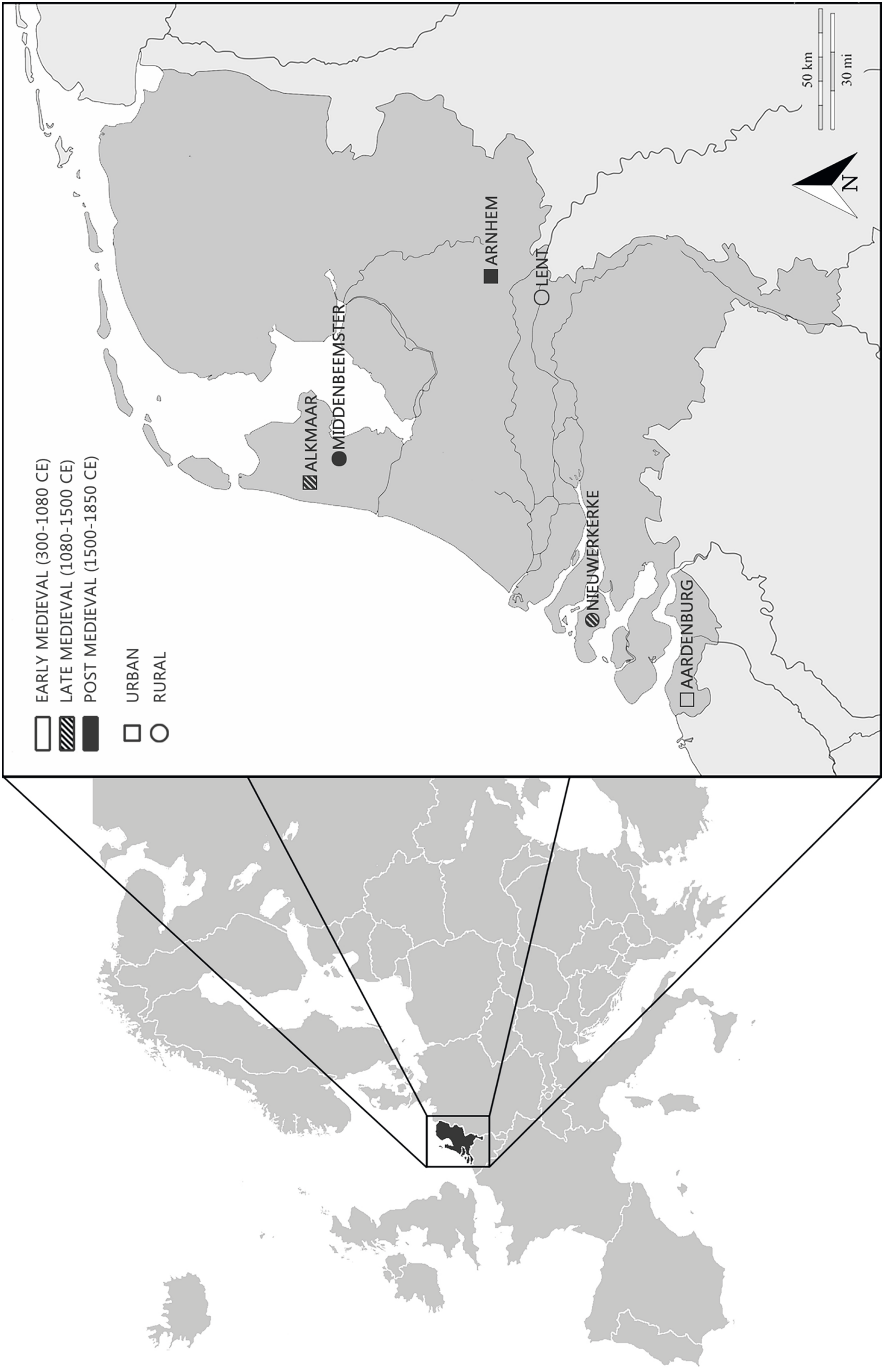


Figure 3.1. Map of the Netherlands showing the location of the sites under study. Image made by M. Casna.

Table 3.1. Skeletal collections included in this study.

	Collection	Dating	Subsistence economy
Early-medieval (300-1080 CE)	Lent	475-750 CE	Rural
	Aardenburg	1030-1200 CE	Urban
Late-medieval (1080-1500 CE)	Nieuwerkerke	1298-1576 CE	Rural
	Alkmaar	1448-1572 CE	Urban
Post-medieval (1500-1850 CE)	Middenbeemster	1829-1866 CE	Rural
	Arnhem	1626-1829 CE	Urban

3.2.1. Urban sites

The urban populations of Aardenburg (early-medieval), Alkmaar (late-medieval), and Arnhem (post-medieval) were selected as their preservation status and well-understood historical context allowed for a systematic, contextualized, and diachronic investigation of the respiratory health in several urban populations located in the Netherlands.

The skeletal collection of Aardenburg was discovered and excavated in 1948 from the Sint-Baafskerk, following the structural damage that the Second World War caused to the church (Forbes, 1953). Due to the nature of the excavation, no reports were produced at the time and, therefore, no information is available on how many skeletons were originally recovered. For the same reason, the dating of these skeletons was not clear and was attributed to be 1030 CE (the year the church opened) up to 1200 CE, based on the symbols painted on the burial vaults (Cornelis, 1951, 1952; Wagenaar & van den Brink, 2011).

Formerly known as Rodanburg, Aardenburg was among the first Dutch centers to acquire city rights in 1187 CE (Henderikx, 2012a). In the medieval time, Aardenburg was a thriving commercial and industrious city whose cloth market extended not only to England, but also to the Baltic coast, Northern Spain, and Italy (de Pooter et al., 2000; Henderikx, 2012b). Because of its strategic position on the North Sea, already in 1000 CE Aardenburg was part of the London Hanseatic League, a commercial and defensive confederation of merchant guilds and market towns in Northern Europe that dominated maritime trade in the North and Baltic seas (Harreld, 2015). The individuals from Aardenburg included in this study lived during a particularly flourishing time for the city's economic development, albeit it is unlikely (due to the dating of the site) that they witnessed the rise of problems commonly associated with intense urbanization that were discussed above.

In contrast, the dating of the skeletons from Alkmaar suggest that this late-medieval population lived during one of the largest and fastest expansions of the city (Hakvoort et al., 2015; Kaptein, 2007). This skeletal assemblage was excavated in 2010 from the former Franciscan monastery cemetery. Originally, 189 individual coffin burials were recovered dating between 1448-1572 CE, when the monastery was closed during the Eighty Years' War and later demolished (Schatz,

2015). At the time the burials took place, Alkmaar had suddenly become an important port for international trade and, as such, needed more space to expand (Streefkerk, 2004; van Nierop, 2000). Artificial land reclamation from the near waterside (today completely drained) had already started in the 14th century, but intensified between 1483-1516 CE, attracting several workers from the countryside (Bitter, 2007a). On a list kept by the parish church, people buried in the cemetery under study were '*ambachtslieden*', the commoners of Alkmaar, likely employed in various activities such as sail making, chalk production, peat digging, and dyke construction (de Raad, 2015; Kaptein, 2007). Although agricultural production was mainly concentrated among farms established in the dry land around the city, in the late-medieval period many people from Alkmaar still had access to a small garden outside town where they grew their own vegetables (Bitter, 2007b).

The post-medieval population of Arnhem consisted of approximately 350 skeletons excavated in 2017 in the courtyard of the Sint-Eusebiuskerk (the city's largest and most important Protestant church) and is considered as representative of the lower proto-industrial working class (van Laar, 1966; Zielman & Baetsen, 2020). Starting from 1795, systematic immigration caused the population to suddenly grow, making Arnhem almost as populated as other major Dutch centers (Lourens & Lucassen, 1997). People from the whole province came to the city in search of employment, which was mainly offered in small-scale industries such as tobacco production, shoemaking, and typography (Baetsen et al., 2020; van Laar, 1966). According to historical sources, being employed in these proto-industrial settings was particularly hard for both men and women, with working time commonly ranging between 12-20 h/day (Wintle, 2000). Factory conditions were generally very harsh and had a direct impact on health, as workers were often exposed to dust and chemicals and were involved in occupational accidents caused by unsafe working environments (van Braam, 1978; Wintle, 2000). Not only working spaces were considered harmful to the health of the Dutch post-medieval working class. Due to the prohibitive housing costs, employers typically provided living quarters for their employees and deducted the costs from their wages. These living spaces were hastily assembled to accommodate as many people as possible, with one room often housing two or more families (Van Laar, 1966). Starting from the end of the 18th century, many campaigns were launched aiming to improve the living conditions of lower-class citizens in many cities, and many engineers were tasked with testing the livability of both domestic and working spaces (van Laar, 1966; Wintle, 2000).

3.2.2. Rural sites

Three rural skeletal populations were analyzed: Lent (early-medieval), Nieuwerkerke (late-medieval), and Middenbeemster (post-medieval).

The skeletal sample of Lent comes from two different collections, respectively Lent Azaleastraat (excavated between 1972-1975) and Lentseveld (excavated in 2011). In total, the two collections combined included a total of circa 90 individuals. They were considered as one population as the sites were located less than a kilometer from each other and are both dated to the early medieval period (Lent Azaleastraat: 630-750 CE; Lentseveld: 475-600 CE), suggesting that they

are representative of the same community (Hendriks & De Roode, 2012; van Es & Hulst, 1991). In the early-medieval period, Lent functioned as a vegetable garden for the nearby city of Nijmegen, where farmers were assigned a “standard” cultivable area whose proceeds had to partly be paid to the castle (Jansen, 1981). The population of Lent was likely exclusively employed in some early and exiguous form of agriculture, as suggested by the results of pollen surveys in the excavation area reporting limited human impact on the river landscape (Teunissen, 2016). Because the main economic activities of the region were concentrated around the city, it is believed that inhabitants of Lent depended from Nijmegen for any goods or services that were not produced through cultivation (Bots et al., 2005; Jansen & Willems, 1986).

Similarly to Lent, inhabitants of Nieuwerkerke were also mainly involved in the production of agricultural supply for the neighboring city of Zierikzee, that at the time was one of the largest towns in the whole province of Schouwen-Duiveland (Mijnhardt, 2012). The skeletal assemblage under study (originally comprised by circa 2000 individuals and dated 1298-1576 CE) was excavated in 1951 from what it is thought to be the former church cemetery (Burger, 1992). According to van Cruyningen (2012), late-medieval communities such as Nieuwerkerke were still prevalently based on the commercial farming scheme: crops and livestock were raised with the purpose of being sold to the city, with wheat, madder root, and barley being among the most demanded goods (van Cruyningen, 2012). Despite its economy being dependent on Zierikzee, it is clear from historical sources that Nieuwerkerke did dictate its own autonomy to some extent: in 1298 CE, the village had already grown so large that it could open its own school and cemetery (Meulenberg & Frentrop, 2004). However, Nieuwerkerke’s church was demolished in the early 16th century, following a siege by the Spanish troops. Consequently, the cemetery was closed and the municipality later merged with another nearby village (Meulenberg & Frentrop, 2004).

The skeletal collection of Middenbeemster is representative of a post-medieval rural community from the province of North Holland. It was excavated from the church cemetery in 2011 and is comprised of more than 450 individuals dated between 1829-1866 CE (Griffioen, 2011). As this was the only cemetery active in the area, this population is believed to be representative not only of the village of Middenbeemster but of the surrounding countryside as well (Falger et al., 2012). In the early 17th century, Middenbeemster was one of the first villages established in the reclaimed Beemster polder, a former marshy lake artificially dried to increase local agricultural production (Falger et al., 2012). The reclamation of the Beemster polder is generally considered among the most ambitious artificial modifications of the Dutch soil. It was entirely financed by private investors to grow crops necessary for long sea journeys by the Dutch East India Company and, already in the 18th century, it figured among the most fruitful agricultural centers in the Low Countries (Aten, 2012). Once the Dutch East India Company was dissolved in 1799, Beemster produce (i.e., dairy products, cattle, crops) continued to be directed towards Amsterdam, where it was distributed among citizens and sold at international markets (Aten, 2012). It was calculated that, in 1800, 80% of Beemster dairy and meat production was exported to other countries such as England, Spain, Germany, and even Russia (van der Wiel, 2012a, 2012b). Due to the high demand for export, people in the Beemster area were almost exclusively involved in

manual labor until the late 20th century (Falger et al., 2012). This was recently confirmed with osteoarchaeological research into activity reconstruction at Middenbeemster (Palmer et al., 2016; Vikatou et al., 2017).

3.2.3. Sample selection

The sample comprises a total of 695 individuals whose age-at-death was ≥ 18 years. Non-adults were excluded from this study as their sample size was too poor for meaningful and robust analysis to be carried out. They will however be considered in a future study when more data on this specific age group is collected.

3.2.4. Methods

For every individual, sex and age-at-death were estimated using standard osteoarchaeological methods. Biological sex was estimated using sexually dimorphic features of both the pelvis and skull (Buikstra & Ubelaker, 1994). To test the demographic comparability of the sample, age-at-death estimations were made based on ectocranial suture closure (Meindl & Lovejoy, 1985), morphologic characteristics of the pubic symphysis (Brooks & Suchey, 1990) and of the auricular surface (Buckberry & Chamberlain, 2002). The calculated average age-at-death of each individual was used to assign them to specific age categories adapted from Buikstra and Ubelaker (1994), and defined as early young adult (approx. 18-24 years), late young adult (approx. 25-34 years), middle adult (approx. 35-49 years), and old adult (50+ years). The original category described by Buikstra and Ubelaker (1994) as “young adult (20-35 years)” was here divided into early and late young adult groups in order to align with the established protocol for data collection at the Laboratory for Human Osteoarchaeology at Leiden University.

The presence of each lesion (i.e., chronic maxillary sinusitis, otitis media, and periosteal rib reaction) was macroscopically assessed for all individuals on both sides (i.e., right and left) and noted as either ‘absent’, ‘present’, or ‘unobservable’. Prevalence rates of all conditions were calculated as individuals affected/individuals observed.

The presence of chronic maxillary sinusitis (CMS) was observed in all individuals with at least one sinus with a partial preservation of more than 25% of any of the six sinus walls. If the sinuses were present but not observable with the naked eye, they were examined with a flexible medical endoscope (Pentax, model: FNL-10RBS, $\phi=4\text{mm}$; view angle= 30°) inserted through minor breaks (Casna et al., 2021). A sinus without pathological changes presents smooth surfaces with little associated pitting and channels for blood vessels. Lesions associated with CMS, as defined by (Boocock et al., 1995), were recorded for each individual and classified as ‘present’ whenever either bone resorption or new bone growth were present (Figure 3.2, A). As dental disease (i.e., periodontal disease, abscesses, and granulomas) can influence the presence of maxillary sinusitis (Patel & Ferguson, 2012), individuals showing dental decay and/or antemortem tooth loss in the upper premolars and/or molars were excluded from analysis.

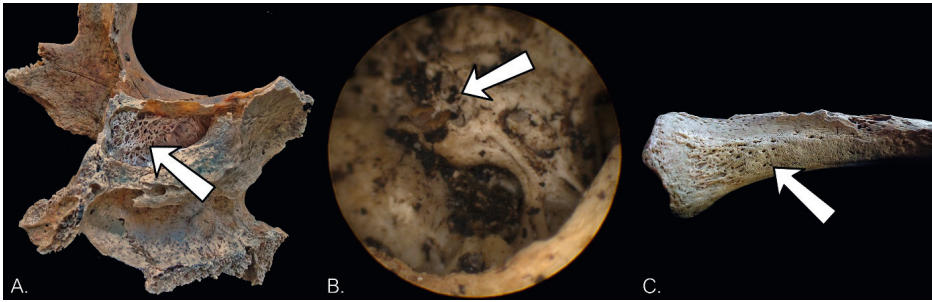


Figure 3.2. Examples of lesions observed in this research, respectively: A: chronic maxillary sinusitis; B: otitis media; and C: periosteal rib reaction. Lesions are indicated by the white arrows. Photographs by M. Casna.

Otitis media (OM) was identified using the criteria by Floreanova et al. (2020) and its presence observed on all individuals with at least one undamaged, accessible ear canal. The ear ossicles (when present) were removed, and the bony walls of the middle ear were carefully cleaned using a wooden tooth pick before the medial wall of the middle ear cavity (i.e., the promontory) was inspected with a medical endoscope. OM was scored as ‘present’ when the promontory surface showed either isolated bony overgrowth with clear margins or general interruption of the integrity of the promontory bony surface due to bone resorption (Figure 3.2, B). It was scored as ‘absent’ in cases when the promontory presented a smooth, unaltered surface (Floreanova et al., 2020).

Inflammatory periosteal reaction on ribs (IPR) was scored for every rib whose shaft was at least 50% complete. To avoid mistakes in serializations, ribs were allocated in four groups based on their most likely position within the rib cage: ‘upper’ (ribs #1-3), ‘upper-middle’ (ribs #4-6), ‘lower-middle’ (ribs #7-9), or ‘lower’ (ribs #10-12). IPR was scored as ‘present’ in groups in which at least one rib showed evidence of bone growth and where new bone formed a distinct layer on top of the original cortical surface, with clearly defined margins and/or a surface texture dissimilar to the original cortical bone (Davies-Barrett et al., 2019) (Figure 3.2, C). In cases where only one rib per group was present and did not show any sign of IPR, the group was considered as unobservable.

Results were analyzed statistically using SPSS for Windows, version 25.0. To test differences between prevalence rates of skeletal lesions, time period, and/or living environments, Pearson’s chi-squared test was used. In cases where expected cell count was below 5, Fisher’s Exact test was used instead. 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 Bonferroni correction method to account for familywise error.

Table 3.2. Demographic composition of the sample included in this study.

	Males					Females				
	Early young adult (18-24 years) (%)	Late young adult (25-34 years) (%)	Middle adult (35-49 years) (%)	Old adult (50+ years) (%)	Total	Early young adult (18-24 years) (%)	Late young adult (25-34 years) (%)	Middle adult (35-49 years) (%)	Old adult (50+ years) (%)	Total
Lent	3 (12.5)	5 (20.8)	10 (41.7)	6 (25.0)	24	5 (16.1)	10 (32.2)	13 (41.9)	3 (9.8)	31
Aardenburg	6 (10.2)	19 (32.2)	26 (44.1)	8 (13.5)	59	16 (36.4)	16 (36.4)	9 (20.4)	3 (6.8)	44
Nieuwerkerke	26 (27.9)	26 (27.9)	30 (32.4)	11 (11.8)	93	27 (50.0)	10 (18.5)	12 (22.2)	5 (9.3)	54
Alkmaar	6 (18.2)	6 (18.2)	14 (42.4)	7 (21.2)	33	7 (19.5)	9 (25.0)	18 (50.0)	2 (5.5)	36
Middenbeemster	9 (12.5)	11 (15.3)	20 (27.8)	32 (44.4)	72	17 (19.3)	22 (25.0)	23 (26.1)	26 (29.6)	88
Arnhem	9 (10.6)	18 (21.2)	27 (31.8)	31 (36.4)	85	16 (21.6)	13 (17.6)	28 (37.8)	17 (23.0)	74
Total	59 (16.2)	82 (22.5)	127 (34.8)	95 (26.5)	365	88 (26.9)	80 (24.5)	103 (31.5)	56 (17.1)	327

3.3. Results

Of the total sample ($N=695$) (Table 3.2), 541 individuals were analyzed for CMS, 585 for OM, and 325 for IPR. Of these, 202 individuals (37.3%) showed signs of CMS, 120 (20.5%) of OM, and 18 (5.5%) of IPR.

3.3.1. Chronic Maxillary Sinusitis (CMS)

Within the total sample, CMS was most common in Arnhem (53.6%) and least common in Lent (11.3%) (Figure 3.3). No statistically significant differences were observed between rural and urban environments among any of the time periods under study. However, strongly significant relationships were noted between sinusitis and time period in both the rural and urban environments, with the lesions becoming more common over time. Separate analyses of the rural and urban sites show that the largest differences exist between the early medieval sites and late medieval/post-medieval sites. No statistically significant differences are found between the late medieval and post-medieval sites in CMS prevalence (Table 3.3).

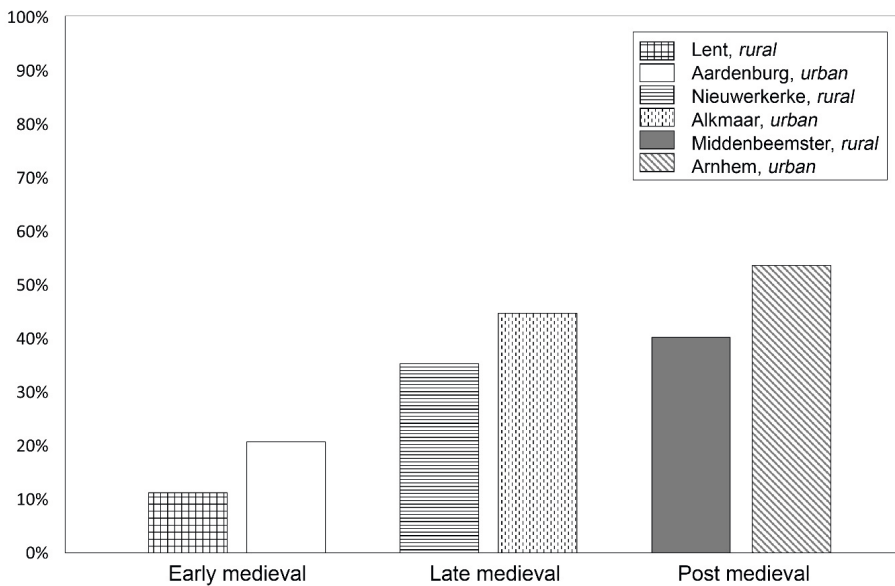


Figure 3.3. Prevalence of chronic maxillary sinusitis for all samples under study ($N=541$).

Table 3.3. Prevalence and statistical analysis of chronic maxillary sinusitis in different time periods and living environments.

Comparison	Skeletal assemblage	N	CMS (%)	χ^2	p-value
Urban versus rural in early medieval period	Lent	53	6 (11.3)	1.751	0.186
	Aardenburg	53	11 (20.8)		
Urban versus rural in late medieval period	Nieuwerkerke	127	45 (35.4)	1.486	0.223
	Alkmaar	58	26 (44.8)		
Urban versus rural in post-medieval period	Middenbeemster	124	50 (40.3)	2.762	0.097
	Arnhem	126	64 (50.8)		
Changes through time in the rural environment	Lent	53	6 (11.3)	14.557	0.001
	Nieuwerkerke	127	45 (35.4)		
	Middenbeemster	124	50 (40.3)		
Changes through time in urban environments	Aardenburg	53	11 (20.8)	13.919	0.001
	Alkmaar	58	26 (44.8)		
	Arnhem	126	64 (50.8)		
Changes through time in rural environments (continued)					
	Lent	Nieuwerkerke	Middenbeemster		
Lent		$\chi^2=10.707, p=0.001$	$\chi^2=14.439, p<0.001$		
Nieuwerkerke			$\chi^2=0.638, p=0.425$		
Changes through time in urban environments (continued)					
	Aardenburg	Alkmaar	Arnhem		
Aardenburg		$\chi^2=7.222, p=0.007$	$\chi^2=13.828, p<0.001$		
Alkmaar			$\chi^2=0.566, p=0.452$		

N= total of individuals with observable feature; CMS= total of individuals showing lesions associated to chronic maxillary sinusitis. Values in bold indicate associations statistically significant by Chi-square test, with Bonferroni correction significance level set at $p=0.017$.

3.3.2. Otitis Media (OM)

With the exception of the late-medieval period, OM prevalence was higher in rural samples (Figure 3.4). Alkmaar had the highest prevalence rate of OM (35.2%), while Aardenburg had the lowest (12.0%). There were significant associations between OM and living environment (i.e., rural versus urban) in the early-medieval and late-medieval periods (Table 3.4). In addition, a statistically significant relationship was also observed between OM and time period within the urban sample. In the rural environment, OM prevalence rates were statistically significantly higher in Middenbeemster when compared to late medieval Nieuwerkerke.

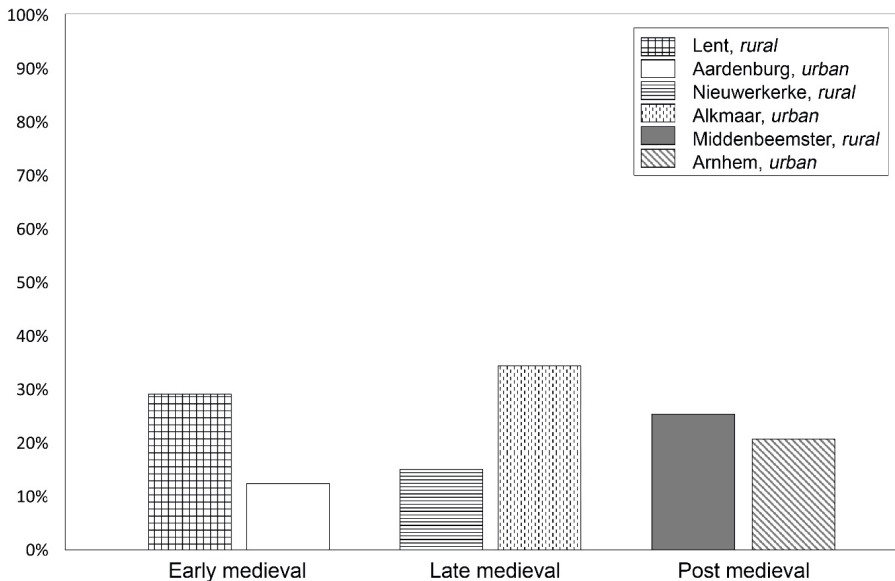


Figure 3.4. Prevalence of otitis media for all samples under study ($N=585$).

Table 3.4. Prevalence and statistical analysis of otitis media in different time periods and living environments.

Comparison	Skeletal assemblage	N	OM (%)	χ^2	p-value
Urban versus rural in early medieval times	Lent	32	9 (28.1)	4.712	0.030
	Aardenburg	100	12 (12.0)		
Urban versus rural in late medieval times	Nieuwerkerke	123	18 (14.6)	9.585	0.002
	Alkmaar	54	19 (35.2)		
Urban versus rural in post medieval times	Middenbeemster	151	37 (24.5)	0.796	0.372
	Arnhem	125	25 (20.0)		
Changes through time in the rural environment	Lent	32	9 (28.1)	5.115	0.078
	Nieuwerkerke	123	18 (14.6)		
	Middenbeemster	151	37 (24.5)		
Changes through time in urban environments	Aardenburg	100	12 (12.0)	11.750	0.003
	Alkmaar	54	19 (35.2)		
	Arnhem	125	25 (20.0)		
Changes through time in rural environments (<i>continued</i>)					
	Lent	Nieuwerkerke	Middenbeemster		
Lent		$\chi^2=3.213, p=0.073$	$\chi^2=0.184, p=0.668$		
Nieuwerkerke			$\chi^2=4.115, p=0.043$		
Changes through time in urban environments (<i>continued</i>)					
	Aardenburg	Alkmaar	Arnhem		
Aardenburg		$\chi^2=11.724, p=0.001$	$\chi^2=2.588, p=0.108$		
Alkmaar			$\chi^2=4.690, p=0.030$		

N= total of individuals with observable feature; OM= total of individuals showing lesions associated to otitis media. Values in bold indicate associations statistically significant by Chi-square test, with Bonferroni correction significance level set at $p=0.017$.

3.3.3. Inflammatory periosteal reaction on ribs (IPR)

Among all recorded lesions, inflammatory periosteal reaction on ribs (IPR) was the least commonly observed (Figure 3.5). In both Lent and Aardenburg, no cases of IPR were recorded. Alkmaar and Middenbeemster showed the same prevalence rate (7.3%). No statistically significant relationships were observed between different time periods and rural-urban environments (Table 3.5).

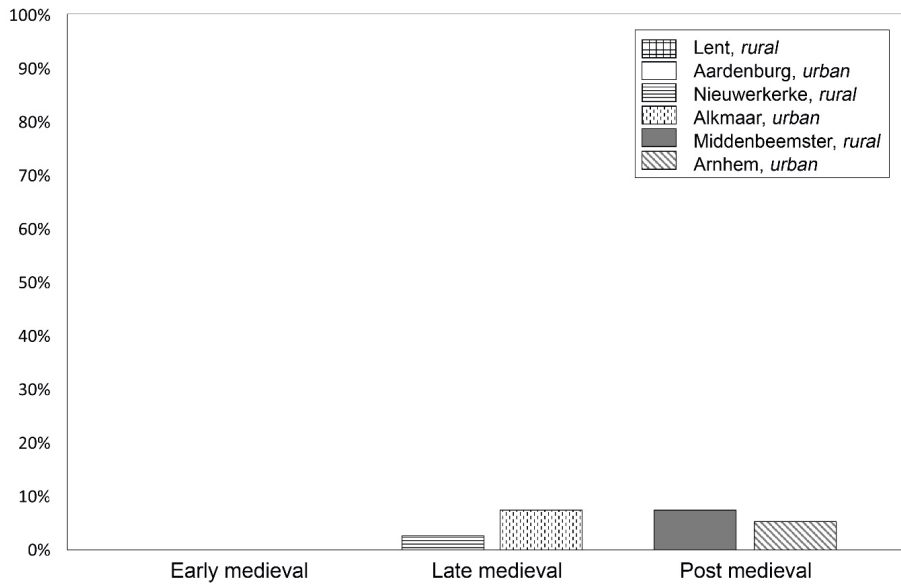


Figure 3.5. Prevalence of inflammatory periosteal reaction on ribs for all samples under study ($N=325$).

Table 3.5. Prevalence and statistical analysis of inflammatory periosteal reaction on ribs in different time periods and living environments.

Comparison	Skeletal assemblage	N	IPR (%)	χ^2	<i>p</i> -value
Urban versus rural in early medieval times	Lent	23	0 (0)	N/A	N/A
	Aardenburg	6	0 (0)		
Urban versus rural in late medieval times	Nieuwerkerke	39	1 (2.6)	†0.951	0.616
	Alkmaar	41	3 (7.3)		
Urban versus rural in post medieval times	Middenbeemster	110	8 (7.3)	0.407	0.523
	Arnhem	115	6 (5.2)		
Changes through time in the rural environment	Lent	23	0 (0)	†2.753	0.252
	Nieuwerkerke	39	1 (2.6)		
	Middenbeemster	110	8 (7.3)		
Changes through time in urban environments	Aardenburg	6	0 (0)	†0.513	0.787
	Alkmaar	41	3 (7.3)		
	Arnhem	115	6 (5.2)		
Changes through time in rural environments (<i>continued</i>)					
	Lent	Nieuwerkerke	Middenbeemster		
Lent		† $\chi^2=0.599$, <i>p</i> =1.000	† $\chi^2=1.780$, <i>p</i> =0.350		
Nieuwerkerke			† $\chi^2=1.125$, <i>p</i> =0.447		
Changes through time in urban environments (<i>continued</i>)					
	Aardenburg	Alkmaar	Arnhem		
Aardenburg		† $\chi^2=0.469$, <i>p</i> =1.000	† $\chi^2=0.329$, <i>p</i> =1.000		
Alkmaar			† $\chi^2=0.245$, <i>p</i> =0.699		

N= total of individuals with observable feature; IPR= total of individuals inflammatory periosteal reaction on ribs; †=Fisher's exact test.

The occurrence of all lesions was also investigated for each context in relation to biological sex (see Table S.1 for all results). The only significant relationship observed was between IPR and sex in the urban population of Arnhem ($\chi^2=5.411$, $p=0.03$), where males showed greater prevalence than females (males: 9.7%; females; 0%).

3.4. Discussion

This paper has investigated three skeletal lesions associated with respiratory stress to study the influence of living environment and time period. Despite small differences in prevalence rates between rural and urban environments, our analysis did not reveal any clear distinction between the two living environments. It therefore supports interesting patterns of occurrence that partly reflect what was previously observed in other osteoarchaeological studies: there is no correlation between urban settings and the presence of skeletally visible respiratory conditions (e.g., Bernofsky, 2010; Casna et al., 2021; Panhuysen et al., 1997; Schats, 2016). In fact, only few associations between rural and urban environments were statistically significant for any of the time periods under study, possibly indicating that past people's respiratory health was equally challenged regardless of where they resided.

Interesting to note is that significant correlations were observed when comparing CMS prevalence rates through time in rural and urban environments separately, as well as when comparing OM prevalence rates through time in urban settings. Previous studies on the impact of increasing urbanization on human health have observed similar patterns when addressing both stress indicators (Scott & Hoppa, 2018) and infectious diseases (Dangvard Pedersen et al., 2019). It was suggested that the expanding urban environment had an increasingly negative impact on people's health. This growth in health challenges may however have been more nuanced between the late-medieval and post-medieval period, as differences in both CMS and OM prevalence rates were found not to be statistically significant between Alkmaar (urban, late-medieval) and Arnhem (urban, post-medieval). This suggests that the largest change occurred between the early and late medieval periods. Historically, this may be explained by the fact that, during the lifetimes of the individuals under study, both cities faced rapid expansions, which probably caused several concerns due to lack of housing facilities and infrastructure (Hakvoort et al., 2015; van Laar, 1966). As suggested by DiGangi and Sirianni (2017), communal living (i.e., eating and sleeping in the same overcrowded, poorly-ventilated environments) exposed past populations to risk factors for respiratory disease. It is then plausible that the citizens of Alkmaar and Arnhem faced similar challenges in terms of lack of access to adequately ventilated and hygienic environments.

Interestingly, the analysis of CMS among rural populations revealed a similar pattern: no statistically significant association was found between Nieuwerkerke (late-medieval) and Middenbeemster (post-medieval), while there were strong differences between Lent (early-medieval) and Nieuwerkerke, as well as between Lent and Middenbeemster. Historical sources on Dutch urbanization indicate that the co-dependent relationship that characterized Dutch cities

and countrysides had grown from being minimal in the late-Roman/early-medieval period to a strict co-dependence affiliation starting from the 14th century (Blockmans & Hoppenbrouwers 2007; Wintle, 2000). This may offer an explanation on why the patterns in CMS occurrence observed within urban samples extended to rural populations as well: as cities began to grow, their demand for food supplies grew alongside. Rural production quickly developed to satisfy the urban demand, shifting from local agricultural communities to big intensive realities able to provide resources not only to the city but also to the international market, which may have exposed people to risk factors for respiratory disease (van Cruyningen, 2012a; Wintle, 2000). So far, the occupational shift from local farming to large scale production has been rarely addressed in bioarchaeology, although it is likely that it had a significant impact on people's lived experiences. In over five hundred years of agriculture, the Netherlands developed from small, autonomous production communities in the early-medieval period to highly productive agribusiness complexes that relied heavily on technological innovation (e.g., enclosure, mechanization, selective breeding) (Bieleman, 2010; Harskamp, 2009). Such developments likely changed the way people lived and worked, suggesting that there may have been a swift in the risk factors for respiratory health that people living in the countryside were exposed to through time.

In the early-medieval and post-medieval periods, OM rates were found to be higher in rural samples compared to urban ones. As seasonality is today considered among the major risk factors for OM (Kong & Coates, 2009), we argue that people living in the countryside may have spent more time outside than their urban counterparts in the coldest and rainiest months, which may explain the higher rates of OM (Camenisch, 2015). In the early-medieval period, we observed great difference in OM prevalence rates between Aardenburg (urban) and Lent (rural). However, such difference mitigated in the post-medieval period between Arnhem (urban) and Middenbeemster (rural). In Middenbeemster, agriculture had developed to an efficient, intensive, and organized sector that worked predominately for the export market (Aten, 2012; Wintle, 2000). Bieleman (2010) argued that processes of agricultural intensification in the past often had large implications on social welfare: while few, large farmers were able to sensitively increase their capital, many others wage laborers remained landless and lived in indigent conditions. When comparing prevalence rates of OM among rural populations, we noticed a higher (albeit not statistically significant) incidence in Middenbeemster (post-medieval) as opposed to Nieuwerkerke (late-medieval). We suggest that our results may be indicative of rural working conditions worsening following the intensification of production in the post-medieval period (van Laar, 1966; Wintle, 2000).

Interestingly, the late-medieval period showed a reverse trend in OM prevalence rates, with Alkmaar (urban) being more affected than both Nieuwerkerke (rural) and the other urban sites. In the 16th century, Alkmaar was located in a lake area, surrounded by large marshy bodies of water in the process of being drained to allow the city to grow (Streefkerk, 2004; van Nierop, 2000). According to clinical literature, living in damp and cold environments can increase the risk for respiratory disease, especially otitis media (e.g., Haines et al., 2006; Lu et al., 2023). Since Alkmaar showed high rates of respiratory infections compared to the other samples under

study (CMS: 44.8%, OM: 35.2%, IPR: 7.3%), it is possible that the vicinity to the draining land (as opposed to Arnhem, located inland, and Aardenburg, at the time located more than 20km away from the coast) negatively impacted their wellbeing.

In this study, IPR was the least common lesion, affecting only 18 individuals within the whole sample ($N=325$). Although the recording of IPR was often severely impacted by preservation status (e.g., only 6 individuals from Aardenburg had ribs that were suitable for analysis), it must be noted that the observed rates fit well within previous research on IPR (e.g., Bernofsky, 2010; Boyd, 2020). While there was an increase in IPR prevalence rates in the rural environments through time (Lent: 0%; Nieuwerkerke: 2.6%; Middenbeemster: 7.3%), this difference was not statistically significant.

The apparent lower prevalence of lower compared to upper respiratory tract conditions is interesting. This difference may be explained by the fact that the skeletal lesions here referred to as IPR may be indicative of many conditions other than lower respiratory tract infections, which makes it difficult for archaeologists to contextualize their presence (Boyd, 2020; Davies-Barrett et al., 2019; Matos & Santos, 2006; Roberts et al., 1994). Important to note is that most of these conditions are quite challenging for the human organism in comparison to otitis and sinusitis. While even in the past it was probably unlikely for someone to die of either CMS and OM, conditions such as tuberculosis, bronchitis, and pneumonia claimed many lives before the antibiotic era (Huisman, 2018; Kenny, 2021); thus, many people could have died before their skeletons could show any sign of infection (DeWitte & Stojanowski, 2015). In addition, although lesions associated with CMS and OM are well-documented in paleopathology, instances of IPR in both the archaeological and clinical record are less common, indicating that only a small percentage of individuals with lung disease will develop these bony lesions (Ortner, 2003).

We argue that the absence of IPR in our sample is not necessarily indicative of people not suffering from pulmonary conditions, but rather of several individuals not showing signs of ongoing infections. These interpretations fall within what is known as ‘the osteological paradox’, and specifically under the concepts of hidden heterogeneity and selective mortality, as presented by (Wood et al., 1992). As these concepts lead to the possibility that individuals without bone lesions may have been the ones most severely affected, to deal with the osteological paradox it is recommended to utilize age-structured comparisons of disease data to check whether the results correspond to a “paradoxical” interpretation (DeWitte & Stojanowski, 2015). Table S.2 and Figure S.1 show how in most cases lesions are evenly distributed within our age-at-death groups, potentially supporting a “non-paradoxical interpretation of results” (Krenz-Niedbała & Łukasik, 2020).

An important limitation in this study, not just for the interpretation of IPR but also for CMS and OM, is the third concept of the osteological paradox, demographical nonstationary. Our sample derives from cemeteries that were in many cases used for several centuries, meaning that temporal variation in health experiences may have affected our results (DeWitte & Stojanowski,

2015). In addition, migration phenomena (i.e., urban-to-rural and rural-to-urban) were common throughout the late-medieval and post-medieval periods, possibly affecting our findings as well. For example, the presence of CMS and IPR in both Nieuwerkerke and Middenbeemster could be explained by the fact that, in time of urbanization and industrialization, people from the countryside still had to spend time in the city for seasonal work and markets, therefore exposing themselves to greater risk factors for infectious disease than people of Lent whose economy was mainly based on a one-way food exchange with the city (Henderikx, 2012a; Henderikx & De Roode, 2012; Wintle, 2000).

While this study provides an abundance of historical contextual information for the skeletal assemblages in order to accurately interpret the data derived from the individuals and reduce the influence of risk heterogeneity, selective mortality, or population non-stationarity, to completely overcome the osteological paradox is difficult due to the inherent nature of not only skeletal collections, but also of the complex etiologies of respiratory infections themselves. Factors such as seasonality and exposure to adverse climate conditions are difficult to address archaeologically, but are still likely to have had an impact on human respiratory wellbeing. Moreover, as exposure to tobacco smoke is today considered among the most common causes of respiratory infections, its spread across the Low Countries from the 17th century may have impacted OM and CMS rates in the post-medieval period (Gulya, 1994; Roessingh, 1979). This is further supported by the fact that Arnhem was one of the major tobacco production centers in the Netherlands (van Laar, 1966), which likely made access to tobacco very easy for Arnhem workers, potentially contributing to the overall high prevalence rates of respiratory disease in this skeletal population.

Methodological limitations are also likely to have impacted our results to some extent. For example, the preservation status of some individuals only allowed observation of lesions (i.e., CMS, OM, and IPR) on one side (i.e., left or right), therefore making it impossible to determine the laterality of such pathological alterations. Unbalanced sample sizes (e.g., early- and late-medieval periods), then, may have impacted our results to some extent, although we believe that our statistical analyses helped to mitigate the impact of this imbalance. Inclusion criteria and methodological choices (especially in the case of OM) also slightly affected the comparability of our results. Their relevance, however, remains significant and valuable in their own right, as they provide a unique contribution to the existing literature and offer novel insights into urbanization phenomenon.

3.5. Conclusions

This study aimed to investigate the impact Dutch urbanization and industrialization had not only on urban residents, but also on rural communities. The outcome of our analysis pointed out the importance to study urbanization not as a point in time, but rather as an ongoing process that continuously affected human health across centuries. Our results showed how respiratory health changed through time not only in urban samples, but also in rural ones, potentially

suggesting that urbanization and intensification of agricultural production did influence life in the countryside as well. Furthermore, prevalence rates of both CMS and OM suggest that the influence of urbanization on human health did not gradually increase throughout the years, but rather affected communities more severely between the early-medieval and late-medieval periods, when the first cities significantly developed.

Bearing in mind the limitations of our study, which mainly related to the complex etiology of respiratory diseases and to the nature of bioarchaeological samples, we can conclude that our research shed light on a new, significant aspect of urbanization: its continuity across time and space, and the importance of addressing such aspects in future bioarchaeological studies of urbanization. Our results showed how generalizations about (respiratory) health in different populations should not be recommended when studying urbanization: rather, it is important to consider and to keep addressing the unique social, economic, and environmental factors that may have impacted the health of each population.

Supporting information

Supplementary materials for this paper are available on the publisher's website: <https://doi.org/10.1016/j.ijpp.2023.07.003>

Data availability statement

The datasets generated and analyzed during the current study are available at: Casna, Maia, 2022, "Data for: "A Distant City"", <https://doi.org/10.17026/AR/9OHROE>, DANS Data Station Archaeology.

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Chapter 3

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CHAPTER 4

Urban beings: a bioarchaeological approach to socioeconomic status, cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia, and sinusitis in the early-modern Northern Low Countries (1626-1850 CE)

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6 In this version of the article, references to “BC” and “AD” have been updated to “BCE” and “CE”, respectively, to align with the terminology consistently used throughout this dissertation. All other content remains unchanged from the original publication.

Abstract

Starting from the 12th century, the Netherlands experienced substantial socioeconomic change. Several towns expanded in terms of size and industrial production, making the gap between rich and poor even greater. Access to certain resources (e.g., food, living spaces, etc.) became largely dependent on socioeconomic status, with the rich being able to afford an overall better lifestyle than the poor. The aim of this study was to determine whether these contrasting urban life experiences impacted the health of citizens. To test our hypothesis that poorer citizens would be more severely challenged by the urban environment than richer ones, we assessed the presence of non-specific stress markers (i.e., cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia) and chronic maxillary sinusitis in four urban populations, representative of different socioeconomic statuses. Analysis of skeletal remains revealed statistically significant differences in the prevalence of cribra orbitalia between different socioeconomic groups. Furthermore, it highlighted significant differences in the prevalence of porotic hyperostosis, linear enamel hypoplasia, and sinusitis between the low and middle-low socioeconomic classes. These results reflected the complicated relationship between socioeconomic status and sources of physiological stress. Living in the city led people to experience very different lives, albeit similar health challenges. Factors such as working conditions, food availability, and cultural practices likely had an important role in shaping the health of Dutch citizens. As our findings have significant implications for understanding the complex reality of the urbanization phenomenon, more research into the prevalence of the non-specific stress markers in relation to socioeconomic status is warranted.

Keywords: Non-specific stress indicators; Social stratification; Post-medieval

4.1. Introduction

For thousands of years, urban systems have shaped the development of human societies. Traces of urbanization are documented all over the world starting from the 4th millennium BCE, but it was only from the 10th century onwards that the urbanization phenomenon became systematic, intensive and, ultimately, global (Creekmore & Fisher, 2012; Liverani, 2006; Zuiderhoek, 2016). Because of its complexity and longevity, the urbanization process has drawn the attention of many scholars from different disciplines. Archaeologists, economic historians, and historical demographers have often focused on the implications that urbanization had for human health and wellbeing. In fact, while cities represented the heart of technological development and societal economic growth, they often had deep implications for a variety of human issues, such as high unemployment rates, poor working conditions, inadequate housing, inaccessibility to healthcare, air pollution, and disease outbreaks (e.g., Rubin, 2020; Simonton & Salmi, 2019; Torres et al., 2019; Western & Bekvalac, 2019).

In the last two decades, urbanization has become of great interest to bioarchaeologists, as the analysis of skeletal remains allows for the assessment of those embodied experiences that are often overlooked by historical research. Many bioarchaeological studies have actively investigated the effects of urban development on human health, presenting different strategies through which we can reconstruct past life challenges of citizens, and yielding varying results (e.g., Betsinger & DeWitte, 2020; Lewis, 2016; Mays & Brickley, 2018; Sparacello et al., 2017). In this framework, the assessment of non-specific stress indicators such as cribra orbitalia, porotic hyperostosis, and linear enamel hypoplasia is among the most common approaches, albeit being sometimes seen as problematic (Betsinger & DeWitte, 2020; Edinborough & Rando, 2020). In fact, in the past years, several scholars have raised concerns over the fact that no consensus exists on the exact meaning of “stress”, and that very few bioarchaeological studies on stress markers have been addressing the issue. Despite that, it seems to be generally accepted in bioarchaeology to define stress as *“a physiological change caused by strain on an organism from environmental, nutritional, and other pressures”* (Reitsema & McIlvaine, 2014, p.181). While the concept of health is also very complicated to define, physiological changes in the body as a result of stress (such as cribra orbitalia, porotic hyperostosis, and linear enamel hypoplasia) may be seen as “unhealthy”, despite numerous effective examples of both human adaptation and adaptability responses that remain extremely variable depending on the context (Edinborough & Rando, 2020; Seckler, 1980; Stuart-MacAdam, 1995; Reitsema & McIlvaine, 2014). For example, when looking at rates of enamel hypoplasia, cribra orbitalia, and osteoperiostitis in the Late Shang dynasty in China (1250-1046 BCE), Zhang and colleagues (2016) found them to be indicative of significant physiological stress caused by factors associated with urbanization (e.g. poor nutrition, lack of access to healthcare, etc.). However, Betsinger & DeWitte (2017) observed how the same skeletal indicators did not significantly change with increasing urbanization in Polish medieval cemeteries (ca. 950-1250 CE). In addition, Lewis (1999; 2002) investigated linear enamel hypoplasia and cribra orbitalia in several British urban and rural medieval and post-medieval sites (850-1859 CE) and found no correlation between lesions and time period. On the other

hand, Roberts (2009) compared data from different studies on cribra orbitalia, linear enamel hypoplasia, stature, dental caries, and chronic maxillary sinusitis in several medieval populations from England (ca. 450-1500 CE), and argued that urbanization did in fact compromise health in the samples under study. In spite of that, several comparisons of sinusitis point prevalence between rural and urban populations in Europe have found no consistent relationship between respiratory health and urban living (e.g., Bernofsky, 2010; Casna et al., 2021; Krenz-Niedbala & Łukasik, 2016).

The studies above represent only a small portion of the countless published bioarchaeological analyses on urbanization,⁷ but they indeed demonstrate the complex relationship between settlement patterns, the urbanization process, and skeletal indicators of survived physiological stress. While bioarchaeological research has now widely investigated the impact of urbanization in terms of comparisons across time and space, it has rarely focused on exploring how urban living experiences varied based on socioeconomic factors, and whether these differences had an impact on human health. As problems such as poverty, hunger, and inaccessibility to healthcare are all commonly associated with urbanization, they usually impact lower socioeconomic classes more severely than upper ones (Liddle, 2017; Tremblay & Reedy, 2020). In the past, the environment in which an individual lived and worked varied greatly on the basis of socioeconomic class, meaning that even living in the same town could lead to extremely different life and health experiences. For example, Yaussy (2019) examined patterns of stress indicators in two samples from the British industrial era (1711-1857 CE) and observed that higher socioeconomic status individuals were less likely to show cribra orbitalia than those who were of lower socioeconomic status. Similarly, Palubeckaite and colleagues (2002) used linear enamel hypoplasia as a proxy for child morbidity and mortality rates in several Danish and Lithuanian populations dating from the 12th to the 19th centuries and suggested both lower morbidity and mortality in the highest socioeconomic class within the total sample. However, Robb and colleagues (2001) compared skeletal stress markers to various grave goods considered indicative of socioeconomic status in an Italian proto-urban sample from the 7th-3rd centuries BC and found no correlation between variables. This again highlights the variability urbanization had on everyday life and lived experiences, not only through time and space, but also based on sociocultural conditions.

4.1.1. Urbanization, social stratification, and health in the Netherlands

While most of European countries started their urbanization process by the end of the 10th century, Dutch cities only began forming from the 12th century onwards (de Vries, 1984). In less than 100 years, the Netherlands became one of the most urbanized areas on the European continent, with approximately one in three inhabitants reportedly living in an urban center (de Vries, 1984; van Zanden, 1993). The sudden development of Dutch towns suggests an equally sudden specialization of economic activities. As more markets for products and labor developed, workers went from versatile agricultural laborers to urban employees specialized in only one

7 Betsinger and DeWitte (2021) offer a broad and complete overview of bioarchaeological studies published on urbanization.

or two tasks (Blockmans et al., 1980; van Bavel, 2010). The social structure that evolved with the urbanization of Dutch centers was complex and divided into four rigidly marked categories: the upper class, the business class, the working class and, finally, an impoverished social group composed of individuals without possessions that public administration considered insignificant (Wintle, 2000). Unlike other parts of Europe, the Netherlands lacked a conservative, strong aristocratic group, as the Dutch elite was mostly composed of wealthy financiers who rarely held a noble title (Wintle, 2000). The true, administrative power was therefore not in the hands of noble families but in those whose fortunes were made as merchants or investors. Both artisans and small businessmen comprised the middle working class of most Dutch centers; autonomous workers such as sailors, shipbuilders, and fishermen were part of this class that, in the Low Countries, had generally higher standards of living than other European cities (ten Hove, 2005). The lowest, poorest socioeconomic class (of which most factory workers were part) had no say in public and administrative matters. They were generally not considered to be part of the broader society, and their limited socioeconomic means prevented them from improving their lived environment (i.e., occupation, housing, access to food resources, etc.) (ten Hove, 2005; Wintle, 2000).

Although in the Netherlands the quality of life was reportedly marked by less disparity between classes than elsewhere, social stratification in the early-modern Northern Low Countries⁸ remained rigid until the second half of the 19th century and likely led people to experience the urban environment in very different ways (Wintle, 2000). For example, in the early-modern period (ca. 1453-1800 CE), taxes were notoriously high throughout the Low Countries and, although they were always based on each family's income, they were often miscalculated and particularly hard to pay for the poorest socioeconomic classes (Lintsen & Thoben, 2009). Historical sources suggest that, until at least the 19th century, most of the population suffered from a light but chronic form of malnutrition which, together with inadequate housing and working environments, probably led to an increase in infectious disease among the less wealthy (van Poppel, 2018; Wintle, 2000). The regulation and professionalization of the medical field came slowly in the Low Countries and, although programs to guarantee access to healthcare to less wealthy citizens were well established already in the 16th century, health care for the sick remained almost exclusively a burden of families and neighbors until modern times (Houwaart, 2018; Huisman, 2018).

While a deep division among urban living experiences in the Northern Low Countries seems evident from historical literature, to date the number of bioarchaeological studies that focus on socioeconomic status differences and the implications for lived experience in this region is extremely limited. A thorough search of the relevant literature yielded in fact only one related article: Panhuysen and colleagues (1997) studied the spread of respiratory disease using maxillary

8 The most widely accepted definition of the Low Countries includes the modern countries of Luxembourg, Belgium, and the Netherlands. In this study, the authors use the term "Northern Low Countries" to indicate the area currently encompassed by the Netherlands.

sinusitis as a proxy in three Dutch rural and urban populations of mixed social status. While higher status individuals showed lower infection rates than low-status individuals, no significant relationship was observed between wealth and maxillary sinusitis prevalence, indicating perhaps that both rich and poor were equally exposed to risk factors for respiratory disease (Panhuysen et al., 1997).

Contributing to this scarce body of literature, our study investigates the presence of commonly used skeletal stress markers (i.e., cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia) and of chronic maxillary sinusitis among three post-medieval populations (1626-1850 CE) from the Netherlands for which socioeconomic status can be inferred (i.e., low; middle-low; middle-high; high). While chronic maxillary sinusitis was considered here as an indicator of respiratory health, cribra orbitalia, porotic hyperostosis, and linear enamel hypoplasia were chosen because their presence is widely recorded in bioarchaeological literature and is therefore highly comparable with other studies. Our main hypothesis was that the urban experience of individuals from wealthy categories (i.e., high and middle-high socioeconomic status) would result in less physiological stress than poorest classes (i.e., middle-low and low socioeconomic status), and that richer individuals would therefore show lower frequencies of stress markers and respiratory disease than poor ones.

4.2. Materials

The skeletal collections used here originate from three major Dutch centers: Arnhem, Zwolle, and Eindhoven (Table 4.1; Figure 4.1). The collections are today curated at the Laboratory for Human Osteoarchaeology, Faculty of Archaeology, Leiden University. Together, these three sites represent a window into the lived experiences of various socioeconomic classes prior to the industrial revolution in the Netherlands.

Table 4.1. Skeletal collections included in this study.

	Date	Socioeconomic status
Eindhoven, inside the church	1650-1850 CE	High
Zwolle	1681-1828 CE	Middle-high
Eindhoven, outside the church	1650-1850 CE	Middle-low
Arnhem	1626-1829 CE	Low

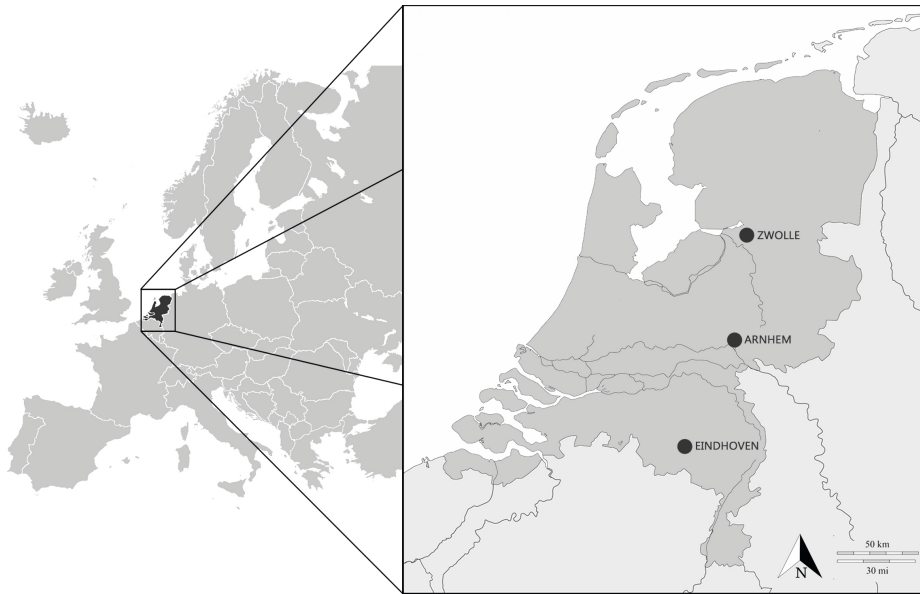


Figure 4.1. Map of the Netherlands showing the location of the sites under study. Image made by M. Casna.

4.2.1. Arnhem

The skeletal assemblage of Arnhem was excavated in 2017 in the courtyard of the St. Eusebius' Church, and it comprises approximately 350 skeletons interred between 1626 and 1829 CE, when the cemetery was moved outside the city walls (Baetsen et al., 2018; Zielman & Baetsen, 2020). According to Baetsen and colleagues (2018), the individuals excavated at St Eusebius belonged to a low socioeconomic class due to the fact that they were excavated from the northern side of the churchyard, which at the time was the cheapest location for people to be buried. In the early-modern period, a burial in the church was very expensive, as the church itself was considered the most sacred place for the body to be interred (Van Steen & Pellenbarg, 2006). Dutch burial costs were reportedly prohibitive for most citizens and sometimes could not be met without the financial help of the government (Daniell, 1997; Van Steen & Pellenbarg, 2006). The cheapest (but still somewhat acceptable) place for someone to be buried, then, was outside the church, on the northern side of the graveyard, where fees were low enough to be paid through poor relief actions (Daniell, 1997).

Between 1626 and 1829 CE, Arnhem was a growing and flourishing center of the province of Gelderland. Systematic immigration, which had started in 1795, caused the population to grow to almost 20,000 inhabitants by the first half of 19th century, making Arnhem almost as populated as other major Dutch centers (Lourens & Lucassen, 1997). People from all over Gelderland came there in search of employment, which was mainly offered in small-scale productions such as the tobacco industry, shoemaking, and typography, where the individuals buried at St. Eusebius likely worked (Baetsen et al., 2018; van Laar, 1966). Factory work in the early-modern period

was notoriously hard and problematic; working hours varied between 12 and 20 per day, and the salary was barely enough to allow employees to rent a small house (van Braam, 1978). As the housing market was prohibitively expensive, living facilities were usually provided by the employer and deducted from the workers' salaries. Workers' housing was quickly put together to accommodate as many people as possible and usually housed two or more families in only one room (van Laar, 1966). Good hygiene, clean air and water, and privacy were luxuries workers in Arnhem could not afford, and these precarious living conditions continued to be the norm until the end of the 19th century, when campaigns were launched to improve the workers' situation (van der Woud, 2010; Wintle, 2000).

4.2.2. Zwolle

The settlement of Zwolle originated in the Middle Ages and rapidly gained importance thanks to its significant economic growth (ten Hove, 2005). It acquired the title of city in 1230, while in 1798 it was officially proclaimed capital of the Overijssel province (ten Hove, 2005). Becoming the capital allowed Zwolle's elite to rapidly gain power over the city's administration and to start investing systematically into the economic development of new trade routes with both Germany and Holland (de Vries, 1961; ten Hove, 2005). Historical sources show that the average income per citizen in Zwolle was the highest in the Overijssel region and that it was sometimes double the income of other Dutch cities (ten Hove, 2005).

The sample included in this research was excavated in 1987-1988 from inside the Broerenkerk and originally consisted of 529 individuals (Aten, 1992a). The comparison of osteological data with church records and the information on the gravestones allowed for the personal identification of 141 individuals, all members of the middle-upper socioeconomic class of Zwolle (i.e., merchants, municipal officers, and small investors) (Aten, 1992a). In the post-medieval period, the Broerenkerk was one of the many churches of Zwolle to host the burial of wealthy citizens. While the city's elite were willing to pay good money for being buried inside the Grote of St. Michaelskerk (Zwolle's main church), middle-high socioeconomic status individuals opted for cheaper (but still sacred) spots in smaller churches such as the Broerenkerk itself (Aten, 1992a; Hagedoorn, 1992; ten Hove, 2005). Previous osteoarchaeological research on the individuals of Zwolle included in this study revealed that, despite being among the wealthiest citizens, the people buried in the Broerenkerk likely suffered from Zwolle's restrictive political and economic situation. In fact, several cases of osteomyelitis, rickets, and spinal curvatures (i.e., scoliosis and kyphosis) were observed. In addition to their congenital etiology, these conditions were also considered indicative of a generally poor state of health (Aten & Clevis, 2019).

4.2.3. Eindhoven

The third population was excavated at the church of St. Catharina in Eindhoven, a city located in the South of the Netherlands. Excavation was carried out between 2005 and 2006, and a total of 752 skeletons (of which 287 are available for research at Leiden University) were recovered (Nollen, 2013). Skeletons were excavated both inside and outside the church, and their location within the building was considered indicative of their socioeconomic status (i.e., inside=high,

outside=middle-low) based on the diverse costs associated with burying people in different locations (Melssen, 2013). In fact, the fee associated with a choir burial at St. Catharina between 1637 and 1640 was recorded as $\frac{1}{4}$ of a guilder, while the price would have been half for a burial within the church cemetery (de Vries & Van der Woude, 1997; Melssen, 2013). In the 17th century, the average wage-earnings for a middle-income family were about 250 guilders annually. Wealthy citizens and nobles, on the other hand, could live on an annual income of 1,000 and up to 5,000 guilders, respectively (de Vries & Van der Woude, 1997). It is then clear that the costs for burials for the lower-class members of society were comparatively prohibitive. Therefore, it was deduced that individuals located outside of the church were of lower socioeconomic status than those buried inside the church, although still wealthier than those from Arnhem's Eusebius' Church, who in most cases were buried without even a headstone (Zielman & Baetsen, 2020).

4.2.3.i. Eindhoven inside the church

St. Catharina was Eindhoven's most important church, and the individuals excavated in the choirs are considered representative of Eindhoven's highest socioeconomic class, composed of clergy, nobles, and gentry families. While life in the Netherlands was difficult for low-income citizens, living conditions were likely different for those who could rely on a steady income. Dutch elite lived in luxurious, refined mansions with more than ten rooms to accommodate the needs of just one family (ten Hove, 2005). Richer families rarely resided in the city center; they rather lived in dedicated areas, far from the dirty and cramped streets where urban activities had developed (ten Hove, 2005). Putting food on the table was rarely a problem for members of the Dutch elite; fresh meat, hard grain wheat bread, butter, and eggs were consumed daily, despite increasing prices due to rising demand (Gentilcore, 2015). Previous research on the individuals buried in St. Catharina has revealed overall high rates of diffuse idiopathic skeletal hyperostosis, possibly indicating the negative impact of excessive animal protein consumption on richer individuals (Baetsen & Weterings-Korthorst, 2013; Western & Bekvalac, 2019).

4.2.3.ii. Eindhoven outside the church

Burials in the churchyard of St. Catharina are considered representative of the middle-lower socioeconomic class of Eindhoven. These were the workers who were sometimes still dependent on an employer for their salary, but who could still count on a stable income and inclusion in the local social economy (Melssen, 2013; Nollen, 2013; Wintle, 2000). For those people, living conditions were not always ideal. They did, however, engage in less strenuous activities than lower-socioeconomic class citizens; working in their own workshops, municipal offices, or in the city markets granted these people acceptable working hours, in warm, bright, and ventilated environments. This could potentially be reflected in the overall low prevalence rates of degenerative joint disease (osteoarthritis spine: 37%; osteoarthritis appendicular: 39%) observed on 206 adult individuals from in and outside the St. Catharina church in Eindhoven, although further analyses would be required investigating prevalence rates between in- and outside the church, as well as across age categories (Baetsen & Weterings-Korthorst, 2013).

4.3. Methods

The total sample consisted of 252 adult individuals (i.e., age-at-death ≥ 20 years old) (Table 4.2; Table 4.3). Key features for including individuals in the total sample were orbital roofs, cranial vault, maxillary sinuses, as well as both upper and lower dentition. For inclusion in the sample, at least two among the features presented above were required to be $>25\%$ complete.

Table 4.2. Demographic composition of the total sample, divided by sex.

	Males	Females	Total (%)
Arnhem	62	47	109 (42.9)
Zwolle	44	39	83 (32.7)
Eindhoven, inside the church	9	13	22 (8.7)
Eindhoven, outside the church	22	18	40 (15.7)
Total (%)	137 (53.9)	117 (46.1)	254 (100)

Table 4.3. Demographic composition of the total sample, divided by age-at-death.

	Young adult (20-34 years)	Middle adult (35-49 years)	Old adult (50+ years)	Total (%)
Arnhem	39	45	25	109 (42.9)
Zwolle	20	43	20	83 (32.7)
Eindhoven, inside the church	11	3	8	22 (8.7)
Eindhoven, outside the church	14	13	13	40 (15.7)
Total (%)	84 (33.1)	104 (40.9)	66 (26.0)	254 (100)

For every individual, sex was estimated based on the observation of morphological features on the skull (i.e., nuchal crest, mastoid process, supraorbital margin, prominence of glabella, and mental eminence) (Buikstra & Ubelaker, 1994) and os coxae (Bruzek, 2002; Phenice, 1969). Age estimations of adults were made using morphologic characteristics of the pubic symphysis according to Brooks & Suchey (1990) and of the auricular surface (Lovejoy and colleagues, 1985). The age groups were defined as young adult (approx. 20-34 years), middle adult (approx. 35-49 years), and old adult (50+ years), according to Buikstra & Ubelaker (1994).

The presence of each lesion (i.e., cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia and chronic maxillary sinusitis) (Figure 4.2) was macroscopically assessed for all skulls and noted as either 'absent' or 'present'.

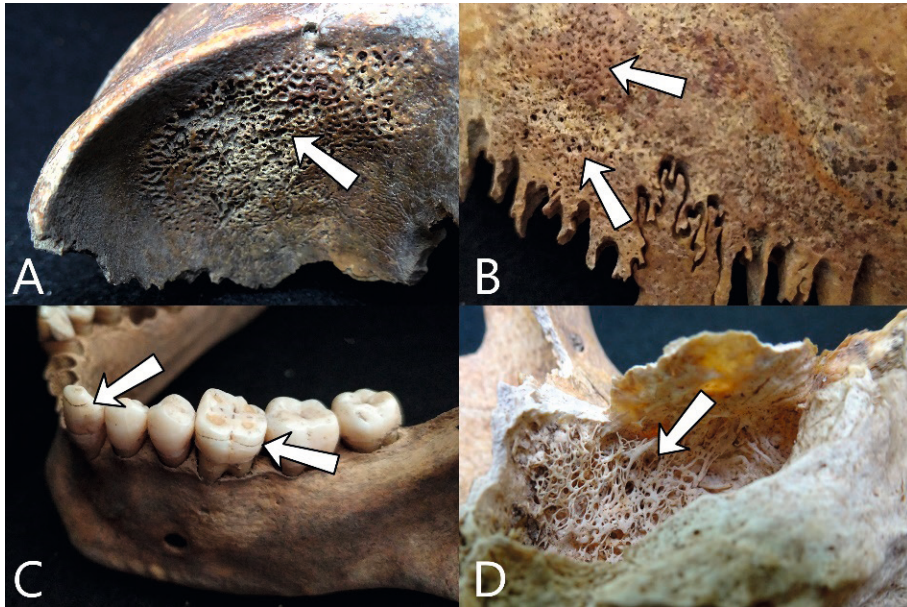


Figure 4.2. Examples of lesions observed in this research, respectively: A: Cribr orbitalia, B: Porotic Hyperostosis, C: Linear Enamel Hypoplasia; and D: Chronic Maxillary Sinusitis in the form of ‘spicule-type bone formation’, according to Boocock et al. (1995). Lesions are indicated by the white arrows. Photographs by M. Casna.

Cribr orbitalia was scored as ‘present’ when either one or two of the orbital roofs showed pitting (Waldron, 2008). It was scored as ‘absent’ when observable orbital roofs presented a thin, smooth surface with no bony alterations. Although being among the most studied lesions in bioarchaeology, the etiology of cribr orbitalia remains highly debated (e.g., Brickley, 2018; Cole & Waldron, 2019; Rivera & Mirazón Lahr, 2017; Rothschild et al., 2021; Walker et al., 2009). Most bioarchaeologists associate cribr orbitalia with anemia, vitamin deficiencies, and infectious disease (Brickley, 2018; O’Donnell et al., 2020; Walker et al., 2009). Given the association with anemia as well as scurvy and rickets (iron, vitamin C and D deficiency, respectively), it is agreed that some sort of dietary deficiency can play a role in most cribr orbitalia cases (Walker et al. 2009). Such dietary deficiencies could stem from restricted access to resources, as well as from intestinal parasitic infections (Hesham et al., 2004; Ihejirika et al. 2019).

Porotic hyperostosis was scored as ‘present’ when the cranial vault presented clearly identifiable areas of pitting and porosity on the external surface, and ‘absent’ when the whole observable cortical surface was smooth and unaltered (Oxenham and Cavill, 2011; Walker et al., 2009). Rates of porotic hyperostosis are often associated with a wide range of pathological or traumatic conditions, such as neoplasms, infectious diseases, anemia, injury, and vitamin deficiencies (Brickley, 2018; Mays & Brickley, 2018; Ortner, 2003; Ortner & Mays, 1998; Walker et al., 2009). Based on clinical evidence, Walker and colleagues (2009) suggested that high rates of porotic hyperostosis in archaeological populations may be indicative of a synergy between poor hygienic

conditions, infectious diseases, and vitamin B₁₂-deficient diets. In fact, nutritional megaloblastic anemia (a form of macrocytic anemia caused by deficiencies of either vitamin B₁₂ or B₉) can lead to marrow hyperplasia and, subsequently, to the associated porosity of the cranial vault (Walker et al., 2009). While vitamin B₉ is commonly found in a large variety of foods such as eggs and vegetables, vitamin B₁₂ is mostly derived from animals; therefore, it was suggested that populations with minimal access to animal foods would be at higher risk for megaloblastic anemia (Walker et al., 2009).

Linear enamel hypoplasia (or “developmental defects of enamel”) was observed macroscopically in all types of permanent, undamaged teeth and recorded as either ‘present’ or ‘absent’ throughout the whole dental arcade. It was scored as present in cases where at least one tooth manifested a reduction in the normal thickness of enamel, usually in the form of horizontal grooves (Riga et al., 2014; Ritzman et al., 2008). In bioarchaeology, linear enamel hypoplasia is considered indicative of metabolic stress during childhood, as the physiological disruptions that cause it only affect the portion of the crown that is in the process of forming (Dąbrowski et al., 2021; Guatelli-Steinberg, 2004; Ritzman et al., 2008). Although the precise etiology of linear enamel hypoplasia is not well understood yet, it is most commonly associated with protein and vitamin deficiencies, childhood disease and injuries (Armelagos et al., 2009; Nunn, 2001; King et al., 2002; Tomczyk et al., 2012).

Finally, chronic maxillary sinusitis was considered as ‘present’ in those individuals whose sinuses showed signs of either bone deposition or absorption on one of the sinus walls, according to the standards set by Boocock and colleagues (1995). Chronic maxillary sinusitis was scored as ‘absent’ in cases where the sinus presented smooth surfaces with little or no associated pitting. As dental disease (i.e., severe caries lesions, abscesses, and granulomas) can affect and potentially cause sinusitis (Patel & Ferguson, 2012), individuals presenting periapical lesions in the upper premolars and molars were excluded from analysis.

Fragmented sinuses were examined macroscopically, with the use of a magnifying glass when needed. Complete skulls were examined with a flexible medical endoscope (Pentax, model: FNL-10RBS, $\varnothing=4\text{mm}$; view angle=30°).⁹ In recent comparative studies of sinusitis, bioarchaeologists have considered it as indicative of air quality and therefore have used it as an indicator of how urbanization challenged the respiratory health of citizens (e.g., Bernofsky, 2010; Boyd, 2020; Casna et al., 2021). Although exposure to polluted air is among the most common causes of sinus infection, both tobacco smoking and periodontal disease are known risk factors in clinical practice, although their impact on archaeological populations has not been fully explored yet (Lieu & Feinstein, 2000; Patel & Ferguson, 2012).

Results were analyzed statistically using SPSS for Windows, version 25.0. A p -value ≤ 0.05 was considered to be statistically significant. Chi-squared tests were used to investigate significance

9 See Casna and colleagues (2021) for how the endoscope was inserted into the maxillary sinuses.

in the relationship among different populations and the occurrence of stress markers and chronic maxillary sinusitis. In the cases where expected cell count was below 5, Fisher's Exact test was used instead.

4.4. Results

Figure 4.3 displays the observed prevalence of cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary sinusitis between the four socioeconomic classes under study. While linear enamel hypoplasia and chronic maxillary sinusitis have similar prevalence across sites, cribra orbitalia and porotic hyperostosis show greater variance. The smallest sample ($n=22$), Eindhoven inside the church (high socioeconomic status), almost always displayed the highest prevalence rates of lesions, with the exception of linear enamel hypoplasia, for which Zwolle (middle-high status) and Eindhoven outside the church (middle-low status) showed higher frequencies.

When testing differences in the occurrence of each lesion across all populations, Fisher's exact test revealed a significant correlation between sites and cribra orbitalia (Table 4.4), with Eindhoven inside the church reporting the highest prevalence rate. No other significant relationships were noted for the other lesions under study.

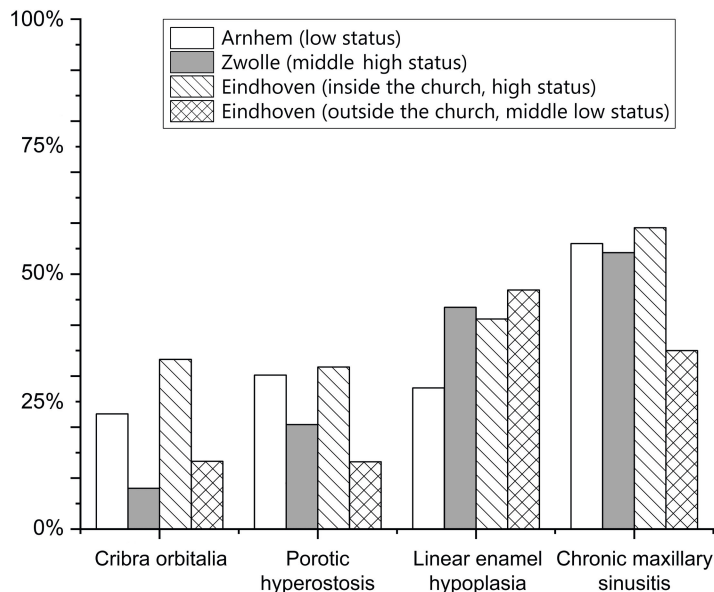


Figure 4.3. Prevalence of cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia and chronic maxillary sinusitis for all samples under study.

Table 4.4. Summary of chi-squared test results, per site (df=3).

	Cribra orbitaliat			Porotic hyperostosis			Linear enamel hypoplasia			Chronic maxillary sinusitis		
	N	n (%)	χ^2	p	N	n (%)	χ^2	p	N	n (%)	χ^2	p
Arnhem	106	24 (22.6)	10.352	.013*	106	32 (30.2)	5.859	.119	94	26 (27.7)	6.138	.105
Zwolle	83	7 (8.4)			83	17 (20.5)			62	27 (43.5)		
Eindhoven, inside the church	18	6 (33.3)			22	7 (31.8)			17	7 (41.2)		
Eindhoven, outside the church	30	4 (13.3)			38	5 (13.2)			32	15 (46.9)		

N= total of individuals with observable feature; n= total of individuals showing lesions; †=Fisher’s exact test; *=statistically significant at 95% confidence level.

In addition, differences were also investigated per site (Table 4.5) to gain a more detailed understanding of how lesions were distributed within the sample. Chi-squared tests revealed statistically significant relationships between Arnhem and Eindhoven outside the church for most lesions (i.e., porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary sinusitis). In addition, there was a significant difference in linear enamel hypoplasia between Zwolle and Arnhem, and one in chronic maxillary sinusitis between Zwolle and Eindhoven outside the church. Finally, cribra orbitalia showed statistically significant difference both between Zwolle and Eindhoven inside the church and between Zwolle and Arnhem.

Table 4.5. Summary of chi-squared test results, per site (df=1).

Cribra orbitalia			
	Eindhoven, outside the church	Arnhem	Zwolle
Eindhoven, inside the church	† $p=.145$	† $p=.374$	† $p=.011^*$
Eindhoven, outside the church		$\chi^2=1.239, p=.266$	† $p=.479$
Arnhem			$\chi^2=6.853, p=.009^{**}$
Porotic Hyperostosis			
	Eindhoven, outside the church	Arnhem	Zwolle
Eindhoven, inside the church	† $p=.102$	$\chi^2=.023, p=.880$	$\chi^2=1.267, p=.260$
Eindhoven, outside the church		$\chi^2=4.249, p=.039^*$	$\chi^2=.940, p=.332$
Arnhem			$\chi^2=2.284, p=.131$
Linear enamel hypoplasia			
	Eindhoven, outside the church	Arnhem	Zwolle
Eindhoven, inside the church	$\chi^2=.146, p=.703$	$\chi^2=1.259, p=.262$	$\chi^2=.031, p=.861$
Eindhoven, outside the church		$\chi^2=4.016, p=.045^*$	$\chi^2=.094, p=.759$
Arnhem			$\chi^2=4.204, p=.004^{**}$
Chronic maxillary sinusitis			
	Eindhoven, outside the church	Arnhem	Zwolle
Eindhoven, inside the church	$\chi^2=3.351, p=.067$	$\chi^2=.073, p=.787$	$\chi^2=.167, p=.683$
Eindhoven, outside the church		$\chi^2=5.144, p=.023^*$	$\chi^2=3.994, p=.046^*$
Arnhem			$\chi^2=.058, p=.809$

†=Fisher's exact test (two-tailed p-value); *=statistically significant at 95% confidence level; **=statistically significant at 99% confidence level.

4.5. Discussion

The results of our analysis reflect the complicated relationship between socioeconomic status and sources of physiological stress. Although they do not fit completely into our initial hypothesis (i.e., low socioeconomic status would show higher occurrence of lesions), these results highlight

the complex and multifaceted nature of urban living by revealing variable relationships between welfare and health.

In accordance with our main hypothesis, Arnhem (i.e., low socioeconomic status) showed overall higher-than-average stress marker prevalence rates when compared to the other populations under study. This may be indicative of harsh living conditions (e.g., limited access to healthcare, appropriate housing facilities, access to food resources) consistently affecting poor people through their lives. Prevalence rates of both porotic hyperostosis and chronic maxillary sinusitis were significantly higher in Arnhem than in Eindhoven outside the church, perhaps highlighting a substantial gap in the quality of living between low and middle-low class citizens. According to historical sources, both living and working spaces varied greatly based on wealth, as well as access to certain foods and to proper medical care (ten Hove, 2005; van Poppel, 2018; Wintle, 2000). Individuals from Eindhoven outside the church were reported to have access to overall better housing facilities than the ones from Arnhem, where several cases of extreme sanitary conditions were reported to the municipality throughout the 18th century (ten Hove, 2005; van Laar, 1966). Factory work was also likely impacting the physiological and respiratory health of Arnhem individuals to a greater extent: in fact, factory employees were often exposed to dust and chemicals, and occupational accidents due to unsafe working environments were common (van Braam, 1978; Wintle, 2000). We argue therefore that the differences in living conditions between low and middle-low socioeconomic classes were somehow characterized by greater disparity than among the upper classes whose status and wealth may justify more subtle differences in living standards.

One unanticipated finding was that, within the total sample, Arnhem showed the lowest rate of linear enamel hypoplasia. As linear enamel hypoplasia is considered to be the result of childhood physiological stress, low occurrence rates in Arnhem could indicate that individuals from the lowest socioeconomic class were exposed to less chronic stress as children than individuals from higher socioeconomic classes. However, it must be noted that the entire post-medieval period in the Netherlands was plagued by several dramatic epidemics that in most cases prevented the urban population from growing (Wintle, 2000). For example, in Zwolle, 71 people were buried due to a dysentery epidemic in 1447, followed by at least twice as many in 1789 due to a smallpox outbreak (Hagedoorn, 1992).¹⁰ In this framework, it is unlikely that individuals from the poorest socioeconomic contexts would not be exposed to the significant physiological stress caused by these epidemics. Even if poor relief organizations were active throughout the 18th and 19th centuries and considered crucial for the survival of many families, their actions are unlikely to have significantly reduced the physiological stress of less wealthy citizens such as the ones from Arnhem (van Leeuwen, 1994). We argue that our results are indeed indicative of the fact that all socioeconomic classes experienced some kind of chronic stress during childhood

10 It must be noted that, even if the dates of these outbreaks coincide with the time window in which the individuals analysed here were likely alive, it is not possible to determine whether these people were directly associated with them.

but, while people from Arnhem may have succumbed to those before developing linear enamel hypoplasia, richer individuals likely had greater access to treatments, foods, and care, and were ultimately able to survive to adulthood (DeWitte & Stojanowski, 2015; O'Donnell & Moes, 2021). This interpretation suggests the presence in this population of a mortality bias, relating to the osteological paradox and to the hypothesis that those who overcame periods of stress (in this case, resulting in linear enamel hypoplasia) were the ones more likely to survive (DeWitte & Stojanowski, 2015; Wright & Chew, 1998). Unfortunately, overcoming the mortality bias in bioarchaeology has been challenging so far (DeWitte & Stojanowski, 2015). We present the full demographic profile of the samples in the supplementary information (Table S1; Figure S1). These data do, broadly speaking, support our suggestions that individuals from low-status Arnhem may have died young, while individuals from higher status populations, such as Zwolle, were more likely to live longer. However, these data are still inherently limited by demographic non-stationarity, preservation bias, and excavation constraints.

Chronic maxillary sinusitis prevalence rates in Arnhem, Zwolle, and Eindhoven inside the church ranged between 50% and 60%. These results are similar to those reported by previous research investigating chronic maxillary sinusitis in several Dutch populations of different socioeconomic statuses from both the medieval and post-medieval periods (Casna et al., 2021; Panhuysen et al., 1997). In particular, Panhuysen and colleagues (1997) analyzed several medieval collections to investigate sinusitis in relation to socioeconomic status, but did not find any significant correlation. Similarly, Boyd (2020) examined the effects of status on respiratory stress in 18th-19th century London and found no differences in maxillary sinusitis rates between middle- and upper-socioeconomic class individuals. In contrast to these findings, however, our results show statistical significance between Eindhoven outside the church and both Zwolle and Arnhem. We did not find any statistical significance between Eindhoven outside the church and Eindhoven inside the church ($\chi^2=3.351$, $p=0.067$), although we noted a 24.1% difference in frequencies between the two populations (Eindhoven outside the church: 35.0%; Eindhoven inside the church: 59.1%). We argue that the overall low rates of chronic maxillary sinusitis in Eindhoven outside the church may be indicative of the fact that middle-low status people were mostly involved in activities that gave them a degree of control over their working environment (e.g., own workshop opening times, amount and nature of workload, time spent outside during the market, etc.), which may have prevented them from having prolonged exposure to pollutants. In the past, just like today, living in a city probably meant that respiratory hazards were numerous. Particulate matter and other pollutants were generated through either the use of fireplaces or stoves and affected citizens both at home and in the workplace. Industry workers such as the ones from Arnhem would likely be exposed to a great degree and quantity of air pollutants because of their prolonged working hours in unventilated and crowded industrial environments (van Laar, 1966; Wintle, 2000). However, those who did not have to engage in such strenuous activities like the Dutch elite would then spend a long time indoors in their offices and homes, and would therefore still be exposed to high rates of indoor pollutants generated by the fireplaces and charcoal stoves that were used to heat up houses throughout the Low Countries (Holwerda & Verleden, 2017). Our findings fit this hypothesis well, as Eindhoven outside the church was the

only population whose lifestyle restricted exposure to pollutants in some way. In fact, individuals from Arnhem were employed in factories and likely had little say over their working conditions. On the contrary, people from both Zwolle and Eindhoven inside the church had complete control over their working and living environment, but were almost never involved with outdoors tasks and probably spent most of their time indoors in meetings, dinners, or gatherings (ten Hove, 2005). Individuals from Eindhoven outside the church, on the other hand, often owned their own workshops and were involved in city markets, meaning they spent more time outdoors than other socioeconomic classes (Melssen, 2013; Nollen, 2013). It is possible, therefore, that the lifestyle of the middle-low socioeconomic class in the Northern Low Countries was still somehow strenuous and challenging as for other classes, but was not as hazardous for respiratory health because of the time people spent outdoors and/or their autonomy in managing their own working hours and space.

Another noteworthy result of our analysis was that *cribra orbitalia* showed statistical significance with socioeconomic status. However, it was unexpected that, among all socioeconomic classes, individuals from Eindhoven inside the church (i.e., the highest socioeconomic class) were the ones to show statistically significant higher rates of *cribra orbitalia* (33.3%). Additionally, significant correlations were observed between Eindhoven inside the church and Zwolle (i.e., middle-low socioeconomic status) and between Zwolle and Arnhem (i.e., lowest socioeconomic class). This finding was unexpected and partially contrary to our initial hypothesis that wealthier individuals lived less-challenging lives in relation to their health. As previously mentioned, the etiology of *cribra orbitalia* is still matter of debate and has been linked to anemia, vitamin deficiencies, as well as to infectious disease and parasitic infections (Brickley, 2018; O'Donnell et al., 2020; Walker et al., 2009). These hypotheses are in line with the overall high rates observed in Arnhem (22.6%) compared to the other sites under study (Eindhoven outside the church: 13.3%; Zwolle: 8.4%), as the inadequate living conditions associated with the lowest socioeconomic class likely made people face several of these physiological challenges. The strong association observed between Arnhem and Zwolle further supports this interpretation, suggesting differences between poor and rich lifestyles were indeed noteworthy and had a meaningful impact on one's life experience. However, the significantly higher presence of *cribra orbitalia* in Eindhoven inside the church (33.3%) still raises the question of how indicative these results are of how status influenced physiological health in the past. As previous bioarchaeological research has associated *cribra orbitalia* with increased mortality risks, it is possible that people from the upper class of Eindhoven were able to get treated quickly and extensively in the case of both infectious disease and parasitic infections, therefore being able to survive long enough to develop skeletal lesions (DeWitte & Stojanowski, 2015; Godde & Hens, 2021; McFadden & Oxenham, 2020). In regard to dietary deficiencies, previous bioarchaeological research on the same skeletal samples analyzed in the present study has identified the presence of both scurvy and rickets in the sites of Zwolle (scurvy: 0.5%; rickets: 2.0%) and Eindhoven (scurvy: 0.5%; rickets: 5.3%), suggesting that these populations were indeed familiar with nutrient deficiencies regardless of their status (Aten, 1992b; Baetsen & Weterings-Korthorst, 2013). Once again, individuals from Eindhoven inside the church could rely on several economic and societal privileges to outlive such deficiencies

(i.e., access to healthcare, rest days, better foods, etc.) that may have allowed them to live long enough to develop cribrotic lesions. We argue here that these results may be indicative of the osteological paradox. Future research on these skeletal assemblages should therefore consider prevalence rates of non-specific stress markers in the sub-adult population as a means for comparing the frailty of survivors and non-survivors in order to potentially navigate the presence of the mortality bias and to further interpret our data (DeWitte & Stojanowski, 2015).

Another limitation of our study was that the sample size for Eindhoven inside the church was unfortunately small, especially when broken down for statistical analysis. In light of this, our results should be carefully considered, as observed rates and differences may be a function of sample size. Furthermore, it must be recognized that even if the categories of socioeconomic status are defined here based on historical sources and burial locations, they are still defined by the observers. Individuals can differ from each other in any bioarchaeological sample. As status does not determine how someone is loved, cared for, or seen, differences between bioarchaeological samples may reflect status, as well as common environmental factors such as gender, political situations, epidemics, famine, and migration. Rural-to-urban migration in particular was common in the post-medieval period and may have introduced a large number of relatively healthy individuals to the urban contexts and/or could have put migrants to the city at a higher risk of mortality. In addition, while migration was common in the post-medieval period, it most likely concerned a very specific part of the population (i.e., the poorest), which could have potentially impacted our results. While many bioarchaeological diachronic studies on rural health have been carried out in the Netherlands (e.g., Schats, 2016; Veselka et al., 2013; Waters, 2018), to date little room has been given to the confounding effects of demographic nonstationarity in Dutch samples. Analysis of different samples could therefore help evaluate how migration might have shaped the health patterns of urban populations.

4.6. Conclusions

Despite the limitations, the comparison of stress indicators, chronic maxillary sinusitis, and socioeconomic status for the urban sites of Arnhem, Zwolle, and Eindhoven yielded complex results that prove the intricate and fascinating nature of the urbanization phenomenon. Although it was not possible to observe any consistent trend in differences between socioeconomic status and non-specific stress indicators or sinusitis, our results still may point to a systematically challenged existence for all urban citizens in the sites under study. This research is significant because it demonstrates the complex relationship between urbanization, socioeconomic status, and health. At least in the samples under study, urban settlements were not putting exclusively poor people's lives at risk. Rather, everyone's existence was challenged in different ways. Therefore, it is only by exploring different indicators of health that we can achieve a more nuanced understanding of one of the most complex yet fascinating human phenomena.

Supporting information

Supplementary materials for this paper are available on Zenodo: <https://zenodo.org/records/7040412>

Data availability statement

The data that support the findings of this study are openly available in DANS Easy at <http://doi.org/10.17026/dans-xf4-jtx3>, reference number 224947.

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CHAPTER 5

The Urban Sea: Cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia, and sinusitis in three diachronic urban sites from the Dutch province of Zeeland (1030–1800 CE)

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Abstract

Until the 17th century, the Dutch coastal region of Zeeland ranked among Europe's most urbanized areas, driven by thriving international trade networks. People living in this time of flourishing economy benefitted enormously from it in terms of employment opportunities and working conditions, which were reportedly better than in the rest of the Low Countries. However, the rapid growth of Zeeland's urban centers likely presented increasing challenges for the population in terms of accessing essential resources, including food, clean water, and housing. In the 19th century, Zeeland's economy ultimately faced a significant downturn due to the decline in the maritime trade, leading to a substantial reduction in its urban population.

Examining patterns of urbanization and economic histories that differ from the commonly studied thriving industrial contexts in bioarchaeological research, as exemplified by Zeeland, is a crucial yet relatively underexplored facet in our efforts to understanding the human past. To address this gap, this study investigates the impact of urbanization on the health of Zeeland's inhabitants over time by analyzing non-specific stress markers (i.e., cribra orbitalia, porotic hyperostosis, and linear enamel hypoplasia) and chronic maxillary sinusitis in a sample of 246 individuals from three urban sites dating from 1030 to 1800 CE. Our analysis of skeletal remains reveals significant differences in the prevalence of porotic hyperostosis, linear enamel hypoplasia, and sinusitis between the medieval and post-medieval periods. These findings suggest that de-urbanization and economic decline adversely affected the health and wellbeing of the populations under study, influenced by factors such as working conditions and food availability. This study provides a new perspective on bioarchaeological approaches to urbanization, shedding light on the intricate realities of urbanization in Zeeland and offering important insights into its complexities.

Keywords: Netherlands; Non-specific stress indicators; Respiratory disease; Urbanization

5.1. Introduction

In recent years, osteoarchaeological studies on urbanization and its influence on the wellbeing of historical populations have witnessed a significant surge in scholarly interest. Through the application of an extensive array of research methodologies, our understanding on the impact urbanization and industrialization had on the health of past populations has significantly advanced to a point where it was never before. Yet, while ongoing studies on urbanization are continuously expanding our current understanding of past societies, archaeologists still struggle to address urbanization in most of its complexities (Betsinger & DeWitte, 2021).

The urbanization process (defined as a population shift from rural areas to cities) has influenced European history and culture for the past millennia (de Vries, 1984). Despite it being generally considered an ever-lasting and ever-growing phenomenon, urbanization has always been an extremely dynamic process, characterized by considerable variations in terms of both intensity, nature, and direction (Seto et al., 2015). In the past, many historiographical approaches have associated urbanization with industrial development, large-scale (factory) employment, and/or general negative effects on the health of the local population. However, it was recently argued that urbanization exhibits regional patterns rather than a single, uniform set of changes, and that various factors such as population composition, environment, local resources, types of labor, and economic disparities between urban sites in the same region or country can lead to vastly different experiences (Betsinger & DeWitte, 2020).

In the Netherlands, urbanization started as early as the 12th century, initially exclusively in the coastal and northern regions and ultimately expanded to the hinterland during the 17th century (de Vries, 1984). Right from the outset of their urbanization process, Dutch cities exhibited remarkable heterogeneity. Some cities served as government seats, others primarily functioned as military centers or industrial hubs, while others (such as Amsterdam) focused the development of their economy and wealth on international trade (Brusse & Mijndhardt, 2011). While these remarkably different characterizations must have influenced people's lives and health in different ways, to date this has been only scarcely addressed in bioarchaeological research on Dutch urbanization (e.g., Casna & Schrader, 2022). While a considerable number of bioarchaeological studies have explored the lives of people residing in industrial (or proto-industrial) settings in other areas of Europe (e.g., Boyd, 2020; Western & Bekvalac, 2019; Yaussy, 2019), less industrialized (or rather "differently urbanized") environments have generally garnered limited attention (e.g., Davies-Barrett et al., 2021; Floreanova et al., 2020), leaving the life experiences of these inhabitants largely uncharted. To fill this gap, the present study aims to investigate the impact of urbanization on the health of three diachronic communities dating 1030-1800 CE whose urbanization history differs from the industrial/proto-industrial narrative, by analyzing prevalence rates of cribra orbitalia (CO), porotic hyperostosis (PH), linear enamel hypoplasia (LEH), and chronic maxillary sinusitis (CMS) across time. We aimed to test the hypothesis that (de) urbanization processes negatively impacted the health of Zeeuws people, resulting in increasing frequencies of both non-specific stress markers and sinusitis.

5.1.1. Urbanization in Zeeland

The coastal region of Zeeland is located in the southwestern corner of the Netherlands, bordering Belgium to both the south and west (Figure 5.1). Originally only comprising a group of small islands, starting from the 11th century Zeeland underwent significant transformations. Over the centuries, numerous areas in Zeeland were reclaimed from the water, and it is estimated that today almost 80% of Zeeland's landmass was originally submerged and later drained by local populations (van Cruyningen, 2012b). Historical records suggest that Zeeland's cold and wet climate has played a crucial role in shaping its maritime and economic history. This is evident not only in trade routes and in coastal infrastructure development, but also in the construction, spanning approximately ten centuries, of 429 kilometers of dikes, dams, dunes, and quays to protect cities against flooding (e.g., Dekker, 2023, Henderikx, 2012a, 2012b, 2012c). The name "Zeeland" itself translates to "Sea Land", a reflection of its close connection to water. Its unique geography has historically positioned Zeeland as a maritime powerhouse, thanks to its abundance of natural harbors and its strategic location along both the North Sea and the Scheldt River. In fact, throughout history Zeeland served as the first point of contact between the Netherlands and the world, acting as a gateway for international commerce and cultural exchange.



Figure 5.1. Map of the Netherlands showing the location of the province of Zeeland. Image made by M. Casna.

While it is today the least populous region of the Netherlands, up until the 17th century Zeeland formed one of the most urbanized areas in Europe, as opposed to the more rural inland whose proto-industrial economy was based on small freehold livestock farmers (Brusse & Mijndhardt, 2011). Unlike other urban realities in the Low Countries, Zeeuws cities were connected by a singular federal structure where the power sat in the hands of wealthy merchants and guilds (Enthoven, 1996; van Cruyningen, 2012a). This uniquely structured governance facilitated the growing importance of international trade starting from the 11th century, leading to the prosperity of several towns in Zeeland. Following the Middle Ages, private trading companies such as the Dutch West India Company (WIC) and the United East India Company (VOC) established large-scale shipyards in most Zeeuws harbors, propelling both the local shipbuilding industry and international trade networks to become some of the largest in the entire European continent (Brusse & Mijndhardt, 2011). Consequently, Zeeuws cities experienced rapid expansion, with at least 50% of the local population residing in urban centers by the early 18th century (Brusse & Mijndhardt, 2011). It was noted that salaries as well as living conditions in Zeeland were generally higher than in the rest of the Netherlands; however, it is likely that the rapid expansions of Zeeuws centers limited the population's access to various basic resources (e.g., proper housing, healthcare, food, drinking water) (van Laar, 1966; Wintle, 2000). In fact, according to Van Steensel (2012) 15th century Zeeuws citizens were particularly susceptible to death and disease because of their poor living conditions.

Zeeland's economy continued to flourish until around 1670 CE, when major cities, such as Middelburg and Vlissingen, stopped growing following the financial difficulties of the Dutch East India Company in maintaining its international routes (de Vries & van der Woude, 1997; van Cruyningen, 2012a). After 1730 CE, the fortunes of the VOC severely declined and, together with the rise of early industries in the hinterland and with the stop of maritime trade caused by the Batavian Revolution, in 1794 CE Zeeuws economy finally collapsed (Brusse & Mijndhardt, 2011; de Vries & Van der Woude, 1997). By 1815 CE, all urban centers in Zeeland had faced a sharp decline in population numbers (Brusse & Mijndhardt, 2011): in just one or two years, 75% of the working population of Zeeuws cities left, making local economies (and populations) dramatically poorer (Brusse, 2011).

5.1.2. Non-specific stress indicators and respiratory diseases in relation to urbanization

Because the presence within an individual of any non-specific stress indicator (e.g., cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia) is not indicative of a particular cause of stress but rather suggestive of the fact that the individual experienced some physiological challenges during their lifetime, it was argued that the study of non-specific stress indicators may provide valuable insights into the health and life experiences of archaeological populations. While many of these markers are generally considered to be indicative of nutritional deficiencies (e.g., Brickley, 2018; Walker et al., 2009), more recent research has explored their etiologies, suggesting that factors such as parasitic diseases, trauma, and local inflammations might also contribute to the prevalence of these lesions (e.g., King et al., 2002; Schats, 2023; Wapler et al., 2004). Possibly

due to the complex etiology of these markers, comparisons across several populations have yielded complicated results, with no clear pattern indicating whether urbanization negatively influenced the physiological stress of the populations under study (Betsinger & DeWitte, 2021). When examining the occurrence rates of cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia, and periosteal reaction in a medieval Polish population, Betsinger and DeWitte (2017) noted that these skeletal indicators exhibited no significant changes as urbanization increased. Conversely, Zhang and colleagues (2016) investigated the same lesions in the Late Shang dynasty in China (1250–1046 BCE) and concluded that increasing urbanization did increase physiological stress within the population under study. Similarly, Roberts (2009) compared data from multiple studies regarding cribra orbitalia, linear enamel hypoplasia, and stature in various medieval populations from England (ca. 450–1500 CE), arguing that urbanization did indeed negatively impact the health of the analyzed populations.

Besides examining non-specific stress markers, in the past years bioarchaeologists have frequently studied the occurrence of respiratory diseases (i.e., sinusitis, ear infections, and lung diseases) in urban settings under the assumption that these diseases can serve as indicators of air quality, hence providing insights into how urbanization may have posed challenges to the respiratory health of residents (e.g., Collins, 2019; Davies-Barrett et al., 2021; Sundman & Kjellström, 2013). However, the investigation of respiratory diseases in urban contexts has always yielded varying results, and rarely revealed a direct correlation between urbanization and individual health (e.g., Boyd, 2020; Casna et al., 2021). In a recent study by Casna and colleagues (2023) on six Dutch populations dating 475–1866 CE, it was observed that sinusitis prevalence rates remained consistent between rural and urban populations. However, these rates showed a progressive increase over time in both settings, suggesting that the process of urbanization had a detrimental impact on the health of individuals in both rural and urban areas. On the other hand, prevalence rates of ear and pulmonary infection for the same study did not match this pattern, suggesting other factors are at play, such as exposure to cold climates, tobacco smoke, genetic predisposition, and more (Boyd, 2020; Casna et al., 2023; Davies-Barrett et al., 2023).

5.2. Materials

For this study, the total sample was composed of three different populations from the Dutch province of Zeeland, dating 1030–1200 CE, 1300–1590 CE, and 1600–1800 CE, respectively (Figure 5.2). They were selected because they represent a diachronic window into urban life in the province of Zeeland across the medieval and post-medieval periods.

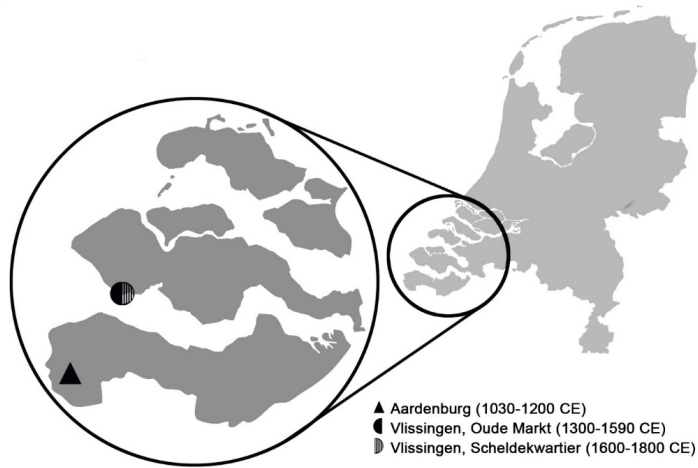


Figure 5.2. Map of the Netherlands showing the location of the sites under study. Image made by M. Casna.

5.2.1. Aardenburg (1030-1200 CE)

The skeletal collection of Aardenburg was excavated in 1948 from the Sint-Baafskerk, one of the city's oldest buildings (Forbes, 1953). Because these burials were discovered following the structural damages that the Second World War caused to the church, no excavation reports were produced at the time and, therefore, no information is available on how many skeletons were originally recovered. Similarly, the dating of these burials (i.e., 1030-1200 CE) remains uncertain, and was based on the interpretation of the symbols adorning the burial vaults (Cornelis, 1951; Haakma Wagenaar & van den Brink, 2011).

Formerly known as Rodanburg, Aardenburg was among the first Dutch cities to acquire city rights in 1187 CE (Henderikx, 2012d). However, the area was already inhabited around the 8th century and quickly flourished thanks to the pre-existing infrastructures (e.g., paved roads; urban hydraulic systems) left by the Romans when they abandoned the settlement in the 5th century (de Pooter et al., 2000). Around 1000 CE, Aardenburg experienced a significant transformation with the emergence of the wool industry (Polderman, 2001). Initially solely relying on domestic wool, the city gradually shifted its focus and began importing wool from England. The imported wool became then a preferred choice for crafting opulent textiles, while the use of domestic wool continued for the creation of more modest clothing (Henderikx, 2012a). However, despite the flourishing wool industry, the primary source of employment for migrants seeking work in Aardenburg was centered around freight shipping, with merchants hiring skippers and occasionally fishermen to transport goods abroad (Henderikx, 2012a). In fact, thanks to its strategic position on the North Sea, already in 1000 CE Aardenburg extended its economic trade not only to England, but also to the Baltic coast, Northern Spain, and Italy, where they exported textiles, clothes, salt, food grains, and fish (de Pooter et al., 2000; Henderikx, 2012e). As a result of the expanding international market, the population of Aardenburg was estimated

to be already around 3,500 inhabitants by the end of the 12th century (Henderikx, 2012b). While this figure may appear modest in comparison to flourishing urban centers like Bruges with 40,000 inhabitants, Ghent boasting 60,000, and London at 80,000, Aardenburg's demographic size held its own against major Dutch centers like Dordrecht, which counted around 5,000 inhabitants by 1200 CE (Henderikx, 2012b).

5.2.2. Vlissingen, Oude Markt (1300-1590 CE)

The skeletal assemblage of Vlissingen, Oude Markt was excavated in 2005 from the cemetery of Vlissingen's former main church and comprised a total of 716 individuals of mixed skeletal sexes and age groups (Koning & Wattenberghe, 2007). Because of their location within the church cemetery, these individuals are thought to be representative of the middle-to-lower socioeconomic class, possibly workers involved with either the sailing or fishing industry (Claeys et al., 2010).

Between 1315-1322 CE, exceptionally adverse weather conditions caused almost all of Western Europe to experience a widespread decline in population attributed to famine resulting from crop failures and livestock losses (van Steensel, 2012). Subsequently, from 1347-1351 CE, the whole continent faced an additional decline due to the devastating impact of the plague (Blockmans, 1980). While the historical documentation for the population development of Zeeland during this period is particularly limited, indications suggest that Zeeland encountered a less significant population decrease compared to its neighboring countries, together with a much faster repopulation in the 15th century (van Steensel, 2012). In Vlissingen alone, population size grew from 500 inhabitants in 1417 CE to 4,000 in just a century (van Steensel, 2012). This significant rise in population during the late Middle Ages in Vlissingen can be attributed to the city's pivotal role as the sole port linking the North Sea to the Dutch hinterland. Already in 1400 CE, Vlissingen was one of Zeeland's most important cities, as it operated as a key hub for several companies trading with Southern Africa and Eurasia (van Cruyningen, 2012a). Constant increase in commercial routes led to an expansion of the original harbor in 1443 CE financed by the city management (Claeys et al., 2010). From there and until the end of the 16th century, Vlissingen was in full development: new governmental buildings were built as well as two more ports, and the settling of several important characters in the Dutch cultural landscape led to the foundation of the Zeeland Society of Sciences (de Ridder, 2002). Between 1572 and 1600 CE, the power of Vlissingen had risen so high that the city was able to cut off both Middelburg and Antwerp (two of the most powerful trade hubs in the area) from their supply roads (van Cruyningen, 2012a).

5.2.3. Vlissingen, Scheldekwartier (1600-1800 CE)

This skeletal assemblage was excavated in 2003 and comprised a total of 128 individuals dating 1600-1800 CE. Dating was estimated based on the analysis of grave goods, including pottery, glass, smoking pipes, leather and textiles, metal, and surrounding building materials (Claeys et al., 2010). Unlike in Oude Markt, grave goods recovered in Scheldekwartier varied significantly in terms of quality, quantity, and provenance, potentially indicating a more heterogenous social

composition of the sample (i.e., both merchants and harbor workers may have been interred there) (Claeys et al., 2010).

By the year 1600 CE, Vlissingen had transformed into a bustling international hub, boasting a diverse population and thriving trade connections (Claeys et al., 2010). While many were employed in supplying companies (i.e., shipbuilding, sail making, rope making, etc.), hundreds of people relocated to Vlissingen to work in the fishing industry, which continued to offer stable incomes and opportunities until the end of the 18th century (van Cruyningen, 2012a).

Vlissingen's economic prosperity began to wane in the late 1600s, as a financial stall of the Dutch East India Company coupled with mounting religious and political tensions inflicted significant damage to the city's administrative structures (de Ridder, 2004). This turbulent environment, characterized by growing instability and dwindling employment prospects, prompted both families and skilled laborers to leave Vlissingen as early as the late 17th century to relocate either towards burgeoning industrial centers inland, or back to the countryside (Brusse, 2011; Brusse & Mijnhardt, 2011). The resulting rapid decline in population was so pronounced that, as Brusse and Mijnhardt (2011) suggest, it must have been directly observable (and deeply concerning) to the residents of that era. The economic collapse of Vlissingen ultimately happened in 1795 CE, when the presence of the French army in the city forced all trading activities to cease.

5.3. Methods

For every individual, skeletal sex was estimated based on the observation of morphological features on the skull (i.e., nuchal crest, mastoid process, supraorbital margin, prominence of glabella, and mental eminence) and os coxae (Buikstra & Ubelaker, 1994; Phenice, 1969). Age estimations were made using morphologic characteristics of the pubic symphysis according to Brooks & Suchey (1990) and of the auricular surface (Buckberry & Chamberlain, 2002). Age groups were defined as young adult (approx. 20-34 years), middle adult (approx. 35-49 years), and old adult (50+ years), according to Buikstra and Ubelaker (1994). In order to be included in the final sample, each individual had to have an age-at-death ≥ 20 years old, and at least two among these features were required to be $\geq 25\%$ complete: orbital roofs, cranial vaults, maxillary sinuses, and/or both upper and lower dentition (Casna & Schrader, 2022).

The presence of each lesion (i.e., cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary sinusitis) (Figure 5.3) was assessed macroscopically for all skulls and noted as either "absent" or "present" according to accepted criteria (Boocock et al., 1995; Waldron, 2008; Walker et al., 2009). Details on how each lesion was assessed are published in Casna and Schrader (2022). As dental disease (i.e., severe caries lesions, abscesses, and granulomas) can affect and/or potentially cause sinusitis (Patel & Ferguson, 2012), individuals presenting periapical lesions in the upper molars were excluded from this analysis. In case of complete skulls, the presence of maxillary sinusitis was assessed through observation with a flexible medical endoscope (Pentax model: FNL-10RBS, $\varnothing=4\text{mm}$; view angle= 30°).

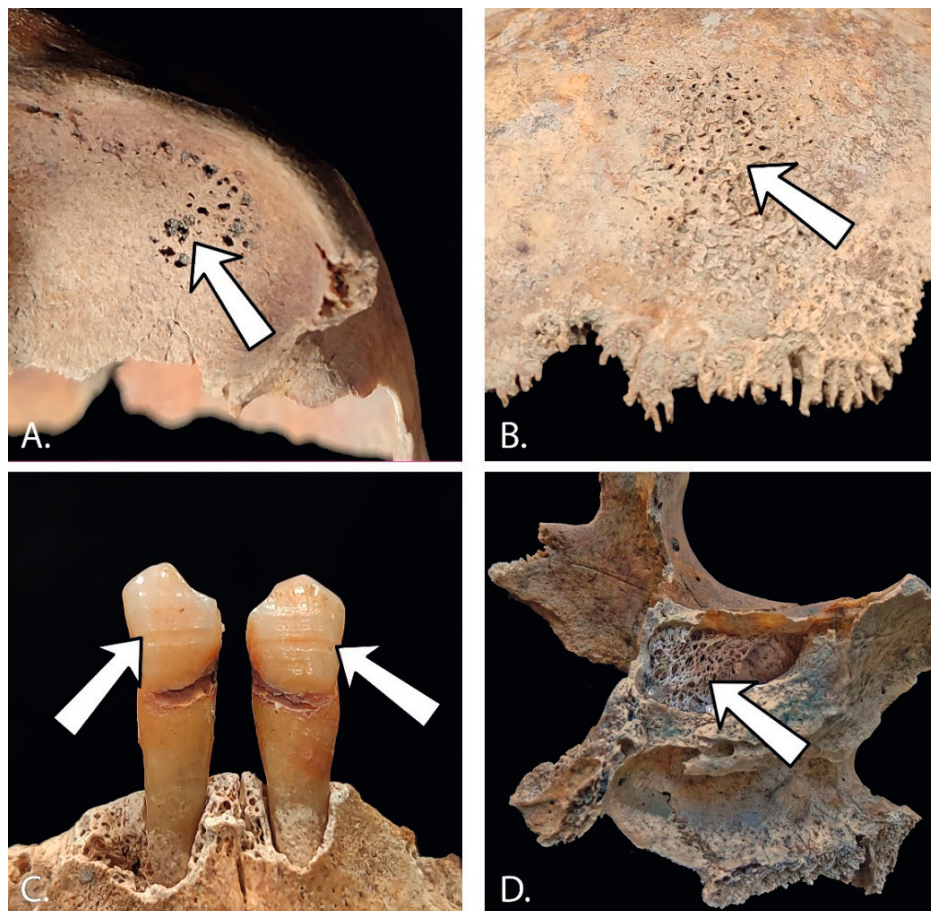


Figure 5.3. Lesions observed in this study and indicated by white arrows. A: Cribra orbitalia; B: Porotic hyperostosis; C: Linear enamel hypoplasia; and D: Chronic maxillary sinusitis in the form of “spicule-type bone formation”, according to Boocock et al. (1995). Photographs by M. Casna.

Statistical analysis of the results was performed utilizing SPSS for Windows, version 29.0. To assess the significance of the relationship between various population groups and the presence of stress markers and chronic maxillary sinusitis, Chi-squared tests were employed. In instances where the expected cell count fell below 5, Fisher’s exact test was used instead. A p -value ≤ 0.05 was considered as statistically significant.

5.4. Results

The total sample consisted of 246 adult individuals (Table 5.1). Figure 5.4 displays the observed prevalence of cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary sinusitis between the three populations under study.

Table 5.1. Demographic composition of the sample included in this study.

	Males			Females				
	Young adult (20-34 years) (%)	Middle adult (35-49 years) (%)	Old adult (50+ years) (%)	Total	Young adult (20-34 years) (%)	Middle adult (35-49 years) (%)	Old adult (50+ years) (%)	Total
Aardenburg (1030-1200 CE)	25 (42.4)	26 (44.1)	8 (13.5)	59	32 (72.7)	9 (20.5)	3 (6.8)	44
Viissingen, Oude Markt (1300-1590 CE)	19 (70.4)	5 (18.5)	3 (11.1)	27	14 (56.0)	9 (36.0)	2 (8.0)	25
Viissingen, Scheldekwartier (1600-1800 CE)	31 (68.9)	10 (22.2)	4 (8.9)	45	28 (60.9)	7 (15.2)	11 (23.9)	46
Total	75 (57.2)	41 (31.3)	15 (11.5)	131	74 (64.3)	25 (21.7)	16 (14.0)	115

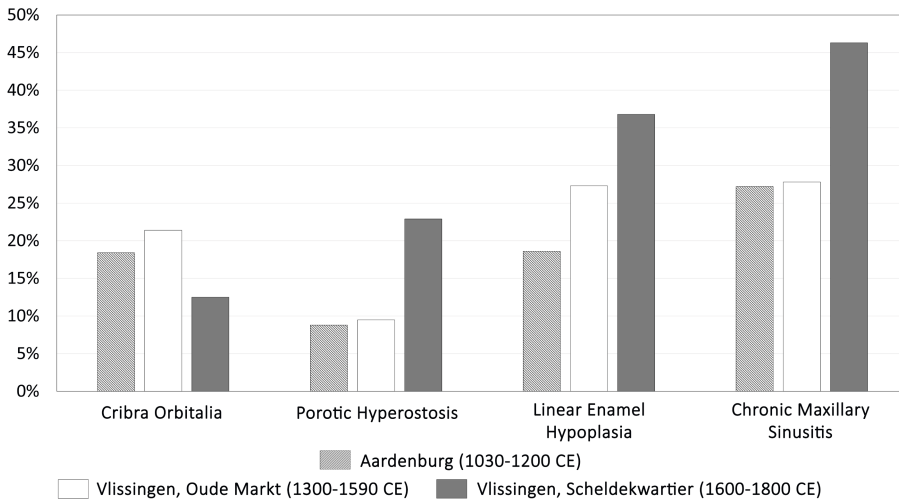


Figure 5.4. Prevalence of Cribra Orbitalia, Porotic Hyperostosis, Linear Enamel Hypoplasia, and Chronic Maxillary Sinusitis for all samples under study.

All lesions increased in prevalence through time, except for cribra orbitalia which was lower in Vlissingen, Scheldekwardier than it was in both Aardenburg and Vlissingen, Oude Markt. Statistically-significant increases were observed between Aardenburg and Vlissingen, Scheldekwardier for the prevalence rates of porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary sinusitis (Table 5.2).

Table 5.2. Summary of Chi-Squared Test Results, per site. (continued)

Chronic Maxillary Sinusitis		
Aardenburg (1030-1200 CE)		Vlissingen, Oude Markt (1300-1590 CE)
Vlissingen, Oude Markt (1300-1590 CE)		Vlissingen, Scheldekwartier (1600-1800 CE)
		$\chi^2=7.146, p=0.008^*$
		$\chi^2=3.515, p=0.061$

N=total of individuals with observable feature; n= total of individuals showing lesions.
*=Statistically significant at 95 percent confidence level.

The distribution of lesions among skeletal sex groups was investigated for all populations under study (Table 5.3). While most lesions were evenly distributed among sex categories, in Vlissingen, Scheldekwardier males showed significantly higher rates of porotic hyperostosis than females. Porotic hyperostosis in males from Vlissingen, Scheldekwardier was also observed to be significantly higher than in males from both Aardenburg ($p < 0.001$) and Vlissingen, Oude Markt ($\chi^2 = 6.368$, $p = 0.018$) (Table S1). Furthermore, female individuals from Vlissingen, Scheldekwardier had significantly higher rates of CMS than female individuals from Aardenburg ($\chi^2 = 5.607$, $p = 0.027$). All other associations among sex categories were observed to be non-significant.

The distribution of lesions among age-at-death groups was investigated for all populations under study. Among all samples, young adults (20-34 years) generally had the highest occurrence rates for every lesion. In Aardenburg and Vlissingen, Oude Markt old adults (50+ years) almost displayed no presence of cribra orbitalia, porotic hyperostosis, and linear enamel hypoplasia. When investigated statistically, no significant associations were observed between presence of lesions and age-at-death (Table S2).

Table 5.3. Summary of Chi-Squared Test Results, per sex groups.

	Cribra Orbitalia				Porotic Hyperostosis				Linear Enamel Hypoplasia				Chronic Maxillary Sinusitis			
	n	N (%)	X2	p	n	N (%)	X2	p	n	N (%)	X2	p	n	N (%)	X2	p
Aardenburg (1030-1200 CE)	Males	59	13 (22.0)		59	7 (11.9)			39	8 (20.5)			59	14 (23.7)		
	Females	44	6 (13.6)	1.181 0.315	43	2 (4.7)	n/a	0.296†	31	5 (16.1)	0.219 0.761		44	14 (31.8)	0.833 0.380	
Vlissingen, Oude Markt (1300-1590 CE)	Males	21	5 (23.8)		21	2 (9.5)			17	6 (35.3)			18	3 (16.7)		
	Females	21	4 (19.0)	n/a 1.000†	21	2 (9.5)	n/a	1.000†	16	6 (35.3)	n/a 0.438†		18	7 (38.9)	2.215 0.264	
Vlissingen, Scheldekwaartier (1600-1800 CE)	Males	39	3 (7.7)		42	17 (50.5)			36	13 (36.1)			40	14 (35.0)		
	Females	41	7 (17.1)	n/a 0.313†	41	2 (4.9)	14.895	<0.001*	32	12 (37.5)	0.014 1.000		40	23 (57.5)	4.073 0.072	

N=total of individuals with observable feature; n= total of individuals showing lesions.

†=Fisher's exact test. *=Statistically significant at 95 percent confidence level.

5.5. Discussion

The aim of this study was to investigate patterns of health and respiratory disease across time in an urban context that differs greatly from the industrial framework on which most bioarchaeological studies on urbanization have focused so far (i.e., international maritime trade hubs).

Even if living and working in harbors and on ships was undoubtedly physically very demanding (Claeys et al., 2010), it was noted that Zeeland's economic growth in the medieval period brought substantial welfare to all citizens, both in terms of access to basic resources (e.g., food and clean water) and of salaries, which historical records attest were higher than in the rest of the country (Brusse & Mijndhardt, 2011). This is partially reflected in our results, as rates of non-specific stress indicators and sinusitis did not show significant variation between Aardenburg (1030-1200 CE) and Vlissingen, Oude Markt (1300-1590 CE), suggesting that these populations were somehow protected by the flourishing economic situation in the region. Inversely, we observed statistically-significant increases in porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary sinusitis prevalence rates between Aardenburg and Vlissingen, Scheldekwardier (1600-1800 CE). While this may be indicative of living conditions (e.g., limited access to food resources) harshening with Zeeland's economic collapse in the 18th century, it is still very interesting to note that the largest increase in both stress indicators and sinusitis did not occur in times of intense urban growth, but rather during significant de-urbanization. As already mentioned, Zeeland's dramatic economic decline reportedly affected the wellbeing and health of people and caused many families to relocate by the end of the 17th century (Brusse & Mijndhardt, 2011). It is likely that the first dissolution of the Dutch West India Company in 1674 CE severely impacted the Zeeuws population both in terms of employment opportunities and of financial wellbeing (Klein, 1965), possibly making it harder to afford certain foods, leading to vitamin/nutrient deficiencies and an increase in cases of malnutrition among workers and the poorest members of society. Therefore, we argue that people from Vlissingen, Scheldekwardier underwent significant physiological stress in response to the declining economic environment in which they were living.

We argue that the effects of Zeeland's economic decline on the health of Zeeuws people are further reflected in our sinusitis results, as CMS prevalence rate was significantly higher in Vlissingen, Scheldekwardier than in Aardenburg and almost significantly higher in Vlissingen, Scheldekwardier than in Vlissingen, Oude Markt ($p=0.061$). In the past, most bioarchaeological studies focusing on respiratory diseases associated higher rates of sinusitis to overcrowding and exposure indoor/outdoor to air pollution (e.g., Bernofsky, 2010; Casna et al., 2021; Sundman & Kjellström, 2013). However, recent research has started to acknowledge the diverse and intricate etiology of sinusitis, shedding light on the challenges linked to pinpointing the particular factors that could be responsible for the fluctuations in prevalence rates within different archaeological populations (e.g., Boyd, 2020; Casna et al., 2023; Davies-Barrett et al., 2023). While changes in risk factors such as working and living conditions, food resources availability, and access to healthcare are usually addressed in most publications on chronic maxillary sinusitis, others

such as exposure to adverse weather conditions, genetic predisposition, and cultural habits (e.g., smoking) have revealed to be very difficult to address in archaeological settings despite them being extremely prevalent in most populations (Casna et al., 2023; Davies-Barrett et al., 2023; Sundman & Kjellström, 2013). For example, as most specialized workers (e.g., shipbuilders, cobblers, and merchants) left Vlissingen following its economic downturn (Brusse, 2011; Brusse & Mijnhardt, 2011), it is likely that the population of Scheldekwardt primarily consisted of non-specialized laborers engaged in activities such as construction, fishing, or ship loading. These individuals generally undertook extremely physically demanding tasks and were exposed to harsh weather conditions, potentially impacting their susceptibility to infectious diseases such as sinusitis. These results reflect those of Casna and colleagues (2023) who compared rates of CMS across three diachronic (i.e., early-medieval, late-medieval, and post-medieval) populations from the Netherlands and observed that prevalence rates significantly increased with time, concluding that urbanization may have impacted negatively the respiratory health of past Dutch populations.

As historical records indicate that Zeeland's maritime industry was run by both men and women (Stuurman, 2023), we did not expect significant differences between sex groups as we considered them to be equally exposed to socioeconomic changes. However, while no differences were observed in cribra orbitalia, linear enamel hypoplasia, nor sinusitis rates, significantly higher rates of porotic hyperostosis were noted in males compared to females in Vlissingen, Scheldekwardt. Moreover, PH prevalence rates in males from Vlissingen, Scheldekwardt were significantly higher than those in males from both Aardenburg and Vlissingen, Oude Markt. Despite its etiology being debated, in the past porotic hyperostosis has been linked to a synergy between poor hygienic conditions, infectious diseases, and diets lacking in vitamin B12 (Walker et al., 2009). Even if men and women were equally contributing to the maritime industry, their roles and expectations differed greatly (e.g., men working on ships, women running markets or making fishing nets at home) (Stuurman, 2023; Wintle, 2000). Working at sea for long periods, likely with limited access to food, clean water, and healthcare, may have drastically and increasingly impacted the health of men, especially during the post-medieval period when basic resources became even more limited.

When looking at the distribution of lesions among age-at-death categories, no significant differences were observed. Although it is important to acknowledge the potential influence of our limited sample size on these findings, the uniform distribution of lesions across all adult age-at-death categories suggests that the factors influencing the health and wellbeing of the three populations under study may have uniformly impacted all groups, thereby posing a pervasive risk independent of age. On the other hand, despite there not being any statistically significant association, older adults from both Aardenburg and Vlissingen, Oude Markt did generally show the lowest occurrence rates of all non-specific stress indicators (in most cases, old adults showed no cribra orbitalia, porotic hyperostosis, nor linear enamel hypoplasia). While it is unlikely that any of the risk factors outlined in this paper affected older populations less than their younger counterparts (or rather, the risk was not present during the early life of old adults), it is possible that the presence of these indicators in the samples under study marks more fragile individuals

who died before old adults. Previous research on enamel hypoplasia identified a link between the presence of LEH and premature mortality, suggesting that early-life stress may be strongly associated with mortality in the younger-adult life stage (e.g., Amoroso et al., 2014; Stutz et al., 2021). While this would fall within the concepts of hidden heterogeneity and selective mortality as outlined by Wood and colleagues (1992), the lack of data on subadults demographic profiles for the populations under study makes it difficult to thoroughly deal with the osteological paradox (DeWitte & Stojanowski, 2015). However, the uniform distribution of lesions across age-at-death categories potentially supports a “non-paradoxical” view of results (DeWitte & Stojanowski, 2015; Krenz-Niedbala & Łukasik, 2020). This implies that our observed prevalence rates may indeed reflect the life experiences of the individuals included in this study, and hence provide with a deeper understanding of Zeeland’s past.

5.5.1. Limitations of the study

While our findings provide valuable insights into the impact of urbanization and economic collapse on the health of Zeeuws citizens during the post-medieval era, it is imperative to acknowledge the presence of several limitations, such as disparities in sample sizes among different assemblages, and difficulties in addressing every risk factor for the health of the individuals under study (e.g., climate). To date, the impact that the natural environment had on the health of past populations has received almost no attention from bioarchaeologists, despite it likely playing a significant role in the wellbeing of many past societies (Casna et al., 2023; Davies-Barrett et al., 2023; Roberts, 2016). In the Netherlands (and in Zeeland specifically) climate has always been heavily impacted by the North Sea (Wintle, 2000). Cold temperatures, strong winds, and frequent floodings must have impacted negatively the health of past Dutch populations, regardless of the time period (Zijlmans, 2017). However, while weather conditions are extremely difficult to address archaeologically, comparisons of different populations from different climatic regions may help addressing the role of climate on past human health. In this framework, Schats (2023) recently underscored the significance of incorporating the natural environment into the interpretation of porous lesions, as high prevalence rates of *cribra orbitalia* can serve as a potential indicator of malaria in skeletal remains from regions with high malaria endemicity. It is worth noting that, even if historical sources explicitly mention malaria in Zeeland only from the 16th century onward, it has been argued that it may have been highly prevalent even during the medieval period (Heide, 1988; Schats, 2015). In our results, *cribra orbitalia* prevalence rates indicate minimal variation over time, suggesting that the factors contributing to it were not influenced by (de)urbanization in the studied area. Consequently, the enduring consistency of *cribra orbitalia* in our samples may indeed hint at malaria’s substantial impact on the health of the populations under investigation, even if more research would be needed to confirm this hypothesis.

An additional limitation in our research stems from the heterogeneity of the investigated populations (Wood et al., 1992). Despite our best efforts to account for all relevant factors shaping the lives of the individuals under study, our data originates from cemeteries that were in use for several centuries. This temporal expanse poses a challenge in addressing factors

associated with temporal variations, such as climate change, natural calamities, epidemics, and wars, which could have impacted both human health and frailty. Furthermore, the dimension of mobility within the populations under investigation also potentially impacted our results. Although it is unlikely that a significant influx of immigrants occurred in Vlissingen during the post-medieval period, both Aardenburg and Vlissingen, Oude Markt experienced substantial prosperity in medieval times, likely attracting diverse newcomers with different backgrounds. The absence of an inquiry into migration is undoubtedly a confounding factor for our analysis, as we are unable to identify individuals with a mobility background, nor to make assumptions regarding their living and working conditions before they moved to the cities. While a few bioarchaeological studies on Dutch populations have addressed migration through isotope analysis (e.g., Kootker et al., 2016, 2018, 2019), there is currently no systematic study that has specifically examined the potential confounding effects of demographic non-stationarity in Dutch samples. Examining different populations would aid in assessing how human mobility could have influenced the health patterns of urban populations, especially the ones with significant migration history.

5.6. Conclusions

This study aimed to examine patterns of health and disease in several urban contexts in the Dutch region of Zeeland, whose economy was based on international maritime trade. While historical urban prosperity is reflected in our findings from the 11th to the 16th century by low, unchanging rates of cribra orbitalia, linear enamel hypoplasia, and chronic maxillary sinusitis, in the post-medieval period (i.e., during times of urban and economic decline) we observed a significant increase in porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary rates. Furthermore, we observed how in the post-medieval period porotic hyperostosis was more frequent in males, suggesting that decreasing job opportunities and financial stability impacted men more than women.

Overall, our findings emphasize the necessity of examining each urban context individually, recognizing unique historical patterns and distinct influences on its inhabitants. We argue that, as we progress in our understanding of past urban populations, it is vital to address the multifaceted aspects of urbanization that have contributed to the health of our ancestors, delving into factors such as economic variability, gender differences in socioeconomic change, and historical climates. By doing so, we can aim to attain a more comprehensive and nuanced understanding of both urbanization, its diverse elements, and of how they have contributed to the wellbeing of past communities.

Supporting information

Supplementary materials for this paper are available on the publisher's website: <https://doi.org/10.1002/oa.3302>

Data availability statement

The datasets generated and analyzed during the current study are available at Casna, Maia, 2023, "Data for: "The urban sea"", <https://doi.org/10.17026/AR/DOHGI1>, DANS Data Station Archaeology.

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CHAPTER 6

Historical Trends and Risk Factors in Chronic Maxillary Sinusitis Prevalence Rates Among Dutch Non-Adults (475-1866 CE)

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Abstract

Objectives: This research examines the prevalence of chronic maxillary sinusitis in non-adults from multiple Dutch sites, while also considering the effects of associated risk factors such as time period (i.e., urbanization), living conditions, and socioeconomic status. Our aim was to investigate how different risk factors impacted childhood respiratory health throughout the Dutch medieval and Post-medieval periods.

Materials and Methods: We selected 13 sites representative of different time periods (475-1866 CE), living environments (i.e., rural and urban), and socioeconomic statuses to provide an in-depth overview of past Dutch societies. We macroscopically and endoscopically analyzed the maxillary sinuses of 227 non-adult individuals to identify paleopathological signs of sinusitis. Adult data on chronic maxillary sinusitis from 11 of these populations were available for comparison.

Results: Statistical analysis revealed that post-medieval non-adults were almost three times more likely to develop sinusitis than their early-medieval counterparts. Additionally, increasing age-at-death statistically increased the likelihood of sinusitis. Post-medieval adolescents were eight times more at risk than adolescents from earlier periods.

Discussion: Our findings highlight the interplay of risk factors affecting respiratory health in non-adults, contributing to a more comprehensive understanding of the historical burden of respiratory diseases in past populations. Despite concerns regarding the representativeness of our sample, we argue that factors such as increased population densities, limited access to resources, and the institutionalization of child labor in the Dutch post-medieval period significantly and negatively impacted the respiratory health of non-adults.

Keywords: Respiratory health; Non-survivors; Paleopathology; Urban development; Child labor

6.1. Introduction

Today, chronic respiratory diseases are among the most prevalent non-communicable diseases worldwide; this is likely a consequence of pervasive exposure to detrimental environmental, occupational, and behavioral factors (Labaki & Han, 2020). Due to their prevalence in contemporary society, respiratory diseases have often been the subject of bioarchaeological studies, as it is assumed that several risk factors (e.g., exposure to air pollution, poor hygienic conditions, and crowded living and working environments) prevailed in many historical contexts and likely negatively impacted the respiratory health of our ancestors (e.g., Boocock et al., 1995; Boyd, 2020; Davies-Barrett et al., 2021; Panhuysen et al., 1997; Riccomi et al., 2021). Previous research on respiratory diseases indicates that these health issues have been prevalent among human populations since at least 2000 BCE, persisting across various time periods and living conditions (Roberts, 2007; Wells, 1977).

According to historical sources, up until the 19th century respiratory diseases were the most common diseases affecting European children and the leading cause of their mortality (Shulman, 2004; Wintle, 2000). “Coughs”, an umbrella term likely encompassing a variety of ailments such as influenza, bronchitis, tuberculosis, and pertussis, were frequently discussed in the earliest pediatric texts dating back to the 1500s, as (according to historical sources) they were prevalent among children of all socioeconomic backgrounds (Pancino, 2015). This is generally supported by the few osteoarchaeological studies focusing on non-adults specifically, which so far have reported respiratory diseases prevalence rates ranging from 10% to 66% (e.g., Krenz-Niedbala & Łukasik, 2020; Liebe-Harkort, 2012; Panhuysen et al., 1997). In most cases, the main aim of these studies has been to investigate how different living circumstances (e.g., urbanization, socioeconomic status) influenced respiratory health. For example, in their study on chronic maxillary sinusitis among non-adults in medieval Denmark, Bennike and colleagues (2005) identified socioeconomic status as a significant risk factor for sinusitis, as they observed higher prevalence rates of bony changes in individuals from economically disadvantaged backgrounds compared to their wealthier counterparts. Furthermore, in order to assess whether urbanization and industrialization impacted child health, Krenz-Niedbala and Łukasik (2020) examined sinusitis, otitis media, and pleural inflammation among 308 non-adult individuals from two medieval rural and proto-urban Polish populations (10th-17th centuries CE) and found that both otitis media and pleural inflammation were more common among urban children compared to rural ones. In contrast, when analyzing 831 individuals from four English sites dating to 850-1859 CE, Lewis (2002) observed higher rates of sinusitis in rural non-adults than in urban ones.

Divergences in results are common in bioarchaeological studies focusing on respiratory diseases and may often be attributed to the complex etiologies of these conditions (e.g., Casna et al., 2023; Collins, 2019; Lewis et al., 1995). It is widely acknowledged that identifying precise risk factors affecting respiratory health in historical populations poses significant challenges and is, in most cases, impossible (Lewis et al., 1995). Nevertheless, the abundance of both paleopathological and historical data available today for (adult) skeletal populations offers foundational insights

into how different risk factors interplayed with each other in past societies, shedding light on how human behavior affected disease and vice versa (e.g., Boyd, 2020; Casna et al., 2023; Casna et al., in press; Davies-Barrett et al., 2023; Roberts, 2007). While paleopathology has advanced our understanding of how various risk factors for respiratory disease interacted and contributed to its prevalence among adults, a comprehensive analysis of their influence on the respiratory health of non-adults is currently lacking. This gap in knowledge presents several issues as: 1) children are clinically disproportionately affected by respiratory diseases due to various physiological and behavioral factors (Ferkol & Schraufnagel, 2014; Zar & Ferkol, 2014); and 2) focusing paleopathological research solely on adults may hinder a comprehensive understanding of a population as a whole (Halcrow & Tayles, 2011). Furthermore, differences in developmental stages, immune system maturity, environmental exposures, and social/cultural behaviors may result in distinct risk factors affecting adults and non-adults differently, leading to different life and disease experiences based on age (Badley et al., 1973; Verhaegh et al., 2008; Zar & Ferkol, 2014). Although recent studies have partially bridged this gap by incorporating both adults and non-adults in their analyses, thereby providing an initial understanding of how past environments and living circumstances affected the respiratory health of past populations, it is currently unclear how these various risk factors interacted within non-adults specifically (Collins, 2019; Davies-Barrett et al., 2021; Zubova et al., 2020). As a consequence, our comprehension of the effects of respiratory diseases on the archaeological populations we examined remains limited, as does our understanding of the diverse influences of various risk factors across different phases of life.

To partially address this gap, the present study analyzed chronic maxillary sinusitis (here considered as a proxy for respiratory disease) in a sample of 227 non-adult individuals from 13 Dutch sites dating from 475 to 1866 CE. We examined the role of various risk factors (i.e., urbanization, living environment, and socioeconomic status) on the observed prevalence rates of sinusitis to investigate their impact and interplay within different populations. Our hypothesis was that urbanization and lower socioeconomic status would correlate with higher prevalence rates of sinusitis among non-adults, reflecting differential exposure and susceptibility to environmental and social factors.

6.2. Materials and methods

6.2.1. Materials

For the purpose of this study, we selected 13 skeletal populations from various regions across the Netherlands (Figure 6.1). Our primary motivation for studying these specific non-adult assemblages was the existing data on chronic maxillary sinusitis in adults from the same groups, enabling us to compare prevalence rates across 11 of the populations under study (Table 6.1). Moreover, these sites benefit from a substantial amount of historical data, as well as a well-understood osteoarchaeological context (see Supporting Information S1 for a comprehensive historical background for all populations included in this study). Together, these skeletal populations offer the most complete overview of past Dutch societies, as they not only span

diverse time periods (from the early to post-medieval periods), but they also encompass various living environments (i.e., rural and urban), and represent a wide range of socioeconomic statuses.

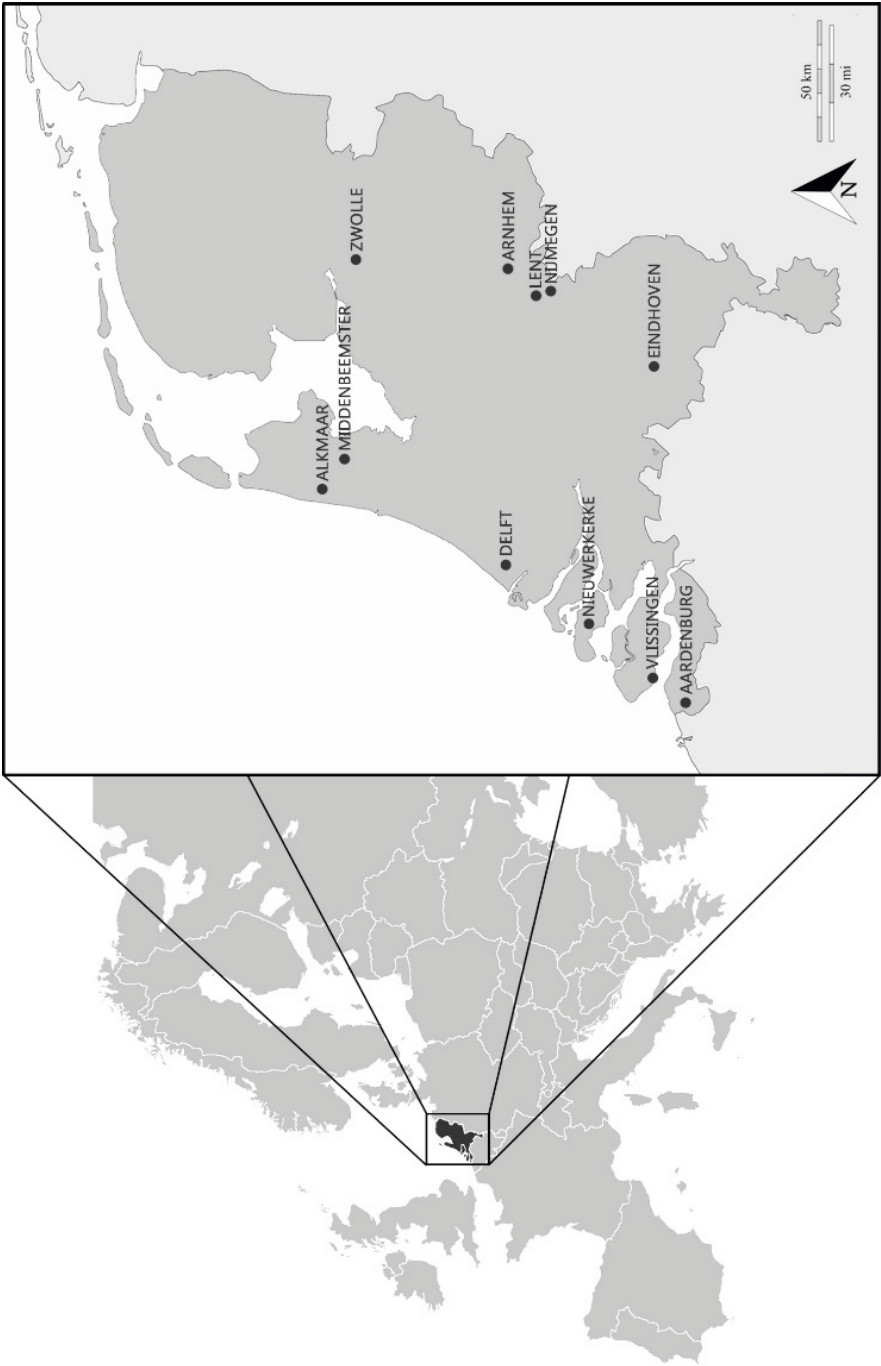


Figure 6.1. Map of the Netherlands showing the location of the sites under study.

Table 6.1. Skeletal collections included in this study. Data on chronic maxillary sinusitis in adult individuals were retrieved from: 1=Casna et al. (2023); 2=Casna & Schrader (2024); 3=Casna & Schrader (2022).

Skeletal collection	Dating	Living Environment	Socioeconomic Status	Observed Chronic Maxillary Sinusitis Prevalence Rate in Adults
Lent, Azaleastraat and Lentseveld	Early-medieval (475-750 CE)	Rural	Middle-low	11.3% ¹
Aardenburg, Sint-Baafskerk	Early-medieval (1030-1200 CE)	Urban	Middle-high	20.8% ¹
Nieuwerkerke, 't Schutje	Late-medieval (1298-1576 CE)	Rural	Middle-low	35.4% ¹
Vlissingen, Oude Markt	Late-medieval (1300-1590 CE)	Urban	Middle-low	27.8 ²
Alkmaar, Paardenmarkt	Late-medieval (1448-1572 CE)	Urban	Middle-low	44.8% ¹
Vlissingen, Scheldekwaartier	Post-medieval (1600-1800 CE)	Urban	Low	46.3% ²
Delft, Nieuwe kerk	Post-medieval (1624-1821 CE)	Urban	High	n/a
Arnhem, Eusebiuskerk	Post-medieval (1626-1829 CE)	Urban	Low	50.8% ¹
Nijmegen, Klooster Hessenberg	Post-medieval (1638-1725 CE)	Urban	Low	n/a
Eindhoven, Sint-Catharinakerk (outside the church)	Post-medieval (1650-1850 CE)	Urban	Middle-low	35.0% ³
Eindhoven, Sint-Catharinakerk (inside the church)	Post-medieval (1650-1850 CE)	Urban	Middle-high	59.1% ³
Zwolle, Broerenkerk	Post-medieval (1681-1828 CE)	Urban	Middle-high	54.2% ³
Middenbeemster, Keyserkerk	Post-medieval (1829-1866 CE)	Rural	Middle-low	40.3% ¹

To ensure comparability to previously published data, the sites under study were categorized into early-medieval, late-medieval, and post-medieval periods using the same periodization framework presented by Casna and colleagues (2023). This framework emphasizes the transition from an era characterized by landowners and isolated communities (early-middle ages, 300–1080 CE), to the emergence of cities (late-middle ages, 1080–1500 CE), to the rise of industry (post-medieval times, 1500–1850 CE) (Blockmans & Hoppenbrouwers, 2007; Wintle, 2000). Furthermore, differences in socioeconomic status were attributed for each skeletal population following the same methodology outlined by Casna and Schrader (2022), where we distinguished, informed by historical sources, four socioeconomic classes: 1) ‘low’, composed by individuals with almost no possessions, often employed in dependent unspecialized work and socially insignificant at the eyes of the municipal administrations; 2) ‘middle-low’, small businessmen, artisans, and market vendors; 3) ‘middle-high’, the administrative force of the city (e.g., enriched merchants, financiers, etc.); and 4) ‘high’, clergy, nobles, and gentry families.

6.2.1.i. Social and economic developments in historical Netherlands

Between 300 and 1080 CE, Dutch society lacked a unified social and political identity. Instead, it was predominantly organized around kinship ties and familial bonds, with power concentrated in the hands of wealthy local leaders and landowners (Blockmans & Hoppenbrouwers, 2016). While a few cities such as Aardenburg were flourishing thanks to the rise of early market trades (de Vries, 1968), most people in the Low Countries were still employed in subsistence farming (Besteman, 1997; Hoppenbrouwers, 2002). The division between urban and rural lives was then likely already quite significant and marked by distinct economic opportunities that possibly reinforced socioeconomic differences across the region (de Pooter et al., 2000; Henderikx, 2012). While international trade in urban centers allowed craftsmen and merchants to thrive, rural communities such as Lent continued to heavily rely on agriculture and pastoralism and people there often remained tied to the land under feudal obligations (Dumolyn, 2002).

During the period following 1200 CE, the Low Countries experienced significant socioeconomic transformation, resulting in a shift from a cluster of economically disconnected agricultural villages to a network of small urban centers (Hoppenbrouwers, 2002). Work opportunities available in towns spurred exponential population growth and, by 1514 CE, nearly half of Holland’s population resided in urban areas (Blockmans et al., 1980; Hoppenbrouwers, 2001). While towns in the late-medieval period may have still retained a relatively rural character (e.g., most citizens from Alkmaar owned a small vegetable garden to grow their own food), they expanded over time, shifting from self-sufficiency to more market-oriented economies (Bitter, 2007; Hoppenbrouwers, 2002; van Bavel, 2010). As the international trade market intensified in the 14th and 15th centuries, several products such as beer, cheese, and butter began to be regularly exported internationally (Hoppenbrouwers, 2002). Rural realities became then increasingly intertwined with nearby cities, as their purpose increasingly became to satisfy the demands of the growing centers and markets (Mijnhardt, 2012). Social structures were also likely impacted by the rise of the international market: in the late-medieval period, wealthy merchants

and specialized craftspeople started to gain great economic and political influence, challenging the traditional social dominance of the nobility (Dumolyn, 2002).

The rise of this new urban elite continued throughout the post-medieval period. With the expansion of market routes beyond the European continent and the begin of the industrial era, merchants, investors, and bankers accumulated significant wealth, exacerbating socioeconomic disparities (ten Hove, 2005; Wintle, 2000). The newborn industry offered an enormous number of work opportunities, prompting people to flock to the cities (de Vries, 1984). In many cases, municipalities found themselves unable to accommodate the influx of immigrants, leading to overcrowded and inadequate living conditions (van der Woud, 2010; van Laar, 1966). Industry work was notoriously unregulated, and often led to hazardous environments where accidents and diseases were common (Wintle, 2000). Children, who had previously traditionally accompanied their parents in their daily activities, started to be systematically hired in factories already by the age of ten (Smit & Korevaart, 2018). These developments marked the emergence of a new poor class, whose life experiences greatly differed from those of the elites who still lived in spacious, refined mansions located in dedicated areas away from pollution and from the struggles of lower-class communities (ten Hove 2005). It is generally believed that social stratification was less pronounced in rural areas, where agricultural production was still the primary focus of the economy (Bieleman, 2010). However, disparities in land ownership and wealth may still have existed in contexts such as Middenbeemster, where agriculture had evolved into a highly efficient, intensive, and organized sector catering primarily to the export market during the post-medieval period (Aten, 1992; Bieleman, 2010; Wintle, 2000).

6.2.2. Methods

For every analyzed individual, age-at-death was estimated by observing dental development, dental eruption patterns, as well as epiphyseal-diaphyseal fusion (AlQahtani et al., 2010; Cunningham et al., 2016; Demirjian et al., 1973; Moorrees et al., 1963; Schaefer et al., 2009). Skeletal sex was not determined because established macroscopic methods for sex estimation are not applicable to non-adults, as their bones have not yet developed secondary sex traits (Cunningham et al., 2016).

6.2.2.i. Chronic Maxillary Sinusitis

The typical non-pathological visual aspect of the sinus cavity is characterized by its smooth and uniform surface, with channels extending along its walls, which during life would have housed nerves and blood vessels (Whyte & Boeddinghaus, 2019). In bioarchaeology, changes observed on the sinus surface (e.g., bone resorption, bony spicules, cobweb-like lesions) and thickening of sinus walls are typically interpreted as indicators of chronic sinusitis (Boock et al., 1995; Lewis et al., 1995; Merrett & Pfeiffer, 2000; Sundman & Kjellström, 2013a). However, in non-adults, the maxillary sinuses naturally expand and remodel to accommodate the developing permanent dentition (Lorkiewicz-Muszyńska et al., 2015). This remodeling process creates large pits on the sinus floor, which can be mistaken for pathological changes and potentially lead to an overestimation of sinusitis prevalence rates (Lewis, 2018). For this reason, in the present study,

we did not consider bone resorption as indicative of sinusitis. Rather, sinusitis was scored as 'present' based on the presence of either bony spicules and/or cobweb-like lesions on any of the sinus walls (Figure 6.2) (Lewis, 2018). Thickening of the sinus walls was initially included in our criteria, but not observed in any of the individuals under study.

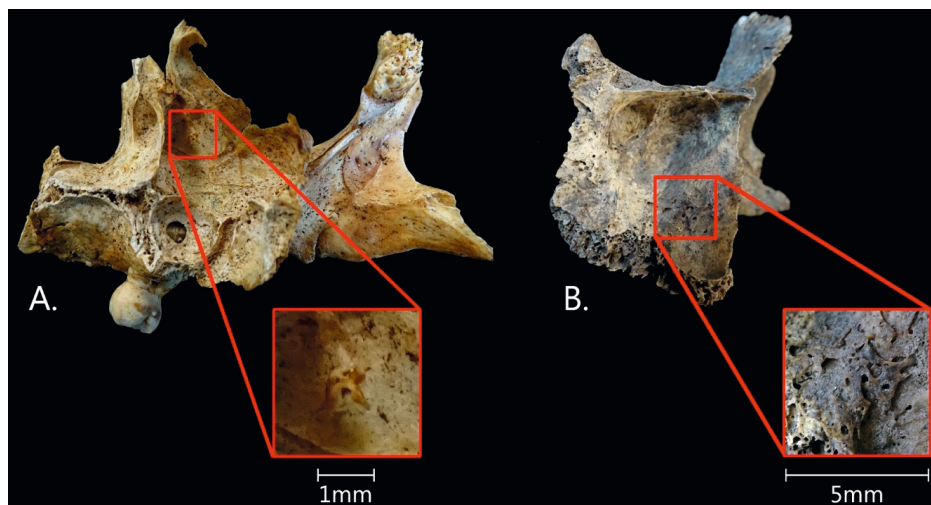


Figure 6.2. Examples of lesions indicative of chronic maxillary sinusitis observed in this study: (a) bony spicules, (b) cobweb-like lesion. Photographs and figure by M. Casna.

The presence of chronic maxillary sinusitis was observed in all individuals with at least one sinus with a partial preservation of more than 25% of the total sinus surface. To ensure accurate examination, sinuses were carefully brushed and, if necessary, cleaned with water before inspection. If the sinuses were not visible to the naked eye, they were examined using a flexible medical endoscope (Pentax, model: FNL-10RBS, $\phi=4$ mm; view angle= 30°) inserted whenever possible through existing post-mortem breaks (Casna et al., 2021).

6.2.2.ii. Statistical Analysis

Statistical analysis was conducted using SPSS version 29.0 for Windows. We used binary logistic regression to investigate the relationship between various risk factors for respiratory disease (i.e., time period, subsistence economy, and socioeconomic status) and the presence of chronic maxillary sinusitis at the level of the individual (Harris, 2021). Age-at-death was also added as a covariate as previous studies suggested that sinusitis may show an increase with age (Lewis, 2018). In binary logistic regression, a 95% confidence interval with an upper limit below 1 indicates that the group in question is significantly less likely to be associated with the disease compared to the reference group. Conversely, a lower limit above 1 signifies that the group is significantly more likely to be associated with the disease than the reference group. *P*-values of ≤ 0.05 were considered to be statistically significant.

6.3. Results

A total of 227 non-adult individuals were analyzed for both age-at-death and for the presence of chronic maxillary sinusitis. Among them, 107 individuals (47.1%) showed evidence of chronic maxillary sinusitis, which was observed less frequently in children (37.1%) compared to juveniles (54.0%) and adolescents (50.0%) (Table 6.2; Figure 6.3). In most cases, the overall prevalence rates observed in non-adults were higher than those previously observed in adults (Figure S2).

Table 6.2. Observed prevalence rates of chronic maxillary sinusitis in the sample under study.

Skeletal population	Age-at-death			
	Child (4-7 years) (N)	Juvenile (8-11 years) (N)	Adolescent (12-19 years) (N)	Total (N)
Lent, Azaleastraat and Lentseveld	4 (9)	1 (2)	2 (5)	7 (16)
Aardenburg, Sint-Baafskerk	0 (1)	0 (0)	1 (4)	1 (5)
Nieuwerkerke, 't Schutje	3 (10)	2 (8)	7 (14)	12 (32)
Vlissingen, Oude Markt	0 (0)	0 (1)	2 (3)	2 (4)
Alkmaar, Paardenmarkt	0 (0)	0 (1)	1 (2)	1 (3)
Vlissingen, Scheldekwartier	2 (4)	1 (2)	1 (1)	4 (7)
Delft, Nieuwe Kerk	2 (8)	5 (7)	4 (8)	11 (23)
Arnhem, Eusebiuskerk	4 (11)	4 (10)	10 (31)	18 (52)
Nijmegen, Klooster Hessenberg	1 (5)	0 (2)	2 (2)	3 (9)
Eindhoven, Sint-Catharinakerk (outside the church)	5 (7)	3 (9)	2 (6)	10 (22)
Eindhoven, Sint-Catharinakerk (inside the church)	0 (2)	2 (4)	3 (3)	5 (9)
Zwolle, Broerenkerk	0 (2)	6 (6)	1 (1)	7 (9)
Middenbeemster, Keyserkerk	5 (11)	10 (11)	11 (14)	26 (36)
Total (N)	26 (70)	34 (63)	47 (94)	107 (227)

N: Total number of analyzed individuals.

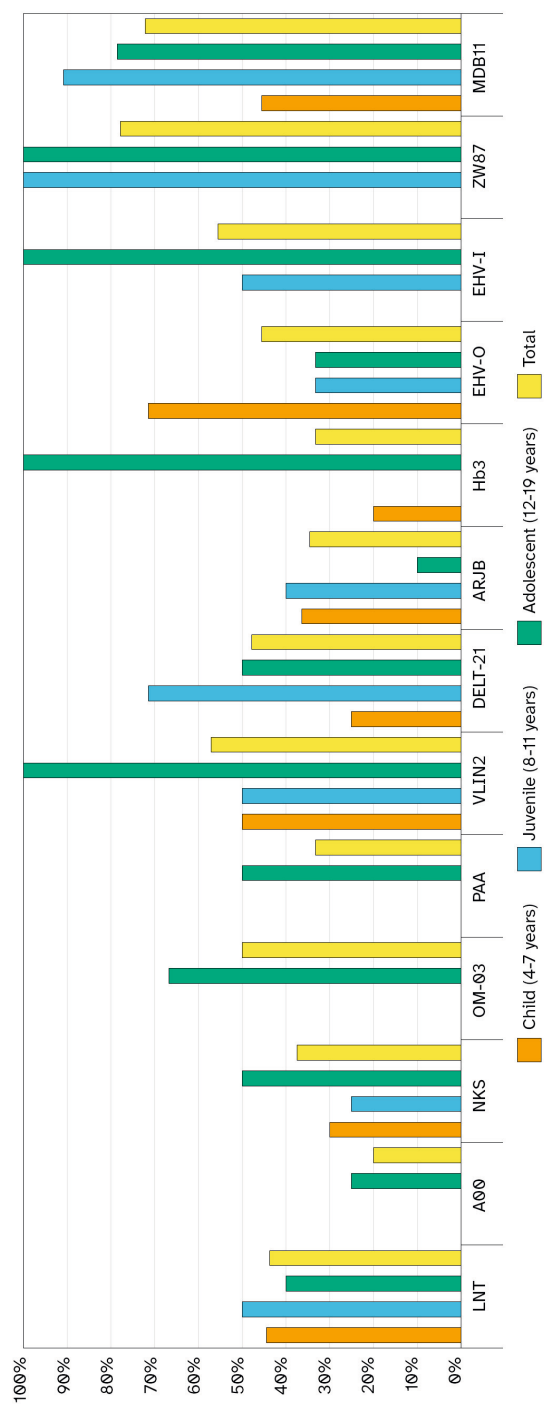


Figure 6.3. Prevalence of chronic maxillary sinusitis for all samples under study. LNT=Lent; A00=Aardenburg; NKS=Nieuwerkerke; OM-03=Vlissingen, Oude Markt; PAA=Alkmaar; VLIN2=Vlissingen, Scheldekwartier; DELT-21=Delft; ARJB=Arnhem, Hb3=Nijmegen; EHV-O=Eindhoven, Outside the church; EHV-I=Eindhoven, Inside the church; ZW87=Zwolle; MDB11=Middenbeemster.

Our statistical analysis indicates that time (i.e., urbanization) significantly impacted the prevalence of chronic maxillary sinusitis in the populations under study ($p=0.011$) (Table 6.3). While individuals from the early-medieval and late-medieval periods exhibited similar prevalence rates, those from the post-medieval period (1600-1866 CE) were almost three times more likely to present with chronic maxillary sinusitis compared to early-medieval populations ($p=0.045$) (Figure 6.4).

Table 6.3. Outcomes of binary logistic regression. Constants: Time period=Early-Medieval; Subsistence economy=Rural; Socioeconomic status=Low; Age-at-death=Child. OR=Odds ratio; CI=Confidence Intervals; *= indicates p -value ≤ 0.05 .

	OR	CI for OR		p -value
		Lower	Upper	
Time period				*0.011
Late-Medieval	1.152	0.388	3.419	0.798
Post-Medieval	2.892	1.023	8.176	*0.045
Living environment	0.460	0.185	1.144	0.095
Socioeconomic status				0.671
Middle-low	1.196	0.480	2.980	0.700
Middle-high	1.934	0.683	5.475	0.214
High	1.164	0.428	3.170	0.766
Age-at-death				0.098
Juvenile	1.885	0.909	3.911	0.089
Adolescent	1.979	1.021	3.839	*0.043

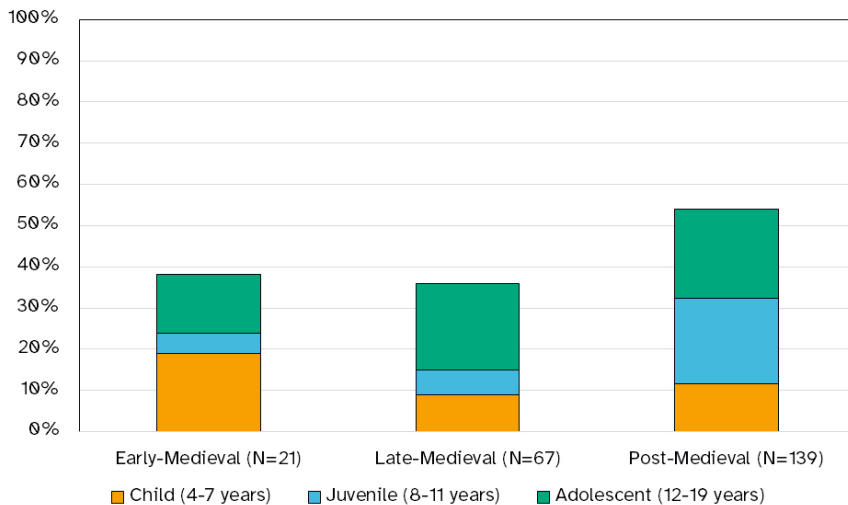


Figure 6.4. Prevalence of chronic maxillary sinusitis in the historical periods under study.

Neither living environment nor socioeconomic status was found to significantly impact chronic maxillary sinusitis in the populations under study. Although rural sites showed a slightly higher overall prevalence of sinusitis compared to urban sites, this difference was not statistically significant (Figure 6.5). Similarly, no statistically significant relationship was observed between sinusitis and socioeconomic status, though individuals from middle-low and middle-high socioeconomic groups exhibited higher overall rates of sinusitis compared to those from low and high socioeconomic groups (Figure 6.6).

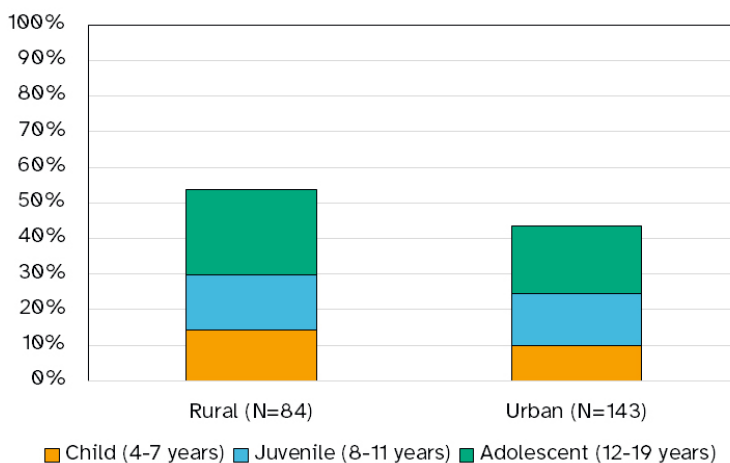


Figure 6.5. Prevalence of chronic maxillary sinusitis in rural and urban populations under study.

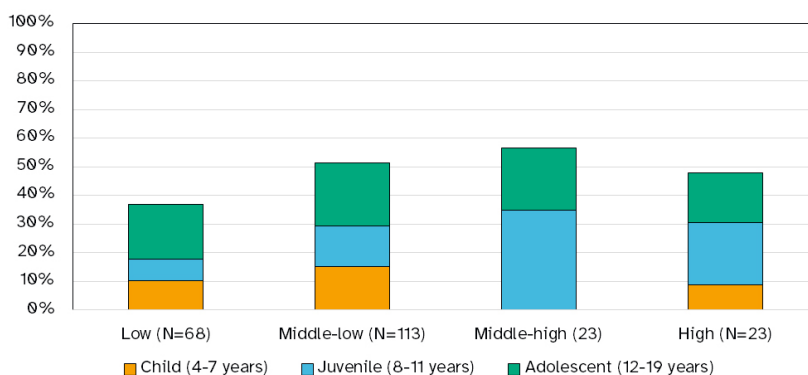


Figure 6.6. Prevalence of chronic maxillary sinusitis in different socioeconomic status groups.

Overall, age-at-death was not found to significantly impact chronic maxillary sinusitis in the populations under study ($p=0.098$). However, both juveniles and adolescents were almost twice as likely than children to present bone changes indicative of sinusitis, with this being statistically

significant in adolescents only ($p=0.043$). This is partly reflected in Table S3, which presents the results of binary logistic regression divided by age group. While no risk factors appeared to influence sinusitis in children and juveniles, adolescents from the post-medieval era were eight times more likely to present sinusitis than adolescents from the early-middle ages ($p=0.026$).

6.4. Discussion

The aim of this study was to explore the impact of various risk factors (i.e., time period, living environment, and socioeconomic status) on the respiratory health of multiple non-adult Dutch populations, using chronic maxillary sinusitis as a proxy. Our results showed that sinusitis was a common condition throughout the medieval and post-medieval periods in the Netherlands, ranging from 20.0% to 77.8% in the populations under study. This is consistent with historical literature, which reports that, up until the 19th century, “coughs” (i.e., respiratory diseases) were among the most prevalent childhood conditions and were frequently cited as the leading causes of death (Pancino, 2015; Shulman, 2004; Wintle, 2000). Furthermore, chronic maxillary sinusitis had already been observed among adults in most of the assemblages under study, further attesting to the presence of risk factors for respiratory diseases in these populations (Casna et al., 2023; Casna & Schrader, 2022, 2024).

Among all risk factors under study, time period was the only variable to have a statistically significant impact on chronic maxillary sinusitis in non-adults. This finding aligns with our earlier observations of sinusitis in adults, in which neither rural/urban differences nor socioeconomic status were found to have had an impact on the respiratory health of the populations under study (Casna et al., 2023; Casna & Schrader, 2022). An initial inference that could be drawn from this is that comparable rates of sinusitis indicate similar levels of exposure to risk factors, implying that disparities in living conditions between city and countryside and socioeconomic backgrounds were not pronounced. This appears implausible, as it contradicts most historical sources (e.g., Brusse & Mijnhardt, 2011; Kuiper & Lengkeek, 1994; van der Woude, 1972; Wintle, 2000). We argue that, while lived experiences changed considerably between different environments and socioeconomic groups, risk factors for respiratory disease to which people were exposed also varied alongside, impacting respiratory health to a significant extent regardless of the variables analyzed (Casna et al., 2021; Casna & Schrader, 2022). For example, lower socioeconomic classes lived and worked in more precarious conditions, often with limited access to resources and in crowded, unsanitary environments (Jansen, 1974; Wintle, 2000). These circumstances naturally exposed them to greater risk factors for infectious disease. However, wealthier individuals, despite their more comfortable lifestyles, often spent significant time indoors near open fires, frequently indulging in hazardous behaviors (e.g., tobacco smoking in the post-medieval period), which also likely facilitated respiratory diseases (Holwerda & Verleden, 2017; ten Hove, 2005). The same variability in risk factors possibly also applied to the differences we observed between rural and urban sites, which were found not to significantly influence sinusitis prevalence rates.

Due to a variety of historical and social factors, urban settlements have frequently been perceived as unhealthy and unsanitary settings where life is continually endangered, especially in contrast to rural environments (Betsinger & DeWitte, 2021; Schell, 2018). Moreover, most bioarchaeological studies on sinusitis have observed higher rates of sinusitis in urban samples compared to rural ones (e.g., Lewis et al., 1995; Panhuysen et al., 1997; Sundman & Kjellström, 2013b). In the present study, we found sinusitis to have a higher prevalence rate in rural populations than in urban ones, despite living environment not significantly impacting the risk for sinusitis, as mentioned earlier. This finding is consistent with that of both Lewis (2002) and Williams and Galley (1995), who also observed higher rates of respiratory disease in rural non-adults compared to urban counterparts. Williams and Galley (1995) specifically discuss the impact of allergic reactions triggered by close contact with animals and exposure to biological particulates in the air (i.e., pollens, molds, and dust produced by agricultural activities) on sinusitis. They argue that these factors account for high prevalence rates of sinusitis in rural areas, contrasting with overcrowding in living environments, general limited access to resources, and air pollution, which may trigger sinusitis in urban areas (Williams & Galley, 1995).

Another factor that could have influenced sinusitis prevalence rates across different environments and socioeconomic statuses is the healthcare dedicated to children. While in poorer households the care of sick children was mostly entrusted to family members who relied on either experience or popular knowledge, historical sources indicate that, as early as the medieval period, it was somewhat common for wealthier children to have a doctor (or, more commonly, a midwife) attending to them during their early years (Pancino, 2015; van Poppel, 2018). However, it should be noted that, at least until the 1700s, respiratory disorders were treated (regardless of the socioeconomic status of the patient, or the living environment) with homemade infusions of herbs, a spoon of animal fat, or (in the post-medieval period) with a paste of tobacco leaves (Pancino, 2015). While these remedies may have alleviated symptoms, it is difficult to believe that they could effectively cure any viral or bacterial infection. We argue that the lack of knowledge regarding how to identify, prevent, and effectively treat respiratory diseases, rather than access to healthcare, may contribute to explain why sinusitis prevalence does not significantly differ between the different populations under study.

In previous studies on historical sinusitis in the Netherlands, it was observed that the transition from the early-medieval to the post-medieval period had the most significant impact on sinusitis prevalence rates (Casna et al., 2023; Casna & Schrader, 2024). This was reflected in our results, as individuals from the post-medieval period were found to be almost three times more at risk for sinusitis than early-medieval ones ($p=0.045$). It was suggested that, while the expanding urban environment had an increasingly negative impact on people's health (regardless of their living environment), this growth in health challenges may however have been more nuanced between the late-medieval and post-medieval period, as differences in sinusitis prevalence rates did not vary significantly (Casna et al., 2023). Historically, this may be explained by the fact that, while urban expansion had already started in the late-medieval period, it was during the post-medieval era that cities developed the most typical urban characteristics that posed

significant challenges to the lives and health of their citizens (e.g., overcrowding, inadequate housing facilities, limited access to resources, fluctuating economy, and unregulated factory work) (Hakvoort, 2013; van Laar, 1966; Wintle, 2000). Moreover, the introduction and wide popularization of tobacco in the 17th century likely contributed to the prevalence rates we observed, as both active consumption and exposure to secondhand smoke are recognized as significant risk factors for respiratory disease (Snelders, 2021; van der Rijst & Garfield, 2023). By 1700 CE, tobacco had become ubiquitous in the Netherlands among all socioeconomic classes, and recent traces of consumption on adult human dentition were identified by Casna and colleagues (2024) in three of the populations under study, with prevalence rates of smokers ranging between 15.6-43.7%. Recording tobacco consumption among non-adults populations fell beyond the scope of this study. However, considering the potential significant impact of tobacco on the respiratory health of past populations (Casna et al., *in press*), we argue that the observed increased risk for sinusitis in the post-medieval period may be partly correlated with the introduction of tobacco to Europe. Further research is warranted to investigate the specific impact of tobacco on non-adult populations.

While looking at the impact of time period among different age groups, it was interesting to note that post-medieval adolescents were eight times more likely to present sinusitis than their early-medieval counterparts ($p=0.026$) and twice more likely to present sinusitis regardless of time period, living environment, and socioeconomic status ($p=0.043$). This was not surprising, as similar patterns were previously observed by both Merrett and Pfeiffer (2000) and Lewis (2002), who noted that sinusitis was more common among older non-adults in the samples they analyzed. DeWitte and Stojanowski (2015) previously addressed the higher frequency of lesions in older age groups, suggesting that non-adults should be viewed not as representative of the population but rather as ‘non-survivors.’ According to the osteological paradox, vulnerable individuals may have succumbed to disease before their skeletons developed observable responses, implying that younger children without lesions should not be seen as indicative of a population free from sinusitis. Instead, this group likely includes both healthy individuals and those who died before their skeletons could manifest any sign of bone reaction (DeWitte & Stojanowski, 2015; Wood et al., 1992). While this offers an interesting perspective on our data, it should be noted that, in most cases, sinusitis prevalence rates were higher among our non-adult samples than among adults. This suggests a “non-paradoxical” nature to our observations, as they lack a positive relationship between sinusitis and age (Bennike et al., 2005; Holland, 2014). Further support for this view comes from our previous study (Casna et al., 2023), in which we observed that sinusitis was mostly uniformly distributed across age-at-death categories. This suggests that, even if sinusitis is considered a marker for compromised immune response (Liebe-Harkort, 2012), it does not appear to have significantly impacted longevity in the populations under study. Rather, we argue that the higher prevalence of sinusitis in adolescents may be a consequence of the fact that, throughout European history, they were effectively considered adults and thus engaged in adult activities (Pancino, 2015). In fact, by the age of ten it was common for children to participate in daily tasks and, later in the post-medieval era, to be formally employed (Vleggeert, 1964; Wintle, 2000). Engaging in the life of adults likely exposed

adolescents to the same risk factors for disease, resulting in similar prevalence rates of sinusitis. This was likely even more exacerbated in the post-medieval period, when the rise of the industrial age made child labor salaried, systematic, and institutionalized (Smit & Korevaart, 2018; van Nederveen Meerkerk, 2009). Children from lower socioeconomic strata were then commonly employed in either factories or rural settings performing specific, dedicated tasks for several hours a day (Smit & Korevaart, 2018; Vleggeert, 1964; Wintle, 2000). We argue that this may have negatively impacted the respiratory health of young workers, observed in our findings as a heightened incidence of sinusitis among post-medieval adolescents.

Our results and historical contextualization offer evidence for a “non-paradoxical” view of factors impacting respiratory disease in the populations under study. However, it is clear that this evidence is not sufficient to fully address the potential impact of the osteological paradox (Wood et al., 1992). As suggested by DeWitte and Stojanowski (2015), more research could be conducted to analyze how different non-specific and specific stress markers responded to the same variables under study. This approach would offer a more comprehensive overview of past disease experiences than relying on sinusitis alone. It is also important to note that, despite sinusitis being observed archaeologically since the 1970s, we still lack a complete understanding of the formation processes of bony lesions such as spicules which may impact the interpretation of results (Mays et al., 2024; Wells, 1977). Furthermore, while we did our best to keep sample sizes even, adolescents were much more represented in the final sample than children and juveniles. Adolescents were also often better preserved, which may have impacted our ability to accurately score sinusitis (Sundman & Kjellström, 2013a). Although we believe that our statistical analysis helped mitigate the impact of these imbalances, our findings may still have been influenced to some extent by the uneven distribution of demographic categories. Specifically, there were fewer individuals from the early and late medieval periods compared to those from the post-medieval period. Additionally, the number of rural individuals was smaller than that of urban individuals, and the proportion of middle-high and high socioeconomic status individuals was relatively smaller than that of low and middle-low status individuals. This specific limitation is inherent to the nature of osteoarchaeological assemblages, making it unlikely that we will ever completely be able to address it. However, the use of biomolecular methods in future research on infectious disease may help identify pathogens in larger samples, providing more comprehensive insights into the challenges and health experiences of our ancestors. Future research should consider integrating biomolecular techniques with traditional osteoarchaeological analysis to uncover more detailed information about pathogen presence and immune responses. Additionally, expanding the scope of studies to include other markers for disease (e.g., non-specific stress markers, other respiratory conditions) could help balance sample representation, offering a clearer picture of how varying living circumstances affected the health experiences of past populations.

6.5. Conclusions

Our study aimed to investigate the impact of various risk factors (i.e., time period, living environment, and socioeconomic status) on chronic maxillary sinusitis among thirteen non-adult populations from the Netherlands. Our findings revealed that sinusitis was prevalent throughout the medieval and post-medieval periods in the Netherlands, aligning with historical and bioarchaeological literature (Casna et al., 2023; Casna & Schrader, 2022, 2024; Pancino, 2015; Shulman, 2004; Wintle, 2000).

Among the risk factors under study, only time period had a statistically significant impact on chronic maxillary sinusitis. This mirrors our earlier observations in adults, where neither rural/urban living environments nor socioeconomic status significantly affected respiratory health (e.g., Casna et al., 2023; Casna & Schrader, 2022). This suggests that, despite varying living conditions and socioeconomic backgrounds, exposure to varying respiratory disease risk factors remained consistent across different social groups. Rather, our findings highlight that the transition from late-medieval to post-medieval periods significantly impacted sinusitis prevalence, likely influenced by factors such as urbanization, tobacco popularization, and institutionalization of child labor (Hakvoort, 2013; Smit & Korevaart, 2018; Snelders, 2021). Among the total sample, adolescents were more susceptible to sinusitis than younger demographic groups. This may be indicative that adolescents lived and worked as adults and were consequently exposed to the same risk factors for sinusitis.

In conclusion, while our study offers insights into respiratory health among non-adult Dutch populations across different historical periods, living environments, and socioeconomic groups, it acknowledges limitations both in sample size distribution and the non-stationary character of osteological assemblages. Moreover, ongoing challenges in understanding osteological lesion formation suggest the need for interdisciplinary approaches in future research on respiratory diseases in archaeological contexts. Future studies may partially overcome these limitations through biomolecular methods, which could enhance our understanding of respiratory pathogen presence in larger samples. While we argue that our findings provide valuable insights, they also undoubtedly underscore the complexity and ongoing evolution of respiratory health research in archaeological and historical contexts.

Supporting information

Supplementary materials for this paper are available on the publisher's website: <https://doi.org/10.1002/ajpa.70050>

Data availability statement

The datasets generated and analyzed during the current study are available at Casna, Maia, 2024, "Data for "Historical Risk factors for childhood sinusitis"", <https://doi.org/10.17026/AR/ZVPNZS>, DANS Data Station Archaeology

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CHAPTER 7

Smoking histories: A bioarchaeological approach to tobacco consumption in two skeletal populations from the Netherlands (1300-1829 CE)

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12 In this version of the article, British English spelling and conventions from the original publication have been updated to American English to ensure consistency throughout this dissertation. All other content remains unchanged from the original article.

Abstract

Over the past decade, the history of tobacco's introduction to Europe and its societal impact has been extensively studied, resulting in prevailing narratives about its adoption and consumption. In the Netherlands, historical records generally concur that: I) tobacco rose in popularity among all socioeconomic classes between 1590 and 1630 CE; and II) it spread throughout the country as a male habit. However, the presence and consumption of tobacco have exhibited profound variations across diverse societies throughout history, manifesting dissimilar patterns of employment and significance over varying temporal and spatial dimensions. By analyzing a sample of 351 human skeletons dating from 1300 to 1829 CE, the present study challenges the limited historical narratives presented above and emphasizes the diverse contextual factors that influenced tobacco's prevalence in two different Dutch centers. Our results suggest that in certain areas of the Netherlands tobacco was likely present and widely consumed well before 1630 CE, while also highlighting overall substantial female participation in the practice. Furthermore, our analysis hints at the possibility of divergent methods of tobacco consumption between sexes, suggesting that the historical narrative of tobacco as solely a male habit may warrant reconsideration. Overall, our study contributes to a deeper understanding of the complex history of tobacco in the Netherlands, shedding light on historical trends and cultural practices.

Keywords: Paleopathology; Pipe-notches; Dental Staining; Post-medieval

7.1. Introduction

Tobacco was first introduced to Europe by the Spanish at the end the 16th century, initially as a remedy for various ailments (e.g., headaches, toothaches, intestinal worms), and later as an intoxicant (Fraga 2010; Goodman 2005). Unlike other trade substances in the Netherlands, such as coffee and sugar, the spread of tobacco did not originate from the higher socioeconomic classes; instead, it started with seamen and lower-class individuals who would gather in port inns and taverns to smoke after work (Snelders 2021). By 1630 CE, the habit of consuming tobacco had permeated across all strata of society, establishing itself as a significant commodity within the national and international market. According to historical sources, what truly allowed tobacco to become such a popular commodity in less than 50 years was the emergence of the pipe-maker business in 1609 CE (Brongers 1964; Snelders 2021). Pipes likely provided a more efficient and enjoyable way to consume tobacco compared to other methods available at the time (e.g., chewing, snuffing). The act of smoking through a pipe allowed users to inhale larger quantities of tobacco, leading to increased consumption and to higher demand (Brongers 1964). The presence of pipe fragments in most Dutch archaeological excavations dating to 1650 CE and onwards attest to how, in the post-medieval period, smoking had become an important part of Dutch culture, regardless of socioeconomic status or geographical location. In a recent study by Inskip and colleagues (2023) on the impact of tobacco on the oral health of a post-medieval rural Dutch population, it was observed that at least 71.7% of male individuals showed dental evidence of smoking (e.g., pipe notches), suggesting the consumption of tobacco was not exclusive to larger urban centers (see also Bartholdy et al. 2023).

Despite its popularity across all socioeconomic classes, just a few years after its introduction tobacco seems to have become exclusively associated with men (Brongers 1964). While the habit of smoking was largely tolerated and, in some contexts, encouraged among men, according to many historical sources tobacco use was considered distasteful and immoral for women, often linked to overt sexuality, prostitution, and unappealing attributes (McShane 2021; Snelders 2021). While Brongers (1964) argues that Dutch women (particularly those from rural areas) have consistently engaged in some degree of smoking, the predominant belief that tobacco use was mainly associated with men prevails to this day, often coupled with limited historical documentation specifically focused on women (McShane 2021). The resulting bias appears to be particularly evident in bioarchaeological studies conducted on Dutch populations where, up to now, most published research on past tobacco consumption only encompasses male individuals (e.g., Bartholdy et al. 2023; Inskip et al. 2023).

To address these biases in historical pre-conceptions about tobacco consumption in Europe, we analyzed dental evidence of tobacco usage in two skeletal populations from the Netherlands, dating to 1300-1829 CE.

7.1.1. Bioarchaeological approaches to tobacco consumption

Despite the direct insights provided by analysis of archaeological human skeletal remains into the identification of tobacco consumption at the level of the individual, the presence of lesions associated with smoking has been, to date, only scarcely addressed in bioarchaeology. Some biomolecular studies have explored the presence of tobacco through the examination of human dental calculus or metabolomic data (e.g., Badillo-Sanchez et al. 2023; Bartholdy et al. 2024), while macroscopic, non-destructive methods have also proven to be valuable tools to address tobacco consumption, especially when dealing with larger samples. In a study conducted by Walker and Henderson (2010), which examined the impact of smoking on the health of a 19th-century skeletal population from London, the presence of either 1) pipe notches; or 2) dental staining on the inner (i.e., lingual) surface of teeth was considered as indicative of tobacco consumption. Pipe notches (here defined as semi-circular abrasions attributed to teeth clenching around clay pipes) have become a routine component of skeletal analyses today. However, only a limited number of studies have addressed their prevalence at the populational level, with reported rates ranging from 39.6% to 77.3% for populations known to have had access to tobacco (Geber and Murphy 2018; Inskip et al. 2023; Walker and Henderson 2010).

The second form of evidence (i.e., dental staining) is allegedly unaffected by the type of tobacco consumption (e.g., clay pipes, chewing) and is instead attributed to the chemical composition of tobacco itself (Kiliçarslan et al. 2022; Dalrymple et al. 2021). Because of this, it was suggested that dental staining has the potential to provide more comprehensive insights into tobacco consumption, extending beyond pipe usage (Davies-Barrett and Inskip, 2024). Unfortunately, dental staining is today largely overlooked, with only a few studies addressing its presence within archaeological samples. Previous investigations into the prevalence of dental staining among archaeological skeletal populations have yielded varying results, with prevalence rates ranging from 25.9% to 48.8% (Davies-Barrett and Inskip, 2024; Walker and Henderson 2010).

7.1.2. Hypotheses

While historical studies of tobacco consumption provide plenty of valuable insights into the impact of tobacco on the health of past peoples, their limited scope and data availability often preclude a comprehensive analysis of the spread and long-term impact of tobacco use on Dutch populations across time and space. To begin addressing this knowledge gap, our study examines the presence of macroscopic evidence for tobacco consumption on human dentition (i.e., pipe notches, dental staining) in various archaeological populations from the Netherlands. Informed by the data presented by historical studies on tobacco consumption in the Netherlands, two hypotheses were formulated:

- (1) Following the introduction of tobacco in Europe and in the Netherlands at the end of the 16th century, its usage had become extremely popular among all socioeconomic classes by 1630 CE. We hypothesized that populations with documented access to tobacco would exhibit heightened skeletal indicators of tobacco consumption (i.e., pipe notches and dental staining) in comparison to their predecessors from earlier periods.

(2) According to historical sources, men were more likely than women to consume tobacco due to the cultural norms and gender-specific expectations surrounding smoking. We hypothesized statistically significant differences in smoking evidence between male and female skeletal sex categories.

7.2. Materials

For the purpose of this study, we selected two skeletal urban populations (i.e., Arnhem and Vlissingen) with known historical backgrounds related to tobacco. The total sample comprised 351 individuals whose age-at-death was ≥ 20 years. Based on the available dating of the skeletal remains, each population was categorized into two distinct groups: 1) “pre-tobacco”, denoting periods predating the widespread adoption of tobacco among European populations; and 2) “post-tobacco”, indicating eras following the dissemination of tobacco and integration into common customs and practices (Table 7.1).

Table 7.1. Demographic composition of the sample included in this study.

		Sex		Age-at-death			Total
		Male	Female	Young adult (20-34 years)	Middle adult (35-49 years)	Old adult (50+ years)	
Arnhem	Pre-tobacco (1330-1650 CE)	54	50	49	34	21	104
	Post-tobacco (1650-1829 CE)	48	56	34	30	40	104
Vlissingen	Pre-tobacco (Oude Markt, 1300-1590 CE)	27	25	33	14	5	52
	Post-tobacco (Scheldekwartier, 1600-1800 CE)	45	46	59	17	15	91

7.2.1. Arnhem

The skeletal assemblage of Arnhem (Figure 7.1) was excavated in 2017 in the courtyard of St. Eusebius’ Church and comprises approximately 350 skeletons interred between 1330-1829 CE (Zielman and Baetsen 2020). Relative and absolute dating of the graves were performed by Zielman and Baetsen (2020) by creating a Harris Matrix and a 3D model to gain insight into the chronological development of the cemetery. To establish absolute dating, bone collagen samples were extracted from the ribs of 16 individuals and subjected to 14C analysis. The rest of the skeletal population was assigned a relative dating based on their spatial relationship to the 16 radiocarbon-dated individuals (Zielman and Baetsen 2020). For the purpose of this study, each skeleton was attributed a specific dating range that corresponds to two time windows: 1330-1650 CE (Pre-tobacco) and 1650-1829 CE (Post-tobacco), respectively.



Figure 7.1. Map of the Netherlands showing the location of the sites under study. Figure made by M. Casna.

The history of post-medieval Arnhem is intricately intertwined with tobacco. From the beginning of the 18th century, tobacco was one of the most important crops grown in the river area where Arnhem is located. According to historical sources, the first tobacco spinning mill in the surroundings of Arnhem was built and put into function in 1705 CE and, from there, urban production increased exponentially in less than 50 years (Roessingh 1976). By 1740 CE, about 3 million pounds of dried tobacco leaves were weighed annually in Arnhem alone (Kuiper and Lengkeek 1994). Following the increase in local agricultural production, several tobacco factories opened in Arnhem during the 18th century, quickly becoming the main employers for people relocating to the city in search of work (van Laar 1966). The individuals buried in the courtyard of St. Eusebius' Church and analyzed in this study are thought to be representative of the lower working class (Casna et al. 2021). Therefore it is likely that at least some of them were employed in the tobacco industry. However, because of how affordable and popular tobacco was at the time, it is also likely that most individuals from the post-tobacco sample had ample access to the commodity regardless of their employment situation (Brongers 1964; Roessingh 1976).

7.2.2. Vlissingen

Today, Vlissingen is a city located in the southwestern Netherlands, on the former island of Walcheren, in the province of Zeeland. With its strategic location between the Scheldt River and the North Sea, Vlissingen has been an important harbor for centuries, managing several commercial routes to South America and the Caribbean as early as the 17th century on behalf of the United East India Company (van Cruyningen 2012).

From 2003 to 2008, different excavations in the city harbor area uncovered a total of 844 burials dated 1300-1590 CE (Oude Markt, $n=716$) and 1600-1800 CE (Scheldekwardier, $n=128$), respectively (Claeys et al. 2010). Whilst differences might exist between the demographic profiles of the two samples, the burials recovered from Oude Markt and Scheldekwardier are both thought to be representative of the lower socioeconomic class and, hence, to be comparable to the skeletal assemblage of Arnhem (Claeys et al. 2010).

The presence of tobacco consumption in Vlissingen was partly addressed by Claeys and colleagues (2010) in the analysis of the archaeological evidence recovered from the excavations: macroscopical evidence of smoking (i.e., pipe notches) was observed in circa 20% of the examined individuals from Scheldekwardier. The relatively small number of clay pipe fragments recovered on site and the dating of most fragments between 1740 and 1860 CE suggest that tobacco smoking became popular in Vlissingen somewhat later than in other harbor cities in the Netherlands, where clay pipes date much earlier (Claeys et al. 2010). Nevertheless, historical records indicate that tobacco plantations existed in Zeeland as early as 1610, albeit for medicinal uses (Enthoven 1996).

7.3. Methods

Standard osteoarchaeological methods were used to estimate the sex and age-at-death of each individual. Skeletal sex was estimated based on the observation of morphological features on the skull (Buikstra and Ubelaker 1994) and os coxae (Bruzek 2002; Phenice 1969). Age estimations of adults were made by observing the morphology of the pubic symphysis (Brooks and Suchey 1990) and the auricular surface (Buckberry and Chamberlain 2002). Age-at-death categories were classified as young adult (20-34 years), middle adult (35-49 years), and old adult (50+ years) (Buikstra and Ubelaker 1994).

7.3.1. Evidence for tobacco consumption

Assessment of tobacco consumption at the level of the individual was based on: 1) the presence of pipe notches; and 2) the presence of dental staining on the lingual surfaces of the dentition, as presented by Davies-Barrett and Inskip (2024) (Figure 7.2). If the dentition was observable, the individual was marked as either 'present' or 'absent' for each type of dental change. Overall evidence of tobacco consumption was scored as 'present' for individuals who displayed at least one of the markers we considered indicative of tobacco use (i.e., pipe notches and dental staining). This allowed a calculation of the overall prevalence of evidence for tobacco consumption in the sample group.

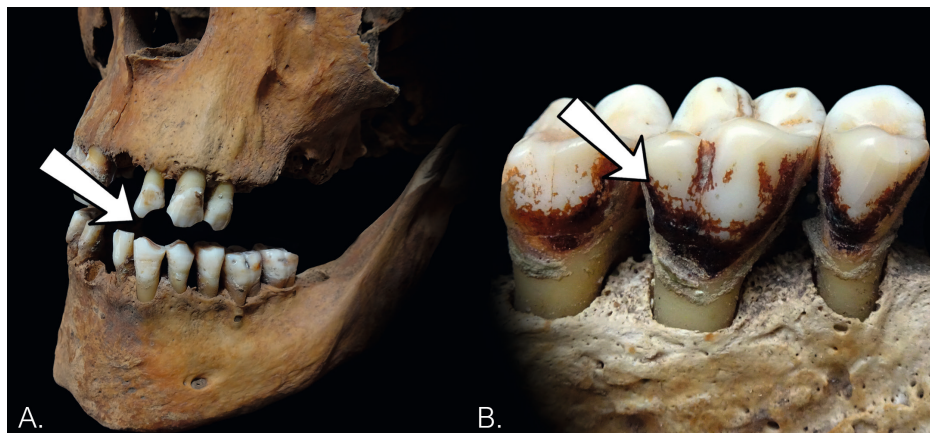


Figure 7.2. Examples of evidence for tobacco consumption considered in this study: A: pipe notch; and B: dental staining on lingual surfaces. Photographs by M. Casna.

7.3.1.i. Pipe notches

The presence of pipe notches (Figure 7.2, A) was assessed for all available dentition within an individual, except for the molars. Accurately determining the presence or absence of pipe notches is difficult as it requires a relatively complete set of incisors, canines, and premolars, as the absence (either postmortem or antemortem) of certain teeth could obscure the fact a pipe notch may have originally been present but is no longer observable. Thus, according to the method outlined by Davies-Barrett and Inskip (2024), the intersections between the incisors, canines, and premolars were divided into nine “sites” across a single jaw, consisting of a pair of neighboring teeth (sites: LP2-LP1, LP1-LC, LC-LI2, LI2-LI1, LI1-RI1, RI1-RI2, RI2-RC, RC-RP1, RP1-RP2).¹³ A site was only considered as observable if both neighboring teeth were present. In order for an individual to be assessed for the presence of a pipe notch, it was required that one of each of the nine sites was accounted for in either the upper or lower jaw. An individual received a score of ‘unobservable’ if there was a lack of at least one site in both the upper and lower dentition (e.g., both the sites of the LC¹-LP¹ and LC₁-LP₁ were absent).

7.3.1.ii. Dental staining

Dental staining is defined as the adhesion of a substance with a variable light brown to black color to the lingual (i.e., inner) tooth surface (Davies-Barrett and Inskip 2024). According to clinical sources, dental staining results from nicotine and/or tar from tobacco permeating the enamel’s micropores, causing noticeable discoloration of the teeth surface (Dalrymple et al. 2021; Kiliçarslan et al. 2022). This process may be influenced by several factors other than tobacco throughout the life of an individual, such as coffee and tea consumption, personal oral

13 According to the Paleoanthropology Dental Notation, the upper teeth are denoted I¹, I², C, Pm³, Pm⁴, M¹, M², and M³. The lower teeth are: I₁, I₂, C, Pm₃, Pm₄, M₁, M₂, and M₃. Left or right is specified by the first letter (i.e., L, R) (see Scott and Turner 1997).

hygiene practices, and inhalation of other forms of smoke (Ness et al. 1977). To discern tobacco-induced stains from those originating from other sources, we observed distinctive characteristics unique to tobacco stains: a) they usually manifest as a lacquer-like coating located exclusively on the lingual surface, unlike stains from alternative substances which typically affect the entire tooth; and b) their appearance resembles that of ‘cracked ink’ or a ‘dry riverbed’, setting them apart with their distinct visual pattern (Davies-Barrett and Inskip, 2024) (Figure 7.2, B).

To ensure comparability with other studies on tobacco consumption (e.g., Davies-Barrett and Inskip 2024), in this paper the presence of dental staining was assessed in individuals who had at least 25% (8 out of 32) of observable dental lingual surfaces present. Dental staining was recorded as ‘present’ for individuals where at least one tooth showed surface discoloration.

7.3.2. Statistical analysis

Statistical analysis was performed using SPSS for Windows, version 29.0. The significance between variables was investigated using Chi-squared tests. Two-tailed Fisher’s exact tests were utilized when the expected cell count was less than 5. To address the issue of multiple tests being run on the same samples, the Bonferroni correction method was applied to adjust the significance levels and account for familywise error. In all statistical tests, an original p -value ≤ 0.05 was considered to be statistically significant, with a final applied Bonferroni corrected p -value of ≤ 0.008 indicating a statistically significant outcome.

7.4. Results

Individuals from the post-tobacco skeletal samples showed higher rates of overall evidence of tobacco consumption, pipe notches, and dental staining (Table 7.2; Figure 7.3).

Table 7.2. Frequencies of observed skeletal markers for tobacco consumption.

		Pipe notch (N)	Dental staining (N)	Overall evidence of tobacco consumption (N)	Co-occurrence of pipe-notch and dental staining (N)
Arnhem	Pre-tobacco (1330-1650 CE)	2 (70)	4 (79)	5 (79)	2 (70)
	Post-tobacco (1650-1829 CE)	20 (57)	21 (63)	28 (64)	13 (56)
Vlissingen	Pre-tobacco (Oude Markt, 1300-1590 CE)	0 (22)	2 (32)	5 (32)	0 (22)
	Post-tobacco (Scheldekwartier, 1600-1800 CE)	16 (61)	20 (63)	23 (64)	13 (60)

N= total of individuals with observable feature.

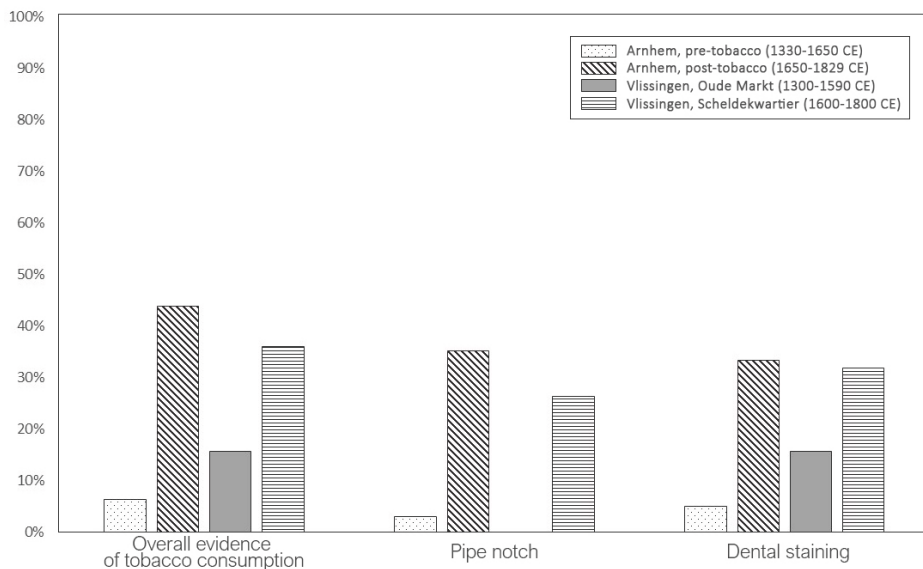
**Figure 7.3.** Prevalence of evidence of tobacco consumption, pipe notches, and dental staining for all samples under study (N=239).

Table 7.3 presents the results of the statistical analysis conducted to assess tobacco consumption across various time periods and among all examined skeletal populations. In the Arnhem sample, tobacco consumption was found to be significantly higher in the post-tobacco period than in the pre-tobacco one for all tobacco consumption categories (i.e., overall evidence of tobacco

consumption, pipe notch, and dental staining). However, in Vlissingen, statistical variation between pre- and post-tobacco periods was observed solely concerning pipe notches.

Table 7.3. Statistical analysis of tobacco consumption in different time periods and skeletal populations.

Comparison	Skeletal assemblage		Total of individuals with observable feature	Total of individuals presenting feature (%)	χ^2	p-value
Overall evidence of tobacco consumption versus time period	Arnhem	Pre-tobacco	79	5 (6.3)	27.062	<0.001
		Post-tobacco	64	28 (43.7)		
	Vlissingen	Pre-tobacco (Oude Markt)	32	5 (15.6)	4.261	0.039
		Post-tobacco (Scheldekwardier)	64	23 (35.9)		
Pipe notch versus time period	Arnhem	Pre-tobacco	70	2 (2.9)	22.789	<0.001
		Post-tobacco	57	20 (35.1)		
	Vlissingen	Pre-tobacco (Oude Markt)	22	0 (0)	n/a	†0.005
		Post-tobacco (Scheldekwardier)	61	16 (26.2)		
Dental staining versus time period	Arnhem	Pre-tobacco	79	4 (5.1)	19.310	<0.001
		Post-tobacco	63	21 (33.3)		
	Vlissingen	Pre-tobacco (Oude Markt)	32	5 (15.6)	2.844	0.092
		Post-tobacco (Scheldekwardier)	63	20 (31.7)		

†=Fisher's Exact Test. Values in bold indicate associations statistically significant by Chi-square/Fisher's Exact test, with Bonferroni correction significance level set at $p=0.008$.

We examined the co-occurrence of pipe notches and dental staining within each sub-sample (i.e., Arnhem pre- and post-tobacco, as well as Vlissingen, Oude Markt, and Scheldekwardier). Statistically significant co-occurrences were observed in all sub-samples (Arnhem, pre-tobacco: $p=0.002$; Arnhem, post-tobacco: $\chi^2=11.731$, $p<0.001$; Vlissingen, Scheldekwardier: $\chi^2=27.959$, $p<0.001$), except for Vlissingen and Oude Markt, where no pipe notches were observed at all. Table 7.4 presents the prevalence rates of tobacco consumption divided by skeletal sex within the samples under study, along with the results of statistical analysis examining their relationship. When investigating tobacco consumption in relation to skeletal sex, we observed that overall evidence of tobacco consumption occurred more frequently in males than females for both post-tobacco sites (Figure 7.4). However, statistical tests revealed no significant correlation between skeletal sex and tobacco consumption, pipe notch, and lingua staining in any of the samples

under study. In the majority of cases, both pipe notches and lingual staining exhibited relatively even distribution across age-at-death categories for both skeletal sexes (Table 7.5). Notably, their prevalence appeared to be higher among young and middle adults (20–49 years) compared to older adults (50+ years).

Table 7.4. Prevalence rates and statistical analysis of tobacco consumption and skeletal sex in the sample under study.

Comparison	Skeletal assemblage		N	N (%)	χ^2	p-value
Overall evidence of smoking versus sex in Arnhem	Pre-tobacco	Males	42	4 (9.5)	n/a	†0.369
		Females	35	1 (2.9)		
	Post-tobacco	Males	29	17 (58.6)	4.765	0.029
		Females	35	11 (31.4)		
Overall evidence of smoking versus sex in Vlissingen	Oude Markt	Males	16	2 (12.5)	n/a	†1.000
		Females	16	3 (18.8)		
	Scheldekwartier	Males	36	15 (41.7)	1.173	0.279
		Females	28	8 (28.6)		
Evidence of smoking versus sex (<i>continued</i>)						
	Skeletal assemblage		N	N (%)	χ^2	p-value
Arnhem (pre- and post-tobacco)	Pipe notch versus sex	Males	65	16 (24.6)	4.944	0.026
		Females	62	6 (9.7)		
	Dental staining versus sex	Males	71	16 (22.5)	2.379	0.123
		Females	71	9 (12.7)		
Vlissingen (pre- and post-tobacco)	Pipe notch versus sex	Males	46	11 (23.9)	2.724	0.099
		Females	36	4 (11.1)		
	Dental staining versus sex	Males	47	14 (29.8)	0.544	0.461
		Females	36	8 (22.2)		

N= total of individuals with observable feature; N= total of individuals presenting pathological lesion; †=Fisher's Exact Test. Statistical significance was set at $p=0.008$ according to the Bonferroni correction method.

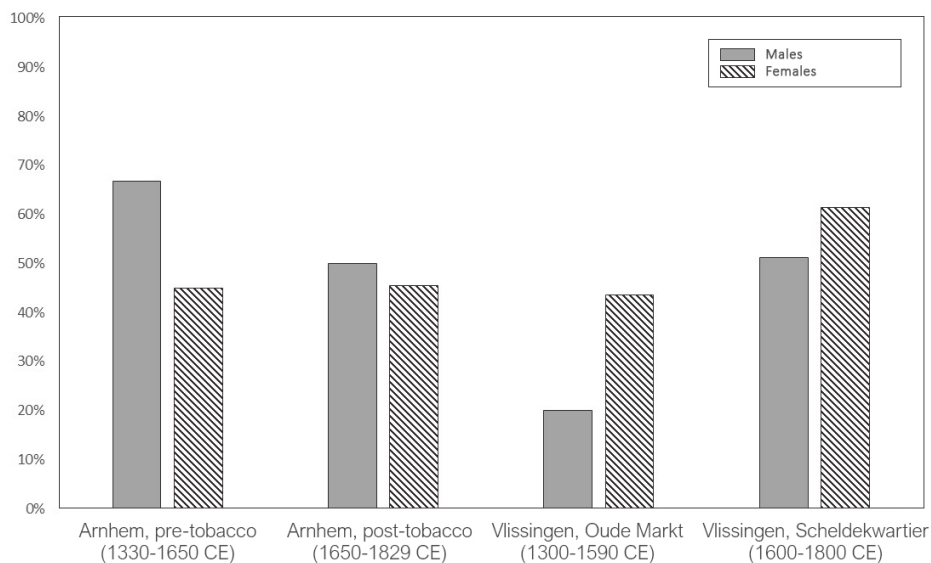


Figure 7.4. Prevalence of evidence of tobacco consumption among all samples under study, divided by skeletal sex.

Table 7.5. Distribution of dental evidence for smoking (i.e., pipe notch and dental staining) within demographics by skeletal sex and age-at-death groups.

Pipe notch		Young adult (20-34 years) (N)	Middle adult (35-49 years) (N)	Old adult (50+ years) (N)
Arnhem, pre-tobacco (1330-1650 CE)	Males	1 (15)	0 (14)	1 (10)
	Females	0 (17)	0 (11)	0 (3)
Arnhem, post-tobacco (1650-1829 CE)	Males	9 (14)	5 (9)	0 (3)
	Females	2 (17)	3 (10)	1 (4)
Vlissingen, Oude Markt (1300-1590 CE)	Males	0 (11)	0 (1)	0 (0)
	Females	0 (7)	0 (2)	0 (1)
Vlissingen, Scheldekwartier (1600-1800 CE)	Males	6 (27)	5 (7)	1 (1)
	Females	2 (21)	2 (4)	0 (1)
Dental staining		Young adult (20-34 years) (N)	Middle adult (35-49 years) (N)	Old adult (50+ years) (N)
Arnhem, pre-tobacco (1330-1650 CE)	Males	2 (18)	0 (15)	1 (10)
	Females	1 (19)	0 (14)	0 (3)
Arnhem, post-tobacco (1650-1829 CE)	Males	9 (13)	4 (9)	0 (6)
	Females	3 (19)	4 (11)	1 (5)
Vlissingen, Oude Markt (1300-1590 CE)	Males	1 (13)	1 (3)	0 (0)
	Females	2 (10)	2 (6)	0 (1)
Vlissingen, Scheldekwartier (1600-1800 CE)	Males	9 (28)	3 (6)	1 (1)
	Females	4 (22)	3 (5)	0 (1)

N= total of individuals with observable feature.

7.5. Discussion

According to historical sources, tobacco was first introduced into Europe in the 16th century, irrevocably impacting and shaping human society and history (Brongers 1964; Goodman 2005). Despite the numerous studies that have been published on the history of tobacco in the Netherlands, there seems to be a prevailing narrative based on both historical sources and material culture (e.g., clay tobacco pipes) that: 1) in the Netherlands, tobacco only became truly popular during the course of 17th century; and 2) tobacco consumption was predominantly a male habit (Brongers 1964; Duco 1981; Goodman 2005). However, while the notion of a singular narrative regarding the spread of tobacco across Europe is prevailing, our findings underscore the remarkable variation that characterized this diffusion, emphasizing the need to acknowledge

the diverse contextual factors that influenced its adoption and prevalence in different areas of Europe.

Our first hypothesis was that our “post-tobacco” populations (i.e., dating from 1600 CE onwards) would exhibit higher rates of oral indicators of tobacco consumption. Our results suggest that tobacco was popular in Arnhem between 1650-1829 CE. This fits with the overall narrative that tobacco smoking became a common habit by 1630 CE, which is evidenced by 43.7% smoking prevalence rate in the Arnhem, post-tobacco sample. However, we did not observe statistically significant differences in evidence of tobacco consumption in Vlissingen between Oude Markt (1300-1590 CE) and Scheldekwardier (1600-1800 CE). According to historical sources, the cultivation of tobacco was first mentioned in Zeeland in 1610 CE by a local physician (Enthoven 1996). A study on more than 1000 datable pipe fragments recovered from Vlissingen further proposed that tobacco was first introduced in Vlissingen around 1630 CE (Claeys et al. 2010). This suggests that tobacco consumption using pipes may not have been prevalent before this date. Our data on pipe notches fully supports this interpretation, as no pipe notches were recorded in individuals dating prior to 1600 CE. However, our data attest that non-pipe-related tobacco use may have been present in Vlissingen well before 1600 CE, indicated by the presence of dental staining, suggesting that tobacco was indeed already a commonly used intoxicant before the introduction of clay pipes. This is especially interesting because, according to Snelders (2021), the first European tobacco users were likely seamen who used to roll dried tobacco leaves in a palm leaf and set it on fire to smoke it. During the 16th and 17th centuries, Vlissingen (and Zeeland in general) had strong trade relations with the Amazon region, where tobacco grew naturally (van Cruyningen 2012). Furthermore, smoking through dried leaves (e.g., cigars) would not cause any dental abrasion (and, therefore, pipe notches), but would likely significantly stain dental surfaces (Dalrymple et al. 2021; Kiliçarslan et al. 2022; Ness 1977). Our results align with this account, as we did not find any significant variation in dental staining across time in Vlissingen. While it must be noted that dental staining may be impacted by various factors such as the consumption of other substances that may cause dental discoloration (e.g., coffee, tea), the presence of dental staining was strongly associated with the presence of pipe notches in three of the skeletal populations we analyzed, providing strong evidence that these two markers are indicative of similar processes (i.e., tobacco consumption). We argue that, while tobacco consumption in Arnhem fits the main historical narrative of a rise in popularity around 1630 CE, our results support an earlier spread of tobacco in Vlissingen.

As tobacco has been historically considered a male habit, our second hypothesis was that we would observe higher rates of evidence for tobacco consumption in males than in females. As noted by Snelders (2021) and Brongers (1964), in the post-medieval period female tobacco use was often associated with immoral behavior. For example, smelling of tobacco was presented as making women (but not men) sexually unattractive, and the presence of women in public spaces where tobacco was consumed was generally associated with prostitution (Snelders 2021). While it is true that we observed generally higher rates of smoking in males than females, we did not observe any statistically-significant differences between the two skeletal sex groups,

suggesting that female individuals were in fact consuming tobacco to a reasonable extent. Similar British historical narratives around tobacco consumption as a predominantly male habit have also been challenged by the findings of Davies-Barrett and Inskip (2024), where evidence of tobacco consumption were observed on 41.0% of female individuals and on 57.6% of males. The discrepancy between our findings and historical portrayals of female smokers carries deep implications for understanding female tobacco consumption in the past. A potential explanation for this discrepancy is that historical representations of female smokers as linked to poverty and/or prostitution may have originated from predominantly male perspectives aiming to define and regulate what they perceived as a male activity (McShane 2021; Davies-Barrett and Inskip 2024). The negative societal views surrounding female smoking may have compelled women to consume tobacco differently from men. While male smoking was often a social activity conducted in public spaces (Snelders 2021), female tobacco consumption was likely a more private endeavor, enjoyed within the confines of private homes or with other women (McShane 2021). The societal pressure against women smoking may also explain the relatively low occurrence of female pipe notches we observed in our samples. Unlike men, who were likely quite accustomed to pipe smoking from young ages, women might have opted for less conspicuous methods such as chewing tobacco leaves or using less abrasive mouthpieces, which would have caused less noticeable damage to their teeth (Dekker 2013). While our study did not reveal any statistically significant correlation between skeletal sex and a specific marker of tobacco consumption (i.e., notches/dental staining), it is essential to acknowledge that the limitations of our sample size may have impacted our observations. Further investigation into the distribution of these markers among different skeletal sex categories could offer fresh insights.

While our overall sample size was adequate for the purpose of this research, its breakdown into skeletal sex and age-at-death categories revealed some limitations in interpreting our results. Specifically, we observed that skeletal markers for tobacco consumption were more prevalent among young and middle adults compared to older adults. Given the permanent nature of both pipe notches and dental stains without surgical intervention, this observation prompts speculation that smokers may have experienced higher mortality rates than non-smokers. However, our ability to draw definitive conclusions about observed prevalence rates is hindered by the disproportionately lower number of old adults with observable features compared to other age-at-death categories. Addressing this challenge remains complex, as it is inherent to the nature of osteoarchaeological research. Furthermore, the accurate osteoarchaeological identification of individuals who engaged in smoking has to-date its limitations, and evidence for other forms of tobacco consumption (e.g., chewing, snuff taking) have yet to be identified in human osteological remains. Consequently, it is plausible that the prevalence of smokers within our sample surpasses our observations. Moreover, although there appears to be a significant link between the existence of pipe-notches and dental staining (Walker and Henderson 2010), it is crucial to acknowledge that the exact mechanism behind the formation of any type of dental staining remains today poorly comprehended both clinically and archaeologically. Further advancements in enhancing our understanding of the mechanisms and attributes underlying dental lingual staining is essential. Moreover, the advancement of future biomolecular analyses

(Badillo-Sanchez et al., 2023; Bartholdy et al., 2024) may provide the means to further explore tobacco consumption among different societal groups.

Another limitation was posed by the dating of our samples. While historical records emphasize a pivotal 40-year period spanning from 1590 to 1630 CE for the dissemination of tobacco among Dutch populations, our osteoarchaeological investigations encountered limitations in precisely identifying individuals from this timeframe within our samples. Consequently, in the Arnhem sample, this period fell within our “pre-tobacco” sample. Our osteological findings support the hypothesis that tobacco was not prevalent in Arnhem before 1650 CE. However, revisiting this analysis using a skeletal sample exclusively from the period 1590-1630 CE holds promise for shedding new light on the spread of tobacco consumption within Dutch societies.

Finally, more research is needed to investigate the many ways tobacco has shaped and influenced our society and culture. For example, larger sample sizes may allow for a better understanding of how social groups that have received less attention, such as women and children, were involved not only in the smoking practice, but also in the tobacco industry (Benedetti et al. 2021). The inclusion of more diverse skeletal collections may also allow a better understanding of how tobacco was not only “popular among all socioeconomic classes” but how its consumption changed on the basis of wealth and societal roles, among other factors (Brongers 1964; Davies-Barrett and Inskip, 2024). As more research into the complexities of tobacco in the Netherlands is underway, we stand to gain valuable knowledge about past societies, shedding light on cultural practices, social interactions, and historical trends.

7.6. Conclusions

By examining a large sample of skeletal remains, this paper presents a comprehensive investigation into the historical spread and impact of tobacco consumption in the Netherlands, with a particular focus on the urban centers of Arnhem and Vlissingen. While historical sources and material culture have contributed to a prevailing narrative on tobacco’s history, the findings from this study challenge and enrich our understanding of this complex phenomenon.

Contrary to the prevailing notion that tobacco became popular in the Netherlands only around 1630 CE, our results suggest that its popularity in the region of Vlissingen may have begun much earlier with tobacco chewing and/or cigars, potentially evolving into pipe smoking practices later on. Similarly, while historical records and previous studies have focused on the prevalence of tobacco consumption as a male habit, our research reveals that women also likely consumed tobacco to a significant extent, underscoring the importance of re-considering gender-specific assumptions from historical sources.

In conclusion, our paper has made significant contributions to the history of tobacco consumption in the Netherlands by challenging prevailing narratives with empirical osteological data. By presenting nuanced findings, our study encourages new research to embrace the contextuality

of tobacco's diffusion and its impact on various societal and historical aspects. Future research into the archaeology of tobacco consumption in the Netherlands will undoubtedly benefit from expanding to a wider and more diverse sample of human skeletal remains, for which information such as socioeconomic class and/or occupational activities is known.

Data availability statement

The datasets generated and analyzed during the current study are available at: Casna, M., 2023, "Data for: "Smoking histories"", <https://doi.org/10.17026/AR/R1Y1KM>, DANS Data Station Archaeology.

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CHAPTER 8

Exploring the Impact of Tobacco Consumption on the Respiratory Health of two Dutch Skeletal Populations (1300-1829 CE)

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14 In this version of the article, British English spelling and conventions from the original publication have been updated to American English to ensure consistency throughout this dissertation. All other content remains unchanged from the original article.

Abstract

This study explored the influence of tobacco consumption on the respiratory health of two historical Dutch populations (1300-1829 CE). We conducted a macroscopic examination of 235 skeletons for which tobacco consumption status was known, focusing on the presence of sinusitis, ear infection, and pulmonary inflammation. Our goal was to investigate the correlation between respiratory diseases and tobacco consumption. Despite all conditions being prevalent in the total sample (sinusitis: 50,2%, ear infection: 23,2%, pulmonary inflammation: 14,1%), almost no significant correlation was found between disease and tobacco consumption. Our findings suggest that additional factors, such as exposure to second-hand smoke and unsanitary living/working environments, may have also impacted respiratory health. However, our interpretations are difficult to confirm due to the limitations of macroscopic analysis in determining tobacco consumption status. Future research should consider employing biomolecular techniques and expand beyond respiratory diseases to enhance our understanding of historical health implications of tobacco use.

Keywords: Paleopathology; Chronic Maxillary Sinusitis; Ear Infection; Pulmonary Inflammation; Smoking

8.1. Introduction

Today, the global tobacco epidemic is considered to be one of the most extensive health hazards of the modern world, causing the death of over 8 million individuals annually (WHO, 2021). According to clinical science, tobacco consumption (i.e., smoking, chewing, snuffing, and vaping) causes cancer, heart disease, stroke, diabetes, and chronic obstructive pulmonary diseases (COPD), such as emphysema and chronic bronchitis (Bonnie et al., 2015; Ligthart et al., 2016; Pelkonen et al., 2019; Stallones, 2015; Vineis et al., 2004). Smoking may also increase the risk for tuberculosis, corneal infections, and immune system problems such as rheumatoid arthritis (Bates et al., 2007; Jetton et al., 2014; Manfredsdottir et al., 2006). Furthermore, tobacco does not only impact its primary user; chronic exposure to environmental tobacco smoke (also known as second-hand tobacco smoke) increases the risk of developing heart disease, lung cancer (Bhat et al., 2018; Dunbar et al., 2013; Kim et al., 2014; Vozoris & Loughheed, 2008). Recently, it was calculated that 1.3 million people died prematurely from exposure to second-hand smoke globally (Su et al., 2023). These significant health implications suggest that tobacco's arrival and popularization in Europe likely had a profound effect on the health of past populations, indicating that the burden of tobacco-induced disease may not solely be a modern phenomenon.

Originally introduced by Spanish sailors at the end of the 16th century, tobacco quickly spread across the European continent and, by 1630 CE, it had already permeated all strata of society (Goodman, 2005; Snelders, 2021). In the Netherlands specifically, local production made tobacco an extremely affordable product, resulting in widespread consumption among the population. (Brongers, 1964a; Roessingh, 1979). Tobacco was generally regarded as non-harmful when consumed in small quantities and often embraced by physicians as a remedy for various ailments, such as headaches and tooth pain (Brongers, 1964a; Fraga, 2010; Goodman, 2005). However, caution was still advised for women, children, and for individuals in poor health, as medical practitioners soon noted a correlation between tobacco consumption and the development of respiratory issues (Snelders, 2021). Already in 1602 CE British physicians were aware of the negative impact tobacco had on the respiratory system by “blocking” the lungs (Charlton, 2005). During this period, tobacco use was banned in public spaces in many Dutch cities and restricted to indoor establishments, as the pervasive smell of smoke was considered a nuisance and a threat to residents' wellbeing (Snelders, 2021).

Surprisingly, despite the presence of several historical sources that discuss the adverse effects of tobacco consumption, there remains a notable scarcity of (bio)archaeological studies on its impact on human health. Walker and Henderson (2010) analyzed 705 individuals from London (1843-1854 CE) and observed a high prevalence of evidence of tobacco consumption (i.e., pipe notches and dental lingual staining). Tobacco consumers were found to have a lower life expectancy, as well as an increased frequency of skeletal evidence for pulmonary inflammation (i.e., inflammatory periosteal bone formation on ribs) compared to the rest of the population (Walker & Henderson, 2010). However, despite these encouraging initial results, there has been limited research to further explore the various ways in which tobacco affected past human

health. This is problematic, as it leaves significant gaps in our understanding of how one of the world's most pervasive commodities influenced historical health outcomes and shaped societal development. To contribute filling this gap, we analyzed the presence of both upper and lower respiratory diseases (i.e., chronic maxillary sinusitis, infectious middle ear disease, and pulmonary inflammation) among 235 individuals from the Netherlands whose smoking status (i.e., tobacco consumer/tobacco non-consumer) was previously determined osteologically by Casna and colleagues (2024). As tobacco smoke has long been recognized as a major risk factor for human health, we hypothesized higher rates of lesions indicative of respiratory disease among individuals showing evidence of tobacco consumption.

8.1.1. Tobacco consumption in historic Netherlands

Unlike other trade substances like coffee and sugar, whose popularity initially stemmed from the upper classes, tobacco spread in the Netherlands began among sailors and lower-income individuals who frequented port inns and taverns after work (Snelders, 2021). From there, the rise of tobacco was rapid and, in just 50 years from its introduction, its consumption had become widespread and accessible to the whole population (Brongers, 1964a; Snelders, 2021). Although historically tobacco use was considered primarily a male habit (Brongers, 1964a), recent osteoarchaeological analyses have shown no significant difference in tobacco consumption rates between males and females, suggesting that smoking was a practice embraced by everyone (Casna, Davies-Barrett, et al., 2024). By the 18th century, tobacco's popularity had grown so significantly that it had become an important part of Dutch culture; smoking pipes were frequently gifted during weddings as a symbol of union, and it was common at funerals to offer tobacco not only to those who attended the function, but also to coffin bearers, constables, and to those who took care of digging the grave (Brongers, 1964a). Today, pipe fragments are among the most common findings in most Dutch excavations dating from 1650 CE onward, reflecting the ingrained nature of smoking in Dutch culture (Claeys et al., 2010; Duco, 1987; van der Lingen & Korpershoek, 2024). Since pipes provided a more efficient and enjoyable way to consume tobacco compared to other methods available at the time (e.g., chewing, snuffing), it has been argued that it was likely the introduction of the pipe in 1609 CE that caused a sudden surge in tobacco's popularity (Brongers, 1964a, 1964b; Claeys et al., 2010). However, recent bioarchaeological research into tobacco consumption in the Netherlands between 1300-1829 CE suggests that, at least in some port communities, tobacco may have become popular well before the 17th century (Casna, Davies-Barrett, et al., 2024). When analyzing prevalence rates of pipe-notches, Casna and colleagues (2024) observed significantly higher rates in populations dating to 1600 CE onwards when compared to earlier samples. However, when analyzing prevalence rates of dental lingual staining linked to tobacco consumption (Davies-Barrett & Inskip, 2024; Walker & Henderson, 2010), Casna and colleagues (2024) did not find significant variation between the two time periods under study. This suggests that, while tobacco consumption in certain populations may have been connected to the introduction and widespread use of clay pipes, in other cases tobacco had gained popularity much earlier, possibly through methods such as chewing or cigar smoking that would not cause notches in the dentition (Casna, Davies-Barrett, et al., 2024).

While much remains to be understood about the history of tobacco consumption in the Netherlands, preliminary research on its impact on human health has yielded intriguing results. For example, when studying the dental calculus of 41 individuals from a rural Dutch population dating to 1829-1866 CE, Bartholdy and colleagues (2024) observed a positive correlation between the presence of nicotine in the calculus and bony lesions indicative of chronic maxillary sinusitis, suggesting that tobacco consumption did indeed have an impact on the respiratory wellbeing of the sample under study. Furthermore, Inskip and colleagues (2023) compared dental disease (i.e., caries, calculus, tooth loss, periapical lesions, and periodontal disease) to the presence of pipe notches in two medieval and post-medieval Dutch assemblages, observing that pipe smoking led to a general decline in oral health among the skeletal population under study.

8.1.2. Respiratory health implications of tobacco use

According to clinical research, tobacco consumers are 11 times more likely to develop lung cancer than non-consumers, and 4 times more likely to develop chronic obstructive pulmonary diseases (Jayes et al., 2016). In addition, tobacco consumption was estimated to increase the risk for sinusitis by approximately 16% and increase the risk for ear infections by 50% (Lieu & Feinstein, 2000; Strachan & Cook, 1998).

Even if unprocessed, tobacco leaves contain harmful chemicals such as nicotine, cadmium, benzene, and nitrates (CDC, 2010). When tobacco is consumed (either smoked, snuffed, or chewed), these chemicals are released and absorbed into the body through the lungs, skin, and/or mucous membranes (van der Rijst & Garfield, 2023). There are several ways in which the absorption of these chemicals can impact human respiratory health. Inhalation of smoke, whether first-hand or second-hand, directly exposes the lungs to the chemicals inherent in tobacco leaves, as well as to additional harmful substances (e.g., tar) generated during tobacco combustion. This inflicts significant damage to lung tissues, leading to impaired breathing, chronic inflammation of the bronchial tubes (i.e., bronchitis), destruction of the alveoli (i.e., emphysema), and lung cancer (van der Rijst & Garfield, 2023). In addition, tobacco consumption may directly irritate and dry the mucous membranes of the entire respiratory tract, exacerbating respiratory symptoms and compromising immune function (Ramasamy & Sivapathasundharam, 2021). Irritation of the nasal passages and throat may lead to congestion, ultimately increasing susceptibility to inflammations, such as sinusitis and infectious middle ear disease (Corey et al., 2000; Reh et al., 2012). Furthermore, tobacco may impair the function of the mucociliary clearance mechanisms, reducing their ability to trap and eliminate pathogens, and, therefore, increasing an individual's vulnerability to upper respiratory tract infection (e.g., sinusitis) (Prasetyo et al., 2021). Pre-existing respiratory issues can also be further exacerbated by tobacco consumption, as chronic tobacco use significantly negatively impacts the immune system and triggers systemic inflammation, hence contributing to the progression of pre-established infectious disease (Jiang et al., 2020).

8.2. Materials

The two Dutch skeletal populations included in this study – Arnhem and Vlissingen (Figure 8.1) – were previously analyzed by Casna and colleagues (2024) for skeletal sex, age-at-death, and macroscopic oral evidence of tobacco consumption (i.e., pipe notches and dental lingual staining¹⁵). These sites were considered as ideal for investigating tobacco consumption in the Netherlands, as historical and archaeological records confirm the presence of tobacco in both cities (e.g., Claeys et al., 2010; Kuiper & Lengkeek, 1994; Roessingh, 1976; Zielman & Baetsen, 2020). Additionally, these sites span an extensive timeframe (1300-1829 CE) and are divided into two distinct periods: ‘pre-tobacco’ (i.e., before the widespread adoption of tobacco among Dutch populations) and ‘post-tobacco’ (i.e., after tobacco had become a widespread commodity) (Table 8.1). This division was highly relevant for studying the popularization of tobacco in the Netherlands, as it enabled a nuanced analysis of tobacco prevalence before and after its widespread adoption in the 17th century (Casna, Davies-Barrett, et al., 2024). As observed by Casna and colleagues (2024), in the ‘post-tobacco’ period, 43.7% of the population in Arnhem and 35.9% of the population in Vlissingen were scored as tobacco consumers (Supplementary Table 1). No disparities in tobacco consumption were identified between skeletal sex groups (Casna, Davies-Barrett, et al., 2024).



Figure 8.1. Map of the Netherlands showing the location of the sites under study. Figure originally published in Casna et al. (2024, Figure 1). Licensed for use by CC BY 4.0.

15 Davies-Barrett and Inskip (2024) define pipe notches as “semi-circular abrasions caused by habitual clenching of the teeth around the stem of a clay pipe while smoking” (p. 144), and dental lingual staining as “the adhesion to the tooth of a substance of variably light brown to black colour” (p. 145) whose appearance resembles that of a “cracked ink” or “dry riverbed” (p. 146).

Table 8.1. Skeletal collections included in this study.

City	Skeletal Population	Dating	Subsistence Economy
Arnhem	Eusebiuskerk, 'pre-tobacco'	1330-1650 CE	Urban
	Eusebiuskerk, 'post-tobacco'	1650-1829 CE	Proto-Industrial
Vlissingen	Oude Markt	1300-1590 CE	Maritime
	Scheldekwartier	1600-1800 CE	Maritime

8.2.1. Historical Context

Even if largely comparable chronologically, the assemblages of Arnhem and Vlissingen are representative of two very different realities: while from 1300 CE onwards Arnhem was one of the most important and industrially-developed centers of the Dutch hinterland, the history and economic growth of Vlissingen have always been tied with its position on the Northern Sea (Kuiper & Lengkeek, 1994; van Cruyningen, 2012). According to Casna and colleagues (2024), such differences are also reflected in the way tobacco gained popularity in each of these centers. In Arnhem, tobacco was intricately intertwined with the city's industrial growth. In fact, up until the late 19th century, the whole province of Gelderland (where Arnhem is located) was a major hub for tobacco production, which offered several opportunities to migrants relocating to the area for work (Kuiper & Lengkeek, 1994; Roessingh, 1979; van Laar, 1966). The tobacco produced in Arnhem was notably of lower quality and larger affordability in contrast to the imported varieties from Southern Europe and the Americas (Roessingh, 1976). This suggests that the demographic cohort under study (representative of Arnhem's lower socioeconomic strata) likely had ample access to locally produced tobacco starting from 1650 CE onwards, as evidenced by the results presented in Casna and colleagues (2024) which show a significant increase in tobacco consumers in the 'post-tobacco' period as opposed to the 'pre-tobacco' one.

On the other hand, Vlissingen's economic power stemmed from its maritime activities. Since 1235 CE, Vlissingen had served as a pivotal harbor for the area where it is located, managing several commercial routes to South America and the Caribbean on behalf of the Dutch West India Company (van Cruyningen 2012). Because of its involvement with international trade, people in Vlissingen were likely among the first to start consuming tobacco as early as 1590 CE. Even if Claeys and colleagues (2010) report that most pipe fragments recovered from the excavation of Vlissingen, Scheldekwartier (1600-1800 CE) date to the second half of the 18th century, Casna and colleagues (2024) observed no statistically significant differences in the prevalence of tobacco consumers between Oude Markt ('pre-tobacco', 1300-1590 CE) and Vlissingen, Scheldekwartier ('post-tobacco', 1600-1800 CE), suggesting that tobacco may have been already a popular commodity by the start of the 17th century.

8.3. Methods

From an initial pool of 239 adult individuals of varying skeletal sex (male/female), age-at-death (young adult/middle adult/old adult), and tobacco consumption status (tobacco consumer/non-consumer), we specifically selected individuals for whom we could score the presence/absence of at least one of the following conditions: chronic maxillary sinusitis (CMS), infectious middle ear disease (IMED), or pulmonary inflammation in the form of periosteal bone formation on the visceral surface of ribs (IPR) (Figure 8.2).

The presence of CMS was observed in all individuals with at least one sinus partially preserved (i.e., more than 25% present). If the sinuses were intact and therefore not visible to the naked eye (i.e., no skull damage), they were examined using a flexible medical endoscope (Pentax, model: FNL-10RBS, $\phi=4\text{mm}$; view angle= 30°) inserted through minor fractures (refer to Casna et al., 2021 for details on how the endoscope was inserted in the skulls). CMS was considered ‘absent’ when sinus walls were smooth and/or presented minimal porosity. It was considered ‘present’ when either pitting or new bone formation was observed on any visible bony walls (Figure 8.2, A) (Boocock et al., 1995).

The presence of IMED was recorded using the criteria established by Floreanova and colleagues (2020) for all individuals with at least one complete and observable tympanic cavity. If ear ossicles were present, they were carefully removed, and the bony structures of the middle ear were cleaned using a wooden toothpick and water before examining the middle ear cavity with a medical endoscope. IMED was scored as ‘present’ if the medial wall of the middle ear exhibited either clear bony growth with well-defined edges or a general erosion of the distal wall bony surface (Figure 8.2, B). Conversely, it was classified as ‘absent’ in instances where the distal wall displayed a smooth, unaltered surface (Floreanova et al., 2020).

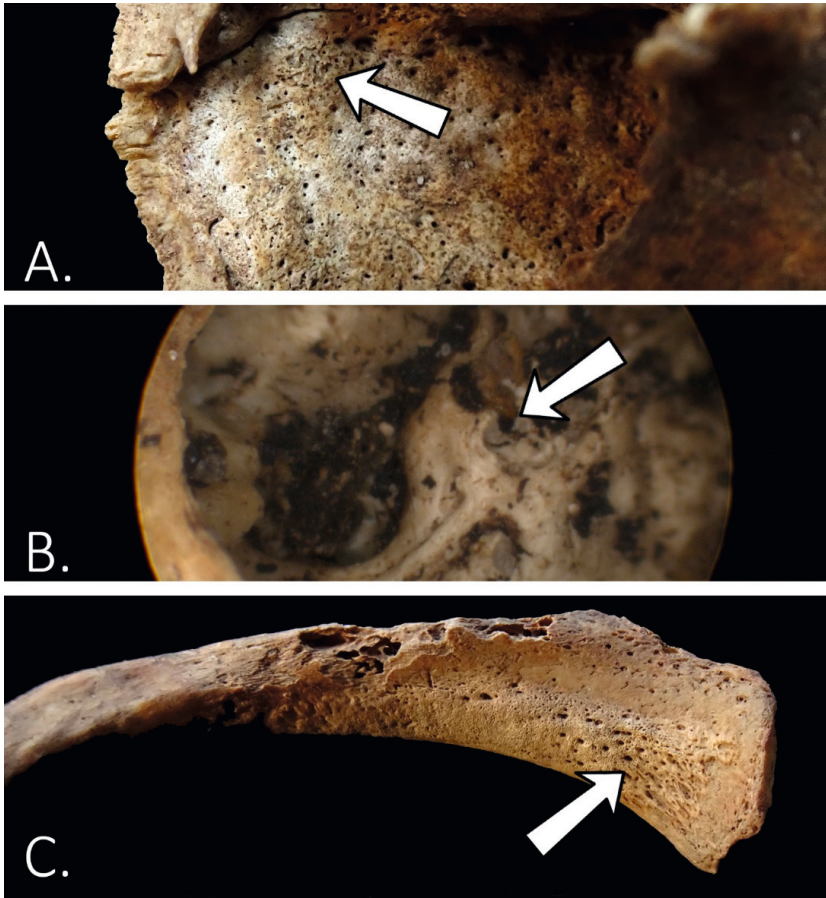


Figure 8.2. Examples of lesions observed in this research: A: chronic maxillary sinusitis in the form of new bone formation on the sinus wall; B: infectious middle ear disease in the form of erosion of the bony promontory of the middle ear; and C: pulmonary inflammation in the form of periosteal bone formation on the visceral surface of a rib. Lesions are indicated by the white arrows. Photographs by M. Casna.

Finally, the presence/absence of IPR was scored for every rib whose shaft was at least 50% complete. To avoid mistakes in serialations, ribs were categorized into four groups based on their most likely position within the rib cage: ‘upper’ (ribs #1-3), ‘upper-middle’ (ribs #4-6), ‘lower-middle’ (ribs #7-9), or ‘lower’ (ribs #10-12). IPR was considered present in groups where at least one rib showed evidence of bone growth, forming a distinct layer atop the original cortical surface (Figure 8.2, C) (Davies-Barrett et al., 2019). If only one rib in a group was present and showed no signs of IPR, the group was deemed unobservable. For IPR to be considered ‘present’ within an individual, it needed to be observed in at least one of the rib groups mentioned above, either on the right or left side of the rib cage.

8.3.1. Statistical analysis

Statistical analysis was performed using SPSS version 29.0 for Windows. We used binary logistic regression to consider various confounding factors (i.e., time period, skeletal sex, and age-at-death) alongside tobacco consumption, and to gain a more comprehensive understanding of how these variables interacted and influenced the risk of respiratory diseases. In binary logistic regression, if the upper limit of the 95% confidence interval is below 1, it indicates that the group is significantly less likely to be associated with the disease compared to the reference group. Conversely, if the lower limit of the 95% confidence interval is above 1, it signifies that the group is significantly more likely to be associated with the disease than the reference group (Harris, 2021). In all statistical analyses, an initial p -value of ≤ 0.05 was considered as statistically significant.

8.4. Results

Our final sample consisted of 235 adult individuals (61 tobacco consumers and 174 non-consumers) for which the presence of respiratory disease (considered here to be the presence of at least one condition among CMS, IMED, and/or IPR) could be determined (Table 8.2). Figure 8.3 displays the demographic composition of the final sample. See Supplementary Table 2 for the complete demographic profile.

Table 8.2. Composition of the sample included in this study.

	Arnhem			Vlissingen		
	1330-1650 CE	1650-1829 CE	Total	Oude Markt, 1300-1590 CE	Scheldekwartier, 1600-1800 CE	Total
	(%)	(%)	(%)	(%)	(%)	(%)
Tobacco consumers	5 (6.5)	28 (45.2)	33 (23.7)	5 (15.6)	23 (35.9)	28 (29.2)
Tobacco non-consumers	72 (93.5)	34 (54.8)	106 (76.3)	27 (84.4)	41 (64.1)	68 (70.8)
Total	77 (100)	62 (100)	139 (100)	32 (100)	64 (100)	96 (100)

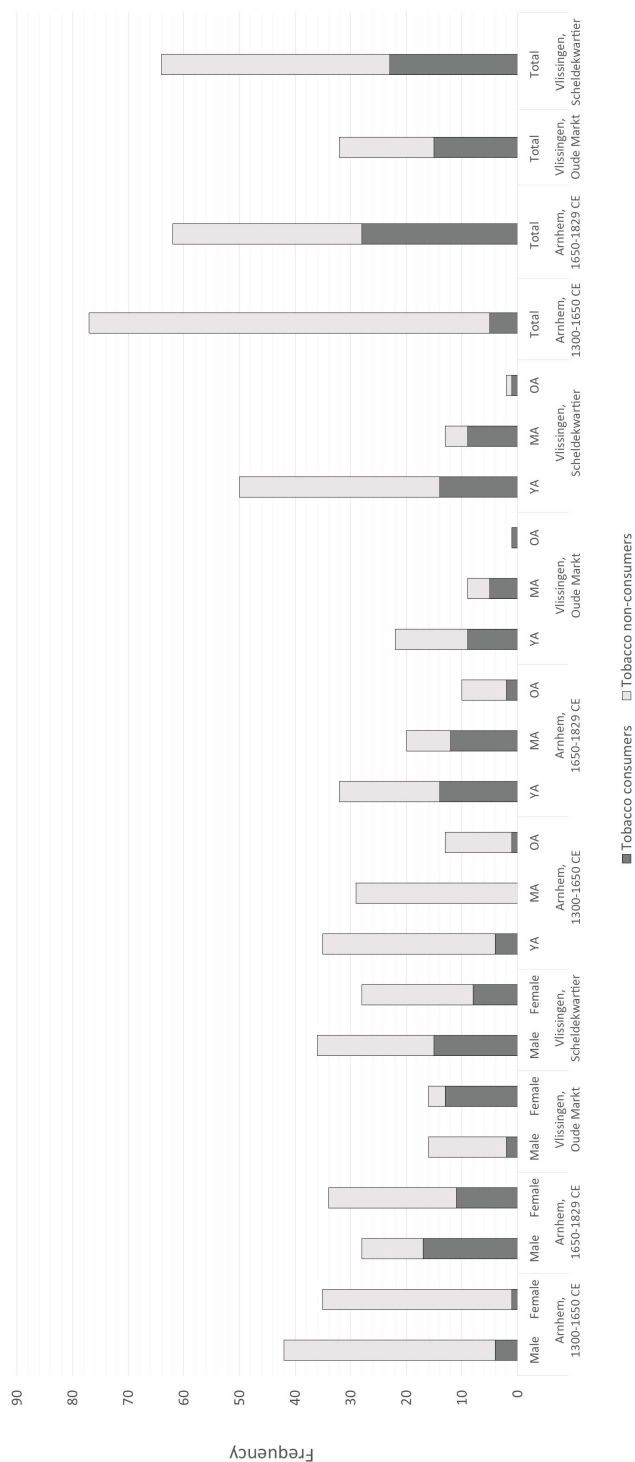


Figure 8.3. Demographic composition of the sample. YA=Young Adult (20-34 years), MA=Middle Adult (35-49 years), OA=Old Adult (50+ years).

Overall, the presence of respiratory disease was observed in 136 (57.9%) individuals (Figure 8.4). Among all populations under study, lesions associated with CMS emerged as the most prevalent, presenting in 50.2% of the total sample. IMED was observed in 23.2% of the sample, while IPR was the least frequent lesion, occurring in only 14.1% of the cases. Surprisingly, in the total sample all three respiratory diseases were more prevalent among non-consumers compared to tobacco consumers (Table 8.3). When analyzing the prevalence of each condition in relation to tobacco consumption across different populations, we observed that tobacco consumers were more affected by CMS in Vlissingen, Scheldekwardier (70% of consumers vs. 41.7% of non-consumers) (Figure 8.5). Additionally, IPR was more prevalent among tobacco consumers in both Vlissingen, Oude Markt (66.7% of consumers vs. 8.3% of non-consumers) and Vlissingen, Scheldekwardier (36.8% of consumers vs. 26.7% of non-consumers). In all other cases, non-consumers showed higher prevalence rates of respiratory diseases (Supplementary Table 3).

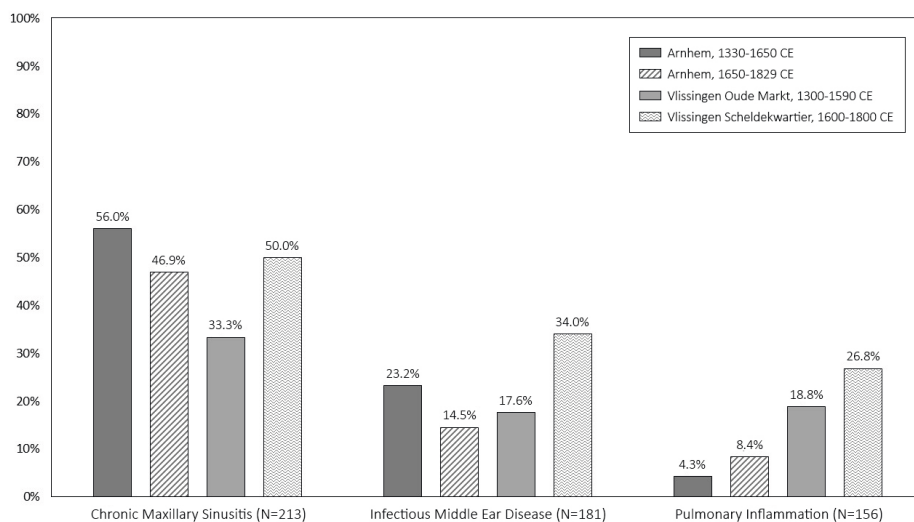


Figure 8.4. Prevalence of evidence of chronic maxillary sinusitis, infectious middle ear disease, and pulmonary inflammation for all samples under study.

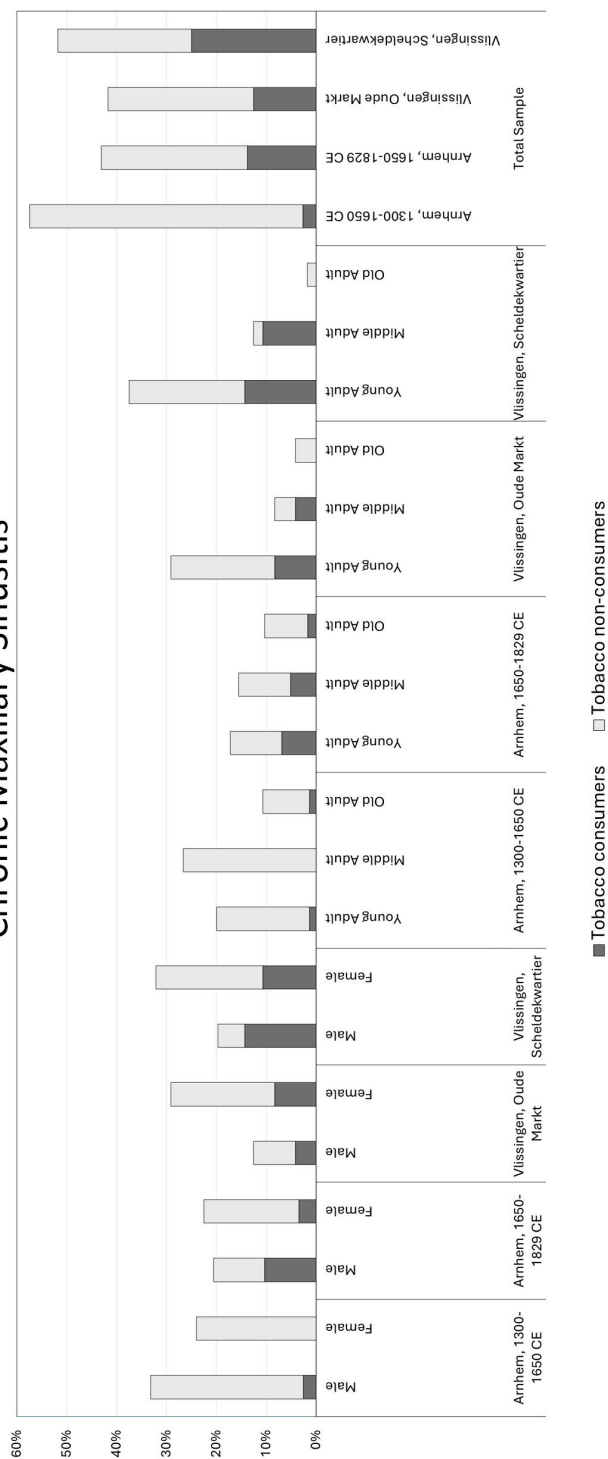
Table 8.3. Prevalence of respiratory diseases observed within the total sample of this study.

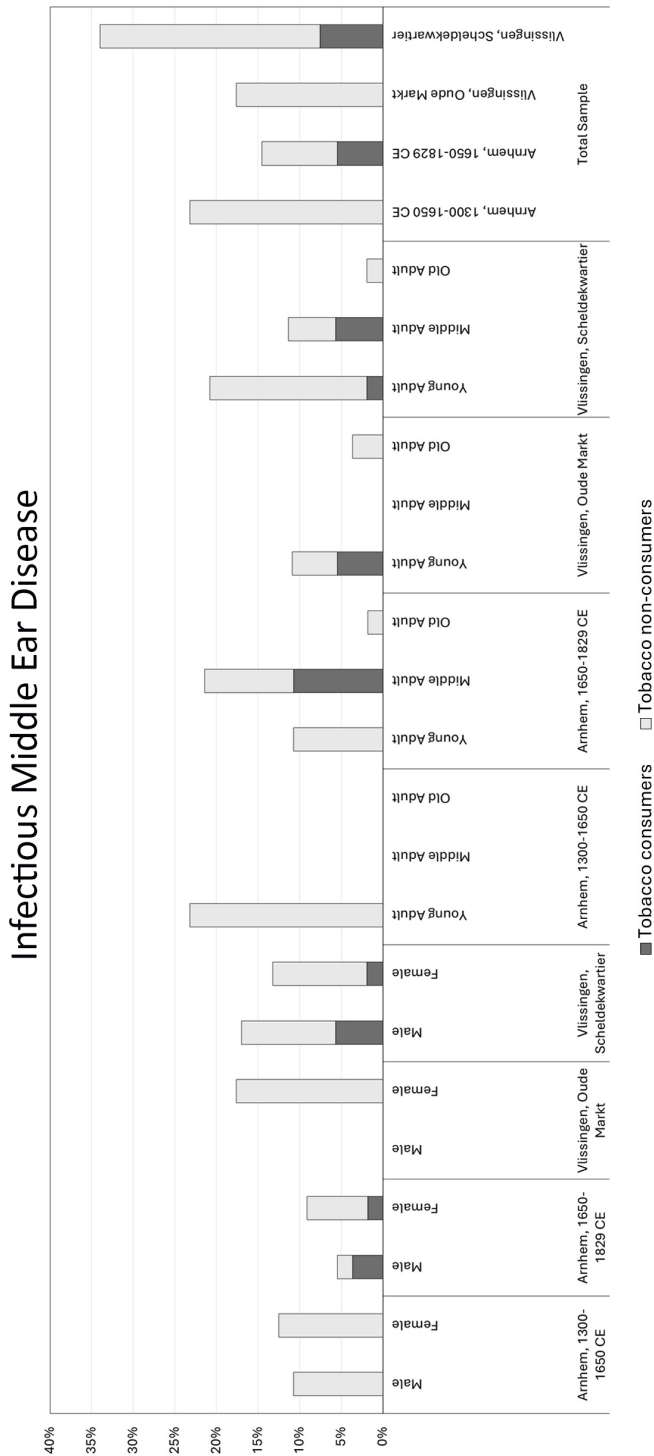
	Tobacco Consumers (%)	Tobacco Non-consumers (%)	Total (%)
Chronic Maxillary Sinusitis	27 (25.2)	80 (74.8)	107 (50.2)
Infectious Middle Ear Disease	7 (16.7)	35 (83.3)	42 (23.2)
Pulmonary Inflammation	9 (40.9)	13 (59.1)	22 (14.1)

Interestingly, the binary logistic regression analysis of the Arnhem population indicated that tobacco consumers were less likely than non-consumers to exhibit evidence of both CMS and IMED (Table 8.4). However, as this finding was not statistically significant, it should be interpreted with caution. Although p -value was again non-significant, individuals from Arnhem dating to 1650-1829 CE (i.e., when tobacco was historically widespread across most Dutch societies) were 4.040 times more likely to show evidence of IPR compared to those from 1330-1650 CE. Additionally, males from Arnhem were also more likely to show evidence of IPR than females. Finally, middle and old adults in Arnhem were respectively 2.150 and 2.696 times more likely to present with CMS compared to young adults, this outcome being statistically significant only in middle adults ($p=0.015$).

In Vlissingen, tobacco consumers were found to be five times more likely to present evidence of CMS than non-consumers ($p=0.012$) (Table 8.5). Over time, individuals from Vlissingen appeared to be at increased risk for all three studied respiratory conditions, though these observations were not statistically significant. Interestingly, females from Vlissingen were 7.24 times more likely to exhibit CMS than males ($p<0.01$). Age-at-death did not significantly impact the results, except for IMED, which was more prevalent in middle and old adults compared to young adults, though this finding was again not statistically significant.

Chronic Maxillary Sinusitis





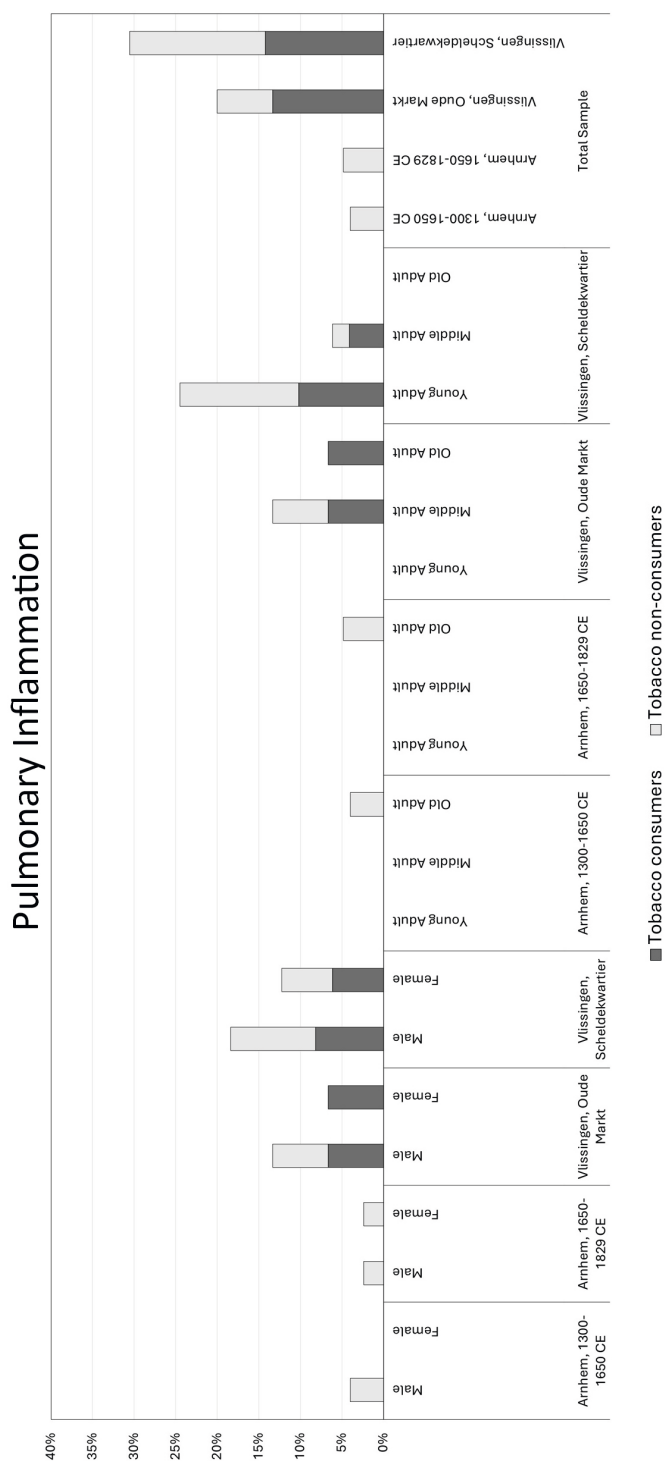


Figure 8.5. Prevalence rates of chronic maxillary sinusitis, infectious middle ear disease, and pulmonary inflammation among tobacco consumers and non-consumers in the populations under study.

Table 8.4. Outcomes of binary logistic regression in the Arnhem population.
 Constants: Tobacco consumption status = non-tobacco consumers; Time = Arnhem, 1330-1650 CE; Skeletal sex = males; Age-at-death = young adult. OR = Odds ratio; CI = Confidence Intervals; * = indicates p -value ≤ 0.05 .

	Chronic Maxillary Sinusitis				Infectious Middle Ear Disease				Pulmonary Inflammation			
	OR	CI for OR		p -value	OR	CI for OR		p -value	OR	CI for OR		p -value
		Lower	Upper			Lower	Upper			Lower	Upper	
Tobacco consumption status	0.418	0.154	1.134	0.087	0.449	0.231	2.029	0.285	n/a	n/a	n/a	n/a
Time	0.786	0.350	1.764	0.559	0.685	0.231	2.029	0.495	4.040	0.384	42.532	0.245
Skeletal sex	0.788	0.374	1.1661	0.532	1.127	0.400	3.177	0.821	0.240	0.018	3.178	0.279
Age-at-death				*0.040				0.592				n/a
Middle adult	2.696	1.208	6.016	*0.015	0.609	0.200	1.851	0.382	n/a	n/a	n/a	n/a
Old adult	2.150	0.785	5.890	0.137	0.566	0.131	2.447	0.446	n/a	n/a	n/a	n/a

Table 8.5. Outcomes of binary logistic regression in the Vlissingen population.
Constants: Tobacco consumption status = non-tobacco consumers; Time = Vlissingen, Oude Markt; Skeletal sex = males; Age-at-death = young adult. OR = Odds ratio; CI = Confidence Intervals; * = indicates p -value ≤ 0.05 .

	Chronic Maxillary Sinusitis			Infectious Middle Ear Disease			Pulmonary Inflammation		
	OR	CI for OR Lower	Upper	OR	CI for OR Lower	Upper	OR	CI for OR Lower	Upper
Tobacco consumption status	4.995	1.421	17.560	*0.012	0.289	0.071	1.185	0.085	2.703
Time	1.335	0.425	4.196	0.621	3.273	0.744	14.396	0.117	1.581
Skeletal sex	7.245	2.451	21.416	*<0.001	1.021	0.343	3.039	0.970	0.899
Age-at-death				0.974				0.139	
Middle adult	1.084	0.270	4.355	0.910	3.982	0.965	16.437	0.056	n/a
Old adult	1.311	0.108	15.918	0.832	3.441	0.167	70.720	0.423	n/a

8.5. Discussion

Because of the great clinical impact that tobacco has on human respiratory wellbeing today, the aim of this study was to investigate whether individuals showing evidence of tobacco consumption would also show evidence of respiratory diseases (i.e., CMS, IMED, and/or IPR).

Unexpectedly, despite the prevalence of respiratory diseases in both populations studied, no clear pattern was observed between tobacco consumption and respiratory health. The only statistically significant association found was between tobacco consumption and CMS in individuals from Vlissingen, where smokers were five times more likely to develop sinusitis than nonsmokers. At first, these findings may seem surprising: however, we argue that when interpreting results it is important to consider the complex and multifaceted etiologies of respiratory diseases, which are often polygenic in nature (Huertas & Palange, 2011; Pokorski, 2017; van den Bergh et al., 2012). As demonstrated by the clinical practice, these conditions often arise from intricate interactions among diverse elements, such as genetic predisposition, environmental influences (e.g., air pollution, tobacco smoke, allergens), lifestyle preferences (e.g., alcohol consumption, dietary patterns), pre-existing conditions (e.g., dental diseases, autoimmune diseases, cardiovascular diseases), and occupational risks (Hoover et al., 1997; Mannino & Buist, 2007; Slavin et al., 2005; Zanobetti et al., 2000). Past urban contexts such as Arnhem and Vlissingen likely offered a wide range of health hazard for the respiratory system (e.g., pollution, overcrowding, hazardous working conditions, limited access to healthcare and to food/drinking water) which co-existed with tobacco consumption (e.g., Boyd, 2020; Casna et al., 2023; Goossens et al., 2021; Kopadze & Jikurashvili, 2023; Krenz-Niedbala & Łukasik, 2020). Individuals from Arnhem were likely employed in the industrial sector, where they were frequently exposed to dust and chemicals (Kuiper & Lengkeek, 1994; van Braam, 1978; Wintle, 2000). Their living arrangements were also reportedly hazardous to their respiratory health: according to historical sources, most factory workers at the time lived in dark, humid, and unventilated residential barracks that often hosted more people than what they could accommodate (van Braam, 1978; van Laar, 1966; Wintle, 2000). Living and working in polluted, overcrowded, and unhygienic indoor spaces (with potential increased exposure to second-hand smoke) likely worsened the spread of infectious diseases in Arnhem, which may have contributed to tobacco consumers and non-consumers showing similar risk for respiratory disease in our analysis. In Vlissingen, it is likely that people had access to cleaner air due to their primary involvement in the naval or fishing industries, which required substantial time spent outdoors (de Ridder, 2004). However, their frequent exposure to harsh and cold weather conditions may have heightened their susceptibility to (respiratory) infectious diseases, hence confounding our observations (Casna & Schrader, 2024). We argue that our results stem from the interplay of various risk factors affecting the populations under study, rather than being solely indicative of tobacco's impact on human health. This interpretation is further supported by the absence of significance regarding time as a risk factor for any of the conditions under study. It might have been expected that the passage of time (here indicative of the transition from a period when tobacco was just introduced to the Netherlands to the time when it had become one of the most consumed commodities) would have played a significant

role in our analysis. However, although a slight increase in respiratory disease is seen over time, our findings align with previous diachronic research on respiratory disease in Dutch populations, which concluded that differences in living and working conditions between the late-medieval and the post-medieval periods were not substantial enough to cause significant variations in respiratory disease rates (Casna et al., 2023; Casna & Schrader, 2024).

Another crucial and potentially confounding factor in our analysis, which could contribute to the absence of a significant impact of tobacco consumption on respiratory disease, is that dental evidence alone cannot identify individuals who were exposed to second-hand smoke. As already mentioned, chronic exposure to second-hand tobacco smoke increases the risk of respiratory disease to a level comparable to that of active consumers (Bhat et al., 2018; Vozoris & Loughheed, 2008). In contexts such as Arnhem, where people lived and worked in crowded spaces with little to no room for privacy, inhalation of tobacco smoke was likely very common. In these circumstances, it is likely that tobacco did indeed influence respiratory health, but its impact extended beyond those who directly consumed it. Conversely, in Vlissingen, working outdoors may have limited exposure to second-hand smoke. This may explain why, in Vlissingen, tobacco consumption was found to significantly put individuals at risk for CMS. This interpretation is further supported by our data when considering our results on skeletal sex and respiratory disease. In Vlissingen, females were more than seven times more likely to present evidence of CMS, a pattern not observed in Arnhem. Historically, Arnhem saw men and women engaged in different tasks but within similar (if not the same) industrial environments where tobacco consumers and non-consumers shared small and unventilated indoor spaces (van Laar, 1966; Wintle, 2000). In contrast, in most Dutch maritime communities men and women were still equally employed, yet their work environments varied significantly (Stuurman, 2023). Men typically worked on ships, spending most of their time (and likely multiple days) at sea, while women often stayed indoors, engaging in tasks such as making fish nets and ropes for market sale (Stuurman, 2023). This likely resulted in both a higher exposure to indoor air pollution for women and potentially to increased exposure to second-hand smoke. This hypothesis is further supported by our findings; while in Vlissingen, Scheldekwartier it was primarily tobacco consumers who presented evidence of CMS among males, among females CMS was prevalent in both tobacco consumers and non-consumers (see Supplementary Table 3).

Alongside the complicated etiologies of respiratory diseases and the role of second-hand tobacco smoke, it is likely that other factors presented as major limitations in our study. Firstly, while the data on tobacco consumers collected by Casna and colleagues (2024) was gathered following established macroscopical methods for detecting tobacco consumers in osteological samples, it should be acknowledged that the observations were confined to individuals exhibiting complete dentition, and that only instances in which tobacco was consumed orally (e.g., smoking or chewing) could be detected. This may have led to an underestimation of the number of tobacco consumers, as: 1) edentulous individuals were excluded from analysis despite the fact that tobacco negatively impacts tooth loss (Holm, 1994); and 2) those who did consume tobacco orally or simply long enough to develop dental evidence were scored as non-consumers.

Biomolecular techniques such as metabolomics offer promising solutions to this limitation, as they are not dependent on the way tobacco was consumed nor by the presence of specific observable skeletal features (Badillo-Sanchez et al., 2023). In the future, the incorporation of biomolecular techniques into paleopathological studies of tobacco consumption may lead to new insights, potentially highlighting distinct correlations between tobacco use and respiratory diseases. Moreover, biomolecular approaches may also help to address the limitation posed by the intrinsic heterogeneous frailty of osteological samples. For example, according to clinical research, tobacco consumers have a significantly shorter life expectancy compared to non-consumers (Preston et al., 2011; Rogers & Powell-Griner, 1991). In our total sample, CMS, IMED, and IPR were often more commonly observed among non-consumers than among individuals showing evidence of tobacco consumption. Additionally, as evidenced in Figure 8.3, most evidence of tobacco consumption was observed in younger individuals. This may suggest that tobacco consumers were less likely to live to old age. However, this was difficult to investigate in the samples under study, as most older adults were often either too highly fragmented or did not present enough preserved dentition to be included in the sample. The role of age was partly addressed in our binary logistic regression as we considered it among the variables that may have put individuals more at risk of respiratory disease. Even if, in most cases, age-at-death did not significantly impact any of the respiratory conditions examined in either of the populations under study, we observed that middle adults from Arnhem were 2.7 times more likely to present evidence of CMS than young adults. This trend may indicate a transition from child to adult labor within factory settings, where tasks evolved from relatively minor duties, such as button making, to more physically demanding roles, such as load lifting (Wintle, 2000). However, it is challenging to confirm this hypothesis based solely on the current dataset. In addition, it is important to note that osteoarchaeological methods for accurately estimating age-at-death in adults are inherently dependent on developmental processes, which are influenced by a variety of factors such as genetics, lifestyle, access to resources, and disease (Milner & Boldsen, 2011). In the past, these factors likely had a significant impact on individuals' bodies, leading to potential inaccuracies and inconsistencies in the aging of skeletons. Although these issues were partially addressed through statistical analysis and the application of diverse methods to estimate age-at-death (Casna, Davies-Barrett, et al., 2024), it is still possible that inaccuracies in age estimation may have impacted the results to some extent.

Finally, while further research on the impact of the popularization of tobacco on historical human health is underway, it should be considered that respiratory disease represents just one of the several outcomes associated with tobacco consumption. Countless other life-impacting conditions stemming from tobacco (e.g., cancer, chronic tissue inflammation, diabetes) were not considered here as they fell beyond the scope of our analysis. However, since tobacco represents such a pivotal cultural feature in Dutch (and global) history, it is imperative for future research to expand beyond respiratory diseases into the other aspects of human wellbeing. This broader approach will yield a more comprehensive understanding of tobacco's historical impact on health, potentially revealing new insights into its effects on mortality and longevity over the past 500 years.

8.6. Conclusions

This study explored the historical impact of tobacco consumption on the respiratory health of two Dutch populations dating to 1300-1829 CE and yielded nuanced insights into the complex interplay of various factors influencing human respiratory wellbeing. Alongside tobacco consumption, factors such as exposure to indoor pollution, overcrowding, adverse weather conditions, and occupational hazards emerged as significant contributors to respiratory disease prevalence rates, highlighting the multifaceted etiologies of respiratory infections.

While exposure to second-hand tobacco smoke and the overall harsh living conditions in past urban Dutch communities undoubtedly posed a challenge to the interpretation of our results, we argue that methodological constraints also severely limited our understanding of the impact tobacco had on people's respiratory wellbeing. Future research should: 1) consider employing biomolecular techniques to address the limitations that come with macroscopical analysis; and 2) expand beyond respiratory diseases to understand broader health impacts of tobacco consumption. We argue that interdisciplinary approaches are vital to unravel the complex interactions between tobacco consumption and human health across different historical contexts. As we continue to explore the historical legacy of tobacco, it is imperative to consider its multifaceted impact on various aspects of human wellbeing.

Supporting information

Supplementary materials for this paper are available on the publisher's website: <https://doi.org/10.1080/00438243.2024.2425814>

Data availability statement

The datasets generated and analyzed during the current study are available at Casna, Maia, 2024, "Data for Exploring the Impact of Tobacco Consumption on the Respiratory Health of two Dutch Skeletal Populations (1300-1829 CE)", <https://doi.org/10.17026/AR/B01AUM>, DANS Data Station Archaeology.

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CHAPTER 9

Conclusions

Over the past decade, the study of respiratory diseases in historical populations has provided valuable insights into how various social and economic processes shaped the health and wellbeing of past societies (e.g., Boyd, 2020; Davies-Barrett et al., 2023; DiGangi & Sirianni, 2017). The data presented in this dissertation significantly contributes to this growing body of research by providing a comprehensive analysis of respiratory disease prevalence in historical Dutch populations while investigating the complex and multifaceted interplay between socioeconomic factors and health outcomes. By integrating bioarchaeological observations with data on historical and socioeconomic contexts, this research examines various populations across different timeframes, offering a nuanced, diachronic exploration of how historical changes (e.g., urbanization, the institutionalization of child labor, and the effects of tobacco consumption) affected the prevalence of respiratory diseases in the populations under study.

Analyzing and contextualizing data spanning over a thousand years of human history is inherently complex. In the case of the Netherlands, this task is particularly challenging due to its unique trajectory, which diverged significantly from the experiences of the United Kingdom and other European countries during the medieval and post-medieval periods (de Vries, 1984; Wintle, 2000). In fact, in the Netherlands, several factors, including political fragmentation, substantial geographical transformations (e.g., land reclamation), frequent wars, and the rise of localized industries, contributed to an asynchronous urban and economic development. As a result, throughout the country, cities and regions experienced cycles of growth and decline at different times (Brusse & Mijndhardt, 2011; de Vries, 1984). This makes the Netherlands a particularly compelling case study, as previous bioarchaeological research has demonstrated how socioeconomic changes from the medieval period to the industrial era affected populations all over Europe in diverse ways across different demographic groups (Betsinger & DeWitte, 2020). The results presented in this dissertation show that in the Netherlands, as in other European contexts, these shifts played a role in shaping health patterns, including the prevalence of respiratory diseases.

The present study is the first in the Netherlands to examine respiratory disease prevalence across such a broad geographic and temporal framework, aiming to reconstruct the impact socioeconomic changes had on historical respiratory health. To do so, four research questions were developed:

Research Question 1: *How did increasing urbanization in the Netherlands influence rates of respiratory diseases in different environments (e.g., rural, urban) in the time period under study?*

Research Question 2: *What are the differences in the prevalence, risk factors, and outcomes of respiratory diseases among urban populations of differing socioeconomic status?*

Research Question 3: *To what extent did urbanization and socioeconomic developments affect the respiratory health of children in the Northern Low Countries?*

Research Question 4: *To what extent did tobacco consumption contribute to the burden of respiratory disease in past Dutch populations?*

Research Question 1 is addressed in Chapters 3 and 5, where rates of respiratory disease are analyzed across different populations over time and geographic regions. The results reveal a progressively worsening impact on health, with more subtle distinctions between the late-medieval and post-medieval periods, and the most severe decline observed between the early-medieval and post-medieval periods. Notably, for each time period analyzed, no significant differences were found between urban and rural populations, indicating an economy that maintained strong connections between city and countryside through time. This suggests that factors beyond air pollution, such as changes in lifestyles, housing conditions, and increased competition for resources due to population growth, may have contributed to the overall decline in respiratory health (Blockmans, 2011; Schmal, 2018; Wintle, 2000).

Research Question 2 is discussed in Chapter 4 by analyzing the prevalence of sinusitis and non-specific stress markers across four post-medieval populations of varying socioeconomic status. Among these groups, the middle-lower socioeconomic class, primarily composed by small businessmen and market stall owners, exhibited among the lowest prevalence rates observed in the total sample. It is likely that the distinctive lifestyle of this socioeconomic stratum significantly contributed to these outcomes: unlike the industrial working class, who endured rigid schedules in poorly ventilated environments, or the upper classes, which were frequently confined to office and domestic settings, the middle-lower class spent substantial time outdoors in environments more favorable to respiratory health (e.g., marketplaces). This group's autonomy over their time and working settings may have afforded them greater flexibility to regulate their exposure to harmful conditions, contributing to better overall health outcomes. Although no consistent trends emerged between socioeconomic status and stress indicators or sinusitis across the urban sites of Arnhem, Zwolle, and Eindhoven, the results suggest that susceptibility to respiratory and other diseases was influenced more by daily life and environmental exposure than by wealth or socioeconomic status alone. Urban settlements did not exclusively endanger the poor, but instead presented distinct health challenges to all social groups, highlighting the intricate interplay between urbanization, socioeconomic status, and health.

Research Question 3 is addressed in Chapter 6, where the impact of several factors (i.e., time period, living environment, and socioeconomic status) on 13 non-adult populations is investigated. The findings reveal a noticeable increase in sinusitis prevalence over time in both urban and rural contexts, with a particularly significant shift from the late-medieval to the post-medieval periods. This shift aligns with the broader historical effects of urbanization, the popularization of tobacco, and the institutionalization of child labor starting from the 17th century (Smit & Korevaart, 2018; Snelders, 2021; Vleggeert, 1964). Among the risk factors analyzed, only time period had a statistically significant impact on sinusitis, a pattern consistent with earlier observations in adults, where neither rural or urban living environments nor socioeconomic status significantly influenced prevalence rates (Casna et al., 2023; Casna & Schrader, 2022).

This suggests that exposure to respiratory disease risk factors was relatively consistent across different social groups, despite varying living conditions and socioeconomic backgrounds. Adolescents were particularly susceptible to sinusitis compared to younger demographic groups, likely due to their living and working conditions resembling those of adults, which exposed them to similar risk factors.

Lastly, Research Question 4 is addressed in Chapters 7 and 8, which analyze the relationship between tobacco smoke and respiratory disease across four diachronic populations. The findings reveal that smokers were more likely to develop respiratory diseases than non-smokers, but only if their lifestyle did not already expose them to significant environmental risk factors. Notably, smokers from a maritime community of sailors, who spent much of their time outdoors, had nearly five times the likelihood of developing respiratory disease compared to local non-smokers. In contrast, smokers from an industrial workers population (who likely spent most of their time indoors) did not show significantly increased risk of respiratory disease compared to non-smokers. This suggests that, while the harmful effects of tobacco are undeniable, the environmental conditions individuals live and work in may have had a more profound impact on their health, potentially overshadowing the effects of smoking.

9.1. Limitations

One of the primary limitations of this study arises from the inherent challenges in defining environments and socioeconomic contexts in a consistent, scientific, and meaningful way. As noted by Betsinger and DeWitte (2021), distinguishing between urban and rural settings can be particularly problematic, especially when examining diachronically diverse settlements where the definition of ‘urban’ may vary significantly. Furthermore, even within the same time period, cities can embody vastly different models of urbanization and industrialization (Reba et al., 2016). For example, as discussed in Chapter 8, the contexts of Arnhem and Vlissingen presented distinct living conditions (i.e., industrial and maritime), leading to different health outcomes for their inhabitants. Similarly, defining socioeconomic classes involves comparable difficulties. In fact, as argued by Peterson and Drennan (2018), the conceptualization and implications of wealth frequently evolve across temporal and spatial dimensions, meaning that the factors that constitute affluence for one individual may not necessarily confer wealth upon another in a different location or historical period. This variability has often been a subject of concern for archaeologists studying inequality in the past, as temporal and contextual variations present challenges both in consistently categorizing populations and in interpreting results (Peterson & Drennan, 2018). Despite efforts to ensure consistency in classifying skeletal populations, it is important to acknowledge that categories such as ‘urban’, ‘rural’, or ‘low/high socioeconomic class’ are inherently human constructs and lack rigid, universally applicable definitions (Smith, 2020). This may imply some degree of interpretive uncertainty into and should be considered when evaluating results.

This research has also been limited to certain extents by the availability of skeletal remains, particularly with regard to specific demographics or social groups. Although the final sample included over 1200 skeletons from 13 different sites, certain groups (such individuals from early-medieval cemetery sites) were in most cases poorly preserved and highly fragmented. The sample size for non-adults was especially limited, with only 227 individuals available for analysis to investigate the impact of socioeconomic changes on children's respiratory health over more than a millennium of history. While statistical analysis helped to mitigate this limitation, in several cases poor preservation further hindered the ability to collect consistent data, particularly regarding ear infections and rib lesions, thus preventing a comprehensive analysis.

Moreover, while data on sinusitis, infectious middle ear disease, and pleural inflammation were collected following established diagnostic criteria for comparability across studies, relatively few investigations have assessed the inter- and intra-observer reliability of these methods (e.g., Malina-Altzinger et al., 2015; Timmenga et al., 2002), leaving the extent of potential variation in observations somewhat unclear. While in this dissertation intra-observer variability testing was not conducted in a systematic manner, preliminary efforts were undertaken to assess data consistency. An intra-observer test was conducted on 42 maxillary sinuses from Middenbeemster, comparing sinusitis scores recorded during the first year of doctoral research with those recorded during the third year (Davies-Barrett et al., 2024). Results indicated moderate agreement between the two sets of observations. Additionally, an inter-observer test for sinusitis was undertaken, comparing data collected at different points during this project with observations made by a more experienced researcher. This comparison demonstrated that agreement increased with growing experience in diagnosing sinusitis, an encouraging result that suggests enhanced familiarity with diagnostic criteria contributed to improved consistency and accuracy of observations over time for this project (Davies-Barrett et al., 2024).

Finally, the osteological paradox (Wood et al., 1992) represents a significant limitation of this study. Despite applying statistical analyses, including non-adults in the total sample, and examining bony lesions across several sub-groups (e.g., socioeconomic classes, age-at-death categories, and sexes), addressing the challenges posed by demographic nonstationarity, selective mortality, and heterogeneous frailty remained complex. Several factors linked to the osteological paradox, such as transient historical events (e.g., disease outbreaks, famines, and natural disasters) and genetic predispositions to disease, could not be fully accounted for (DeWitte & Stojanowski, 2015; Wood et al., 1992). Additionally, many of the populations analyzed spanned multiple centuries, meaning that individuals grouped together may have experienced diachronically distinct risk factors and lived through varying environmental and social conditions (Wilkinson, 1992; Wood et al., 1992).

While Wood et al. (1992) emphasizes the need for a deeper understanding of lesion formation processes at the osteological level, clinical literature provides only limited evidence of the skeletal manifestations of respiratory infections, further complicating interpretations. Recent studies utilizing computed tomography to examine bone involvement have begun addressing

remodeling associated with infectious processes (e.g., Kandukuri & Phatak, 2016; Qiao et al., 2022; Wiatr et al., 2021). However, many lesions, particularly smaller and less discernible spicule formations in the sinuses or within the ear canal, remain poorly understood. Recent debates in paleopathology have questioned whether these formations truly indicate an infectious process, as similar features are not observed elsewhere in the skeleton (e.g., Flohr et al., 2023; Mays et al., 2024). While some evidence supports an association with inflammation and/or infection (see section 2.1.3), it is equally plausible that, in some cases, these changes arise from normal physiological remodeling, aging, or environmental factors such as exposure to cold weather (e.g., Davies-Barrett et al., 2019; Ramakrishnan et al., 2010). Although these alternative explanations do not undermine the conclusions of this dissertation, the potential influence of non-pathological factors on the prevalence rates of observed lesions warrants careful consideration when interpreting the results of this research.

9.2. Future research

This study explored the prevalence of respiratory diseases over time in several Dutch populations, emphasizing the importance of studying urbanization not as a sole point in time, but rather as an ongoing process that continuously affected human health across centuries. While this research has shed light on distinct historical contexts, it highlights the need for future studies to continue investigating diverse populations, both within and beyond the Netherlands, while acknowledging their specific socioeconomic, environmental, and cultural contexts. In this framework, an important aspect would be to develop a better understanding of how the various factors analyzed in this research interplayed with each other (Appleby, 2024). While this study made preliminary efforts to explore these interactions, a more comprehensive examination of risk factors is essential to fully understand how these elements converged at the individual level, rather than being limited to population-level analyses. Biomolecular approaches are particularly promising in this regard, as emerging frameworks continue to enhance our understanding of disease processes (e.g., Gaeta, 2021; Warinner et al., 2022). As these methodologies become increasingly accessible to paleopathologists, they should be utilized not only to confirm the presence of specific diseases in the individuals we analyze, but also to provide broader insights into how diseases interacted with each other, shedding light on how they impacted the burden of morbidity within a specific population (Larsen & Crespo, 2022; Robb et al., 2021).

Moreover, it should be noted that paleopathology (and, thus, the present study), typically focuses on visible markers of disease in skeletal remains and their prevalence within a population (Roberts, 2016). However, many (respiratory) diseases may not leave any osteological evidence, despite having a significant impact on human health (Van Schaik et al., 2014). Recently, there has been a notable increase in paleopathological studies that employ statistical models to estimate the broader health burden of such diseases at a given point in time (e.g., Robb et al., 2021; Van Schaik et al., 2014). These models integrate modern clinical data with contextual information from historical settings, allowing for a more comprehensive understanding of how specific diseases impacted past populations. Future paleopathological research on respiratory diseases

in the Netherlands could greatly benefit from adopting this approach. By not only examining the prevalence of respiratory conditions but also estimating their overall contribution to the historical health burden, researchers could provide a more nuanced and complete picture of how these diseases shaped past Dutch populations.

9.3. Concluding remarks

Despite the respiratory system being one of the most exposed to environmental conditions, there has been a notable lack of paleopathological studies focusing on respiratory disease (Roberts, 2020). This gap in research may, in part, stem from the inherent complexity of studying them. Their multifaceted etiologies, the often unclear link between infectious processes and bone involvement, and the fact that even modern clinicians struggle to fully understand how the respiratory tract responds to disease, all contribute to the reluctance paleopathologists may feel when approaching this subject. While this hesitation is entirely understandable, I believe that this complexity inherently reflects the intricate nature of human societies and, as such, needs to be fully addressed when studying our shared human past. As individuals, we are continuously shaped by a multitude of factors: our living conditions, working environments, socioeconomic status, family ties, habits (whether harmful or healthy), passions, and hobbies, all of which continue to impact our health and wellbeing throughout our lives. Studying respiratory diseases in the past requires careful consideration, as interpreting prevalence rates involves dealing with two distinct layers of complexity. On one hand, there are the multifaceted and sometimes elusive etiologies of respiratory diseases discussed in Chapter 2. On the other, there is the elaborate web of humanity itself, with all its environmental, social, and personal factors.

The results presented in this dissertation contribute to our ever-growing understanding of how the environment shaped the health of our ancestors, while offering important reflections on how environmental and social factors continue to influence health outcomes today. Being able to analyze diachronic populations was particularly valuable in this regard, as it highlighted several observable differences over time (or lack thereof), including changes in living conditions (Chapters 3 and 5), the environmental, economic, and political challenges people faced (Chapters 3, 4, 5, and 6), and even shifts in smoking habits (Chapters 7 and 8). The deep connection we share with our environment is most notably reflected in the ways our bodies respond to it, with disease serving as one of the most telling indicators of this relationship (Western & Bekvalac, 2019). Just as no two environments are alike, the effects on our health are equally unique, shaped by the distinct circumstances of each individual and community, both in the present and throughout history. In this way, I hope that my dissertation has opened new avenues for future research, encouraging more nuanced explorations of the deep, ever-lasting, ever-changing connection we share with our living environments and our health.

After all, we are the air we breathe.

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Summary

The air we breathe. A study into the impact of historical socioeconomic changes on the respiratory health of past Dutch populations (ca. 470-1850 CE)

Chapters 1 and 2

The first two chapters of this dissertation outline the research's objectives and scope, providing comprehensive clinical and paleopathological insights into the respiratory diseases under study (i.e., sinusitis, ear infections, and pleural inflammation).

Today, the global burden of respiratory disease is staggering, impacting millions and carrying significant mortality risks. Respiratory diseases range from mild ailments to severe, life-threatening conditions, with respiratory health risks further exacerbated by rapid urbanization and industrialization, primarily due to rising levels of air pollution. However, while respiratory diseases linked to poor air quality are often seen as a product of the modern world, historical records show that such conditions have been present since ancient times. Specifically, it is believed that the rapid urbanization of Europe in the late- and post-medieval periods significantly contributed to the spread of respiratory infections, with poorer and industrialized populations suffering higher rates of illness than their wealthier, less urbanized counterparts. While previous historical and archaeological research has shaped the trope of life dramatically worsening with urban development, it should be noted that urbanization and industrialization unfolded unevenly across Europe. This complicates efforts to assess how diverse patterns of urbanization influenced human health, as variations in socioeconomic conditions, environmental contexts, and running economies are seldom comprehensively examined. In this framework, osteoarchaeology (i.e., the study of human skeletal remains from archaeological contexts) is particularly relevant, as it allows researchers to examine health data at the level of an individual, thus providing a more nuanced view of the past. This dissertation examines archaeological human skeletons from 13 Dutch populations to explore how factors linked to urbanization (e.g., socioeconomic disparities, running economies, tobacco use) influenced respiratory health, providing a more accurate perspective on historical infectious disease patterns in historical Netherlands.

Chapter 3

Chapter 3 presents diachronic data on the prevalence of various respiratory diseases (i.e., chronic maxillary sinusitis, infectious middle ear disease, and pleural inflammation) among six Dutch populations spanning the early-medieval to post-medieval periods. The overall increasing rates of respiratory diseases over time observed in this study suggest that the expanding urban environment progressively affected population health negatively, both within cities and in the countryside. These findings emphasize the importance of addressing urban and rural environments not as isolated entities, but as interconnected realities, whose development and challenges constantly influenced one another and shaped the health of their inhabitants. Chapter 3 provides an extensive temporal analysis of Dutch urbanization, investigating disease patterns across a millennium-long timeframe. This approach underscores the significance of studying

urbanization as an ongoing process rather than a singular, fixed event, thereby providing a more nuanced context for understanding its implications for historical human health.

Chapter 4

Chapter 4 focuses on the relationship between socioeconomic status and (respiratory) health, aiming to investigate how varying economic circumstances impacted citizens' health. The paper presented in this chapter tests the hypothesis that poorer individuals were more adversely affected by the urban environment than their wealthier counterparts. This is assessed through the presence of non-specific stress markers and chronic maxillary sinusitis in four urban post-medieval populations representing various socioeconomic statuses. Contrary to expectations, the analysis presented in Chapter 4 reveals that differences in prevalence rates were not strictly tied to socioeconomic status, but rather seemed to reflect lifestyles. While sinusitis prevalence rates were relatively consistent across most socioeconomic classes, they were significantly lower among middle-low status individuals. These individuals (specialized workers such as shipbuilders, artists, and market stall owners) likely spent more time outdoors than other socioeconomic groups, and historically maintained greater autonomy over their daily routines, unlike industrial workers or members of the elite, whose lifestyles often involved more sedentary indoor activities.

These findings underscore the complex interplay between socioeconomic status, lifestyle, and health, challenging the traditional notion that poorer individuals faced exclusively hazardous health conditions while the wealthy were largely unaffected by the urbanizing environment. Instead, the results presented in Chapter 4 suggest that lifestyle factors played a more significant role than wealth in shaping (respiratory) health, offering a more nuanced perspective on the challenges of urban populations in the past.

Chapter 5

Chapter 5 focuses on the Dutch coastal region of Zeeland, which stood among Europe's most urbanized areas until the 17th century, largely due to its flourishing maritime international trade networks. During this period of economic prosperity, the population benefitted from improved employment opportunities and comparatively better working conditions than elsewhere in the Netherlands. However, it is likely that the rapid growth of Zeeland's urban centers also posed challenges, particularly regarding access to essential resources such as food, clean water, and housing. By the 19th century, Zeeland experienced a sharp economic decline as maritime trade waned, leading to significant de-urbanization and a drastic reduction in its urban population.

This chapter examines how these shifts in urbanization and economic conditions influenced the health of Zeeland's inhabitants over time. Specifically, it analyzes the prevalence of chronic maxillary sinusitis and non-specific stress markers in a sample of 246 individuals from three sites dating from 1030 to 1800 CE. The results reveal significant differences in the prevalence of health markers between the medieval and post-medieval periods, with notably higher rates during times of urban and economic decline. These findings suggest that de-urbanization in the 19th

century negatively impacted respiratory health and overall wellbeing, likely due to deteriorating working conditions and reduced food availability.

By exploring a context of urban decline rather than the commonly studied thriving industrial settings, this study contributes to a broader understanding of the complexities of urbanization in bioarchaeological research. Together with Chapter 3, Chapter 5 highlights the diachronic complexity of urbanization and socioeconomic changes, offering valuable insights into their long-term effects on public health in the Netherlands across different historical contexts and economic systems.

Chapter 6

According to clinical research, children are particularly susceptible to respiratory diseases due to various physiological and behavioral factors. Chapter 6 examines this susceptibility by analyzing chronic maxillary sinusitis in non-adults from 13 Dutch sites spanning the medieval and post-medieval periods. The study investigates how increasing urbanization, living environment (rural vs. urban), and socioeconomic status influenced childhood respiratory health. Results show that post-medieval non-adults were nearly three times more likely to develop sinusitis than their early-medieval counterparts, with adolescents being particularly affected, experiencing an eightfold increase in risk. While the aim of this study was to explore how urbanization impacted non-adults specifically, adolescents' increased susceptibility likely reflects exposure to adult-like working and living conditions. These results underscore the role of societal and temporal changes in shaping respiratory health rather than specific social or environmental contexts.

Chapters 7 and 8

Today, tobacco use is a well-documented major risk factor for respiratory diseases, significantly contributing to conditions like sinusitis, otitis, lung disease, and other chronic respiratory issues. Despite its importance, the impact tobacco had on past populations remains to date severely underexplored in bioarchaeological research. To address this gap, Chapter 7 focuses on osteologically distinguishing smokers in four diachronic skeletal assemblages, providing new insights into the historical impact of tobacco use. The findings challenge prevailing historical narratives by demonstrating that tobacco consumption transcended socioeconomic boundaries and was widely popularized already before 1630 CE, contrary to previous assumptions stemmed from written and visual sources. This study also argues that smoking was not an exclusively male practice, as substantial female participation was observed across all analyzed post-medieval sites.

Building on these perspectives, Chapter 8 investigates whether smokers that were identified osteologically were more susceptible than non-smokers to respiratory diseases by analyzing individual-level patterns of chronic maxillary sinusitis, infectious middle ear disease, and pleural inflammation. In less industrialized contexts, smokers were found to be five times more likely to develop sinusitis and three times more likely to experience pleural inflammation compared to non-smokers. However, these significant differences were not observed in more industrialized

settings, suggesting that additional factors such as air pollution and poor living or working conditions likely exacerbated respiratory health challenges. These findings are particularly significant in the context of this study, as they highlight the interplay between tobacco smoke and environmental factors, providing critical insights into how diverse living conditions shaped health challenges in the past as well as in the present.

Chapter 9

The final chapter of this dissertation reflects on the contributions this study offers to the understanding of the complex relationship between respiratory diseases and environmental, social, and economic factors in historical Dutch populations. It highlights how changing living situations (e.g., increasing/decreasing urbanization, socioeconomic developments, and tobacco use) shaped respiratory health over time, while also emphasizing the challenges of addressing the various risk factors that likely coexisted and interplayed in the same environment. This work offers a unique context for understanding health patterns over more than a millennium, emphasizing the complexities of human behavior and their contributions in shaping health outcomes. Ultimately, it advocates for more interdisciplinary, comprehensive, and nuanced approaches to studying the effects of historical urbanization on human health, aiming to achieve a more complete understanding of the past while better addressing contemporary health challenges.

Samenvatting

Dutch translation by Lotte Nagelhout

De lucht die we inademen. Een onderzoek naar de impact van historische sociaaleconomische veranderingen op de gezondheid van de luchtwegen van vroegere Nederlandse bevolkingen (ca. 470-1850 CE)

Hoofdstuk 1 en 2

De eerste twee hoofdstukken van dit proefschrift schetsen de doelstellingen en omvang van dit onderzoek en bieden uitgebreide klinische en paleopathologische inzichten over de hier onderzochte luchtwegaandoeningen (d.w.z. sinusitis of bijholteontstekingen, oorontstekingen en longvliesontstekingen).

Tegenwoordig is de wereldwijde last van luchtwegaandoeningen enorm, met gevolgen voor miljoenen mensen en aanzienlijke sterfterisico's. Luchtwegziekten variëren van milde kwalen tot ernstige, levensbedreigende aandoeningen, waarbij snelle verstedelijking en industrialisatie de gezondheidsrisico's voor het ademhalingssysteem verder verergeren, voornamelijk als gevolg van toenemende luchtvervuiling. Luchtwegaandoeningen die verband houden met slechte luchtkwaliteit worden vaak gezien als een product van de moderne wereld, maar historische bronnen tonen aan dat dergelijke omstandigheden al sinds de oudheid voorkwamen. Met name de hoge urbanisatiegraad in Europa tijdens de late en na-middeleeuwse perioden heeft waarschijnlijk sterk bijgedragen aan de verspreiding van luchtweginfecties, waarbij armere, geïndustrialiseerde bevolkingsgroepen zwaarder getroffen werden dan hun rijkere, minder stedelijke tegenhangers. Hoewel eerder historisch en archeologisch onderzoek het beeld heeft gevormd dat leefomstandigheden dramatisch werden verslechterd door stedelijke ontwikkelingen, moet worden opgemerkt dat urbanisatie en industrialisatie zich historisch gezien ongelijk over Europa hebben ontwikkeld. Dit bemoeilijkt pogingen om te beoordelen hoe verschillende urbanisatiepatronen invloed hebben gehad op de menselijke gezondheid, gezien variaties in sociaaleconomische omstandigheden, milieucontexten en economische structuren zelden uitgebreid in kaart worden gebracht. Binnen dit kader is osteoarcheologie (oftewel de studie van menselijke skeletresten uit archeologische contexten) bijzonder relevant, omdat het onderzoekers in staat stelt om gezondheidsgegevens op individueel niveau te analyseren en zo een genuanceerder beeld van het verleden te schetsen. Dit proefschrift onderzoekt archeologische menselijke skeletten van 13 Nederlandse populaties om na te gaan hoe factoren die verband houden met verstedelijking (bijvoorbeeld sociaaleconomische ongelijkheden, economische structuren en tabaksgebruik) de luchtweggezondheid hebben beïnvloed. Dit biedt een nauwkeuriger perspectief op historische patronen van infectieziekten in historisch Nederland.

Hoofdstuk 3

Hoofdstuk 3 presenteert diachrone gegevens over het voorkomen van verschillende luchtwegaandoeningen (bijv. chronische maxillaire sinusitis, middenoorontstekingen en longvliesontsteking) binnen zes Nederlandse populaties uit de vroege middeleeuwen tot de na-middeleeuwse perioden. Over het algemeen zijn toenemende percentages van luchtwegaandoeningen in de loop van de tijd in deze studie waargenomen, wat suggereert dat de groeiende stedelijke omgeving een geleidelijke negatieve invloed had op de bevolkingsgezondheid, zowel in steden als op het platteland. Deze bevindingen benadrukken dat stedelijke en landelijke omgevingen niet als geïsoleerde entiteiten moeten worden gezien, maar als onderling verbonden realiteiten met constante interactie tussen de ontwikkelingen en uitdagingen van beide, wat de gezondheid van hun inwoners vormden. Hoofdstuk 3 biedt een uitgebreide chronologische analyse van de Nederlandse verstedelijking, waarbij ziektepatronen over een millenniumlang tijdsbestek worden onderzocht. Deze benadering onderstreept het belang van het bestuderen van verstedelijking als een continu proces in plaats van een enkelvoudige en statische gebeurtenis, wat een genuanceerder perspectief biedt om haar implicaties voor historische menselijke gezondheid te begrijpen.

Hoofdstuk 4

Hoofdstuk 4 behandelt de relatie tussen sociaaleconomische status en (luchtweg)gezondheid, met als doel de impact van verschillende economische omstandigheden op de gezondheid van een bevolking te onderzoeken. Het artikel dat wordt gepresenteerd in dit hoofdstuk test de hypothese dat armere individuen slechter werden beïnvloed door de stedelijke omgeving dan hun rijkere tijdsgenoten. Dit wordt beoordeeld op basis van de aanwezigheid van specifieke stressindicatoren en chronische maxillaire sinusitis (bijholteontsteking) in vier na-middeleeuwse, stedelijke populaties waarin verschillende sociaaleconomische klassen vertegenwoordigd worden. Tegen verwachtingen in blijkt uit de analyse in Hoofdstuk 4 dat verschillen in prevalentiecijfers niet strikt gebonden zijn aan sociaaleconomische status, maar eerder een weerspiegeling lijken te zijn van verschillende levensstijlen. Hoewel sinusitis relatief consistent voorkwam in de meeste sociaaleconomische klassen, kwam deze luchtwegaandoening significant minder vaak voor bij personen van gemiddelde tot lage status. Deze individuen (gespecialiseerde arbeiders zoals scheepsbouwers, kunstenaars en handelaren) brachten waarschijnlijk meer tijd door buitenshuis dan andere sociaaleconomische groepen en hielden historisch gezien een grotere onafhankelijkheid over hun dagelijkse routines, in tegenstelling tot industriële arbeiders of leden van de elite, wier levensstijl vaak meer zittende activiteiten binnenshuis met zich meebracht.

Deze bevindingen demonstreren de complexe wisselwerking tussen sociaaleconomische status, levensstijl en gezondheid, en betwisten hiermee het traditionele gedachtegoed dat de armen uitsluitend gevaarlijke gezondheidsproblemen moesten verdragen terwijl de rijken grotendeels ongeschonden bleven ondanks de verstedelijkte omgeving. In tegendeel, de resultaten uit hoofdstuk 4 wijzen erop dat aspecten van verschillende levensstijlen een belangrijkere rol

spelen in (luchtweg)gezondheid dan welvaart, waardoor er een genuanceerder perspectief op de dagelijkse beproevingen van stedelijke bevolkingen in het verleden wordt geboden.

Hoofdstuk 5

Hoofdstuk 5 richt zich op de Nederlandse kustprovincie Zeeland, welke tot aan de 17^e eeuw één van de meest verstedelijkte gebieden van Europa vormde, grotendeels vanwege haar bloeiende internationale maritieme handelsnetwerken. Gedurende deze periode van economische welvaart profiteerde de bevolking van betere werkgelegenheid en relatief betere arbeidsomstandigheden dan elders in Nederland. Het is echter waarschijnlijk dat de snelle groei van de Zeelandse stadskernen ook problemen met zich meebracht, met name betreffende de toegankelijkheid van essentiële middelen zoals voedsel, schoon drinkwater en huisvesting. Vanaf de 19e eeuw nam de maritieme handel af en kreeg Zeeland te kampen met sterke economische achteruitgang, wat leidde tot aanzienlijk stedelijk verval en een drastische inkrimping van de stedelijke bevolkingen.

In dit hoofdstuk wordt onderzocht hoe deze veranderingen in urbanisatie en economische omstandigheden invloed hebben gehad op de gezondheid van de Zeeuwse inwoners in de loop van de tijd. Er is gekeken naar de frequentie waarmee chronische maxillaire sinusitis en specifieke stressindicatoren voorkomen in een sample van 246 individuen van drie vindplaatsen die dateren van 1030 tot 1800 CE. De resultaten laten significante verschillen zien in de prevalentie van gezondheidsindicatoren tussen de middeleeuwse en na-middeleeuwse perioden, met opmerkelijk hogere percentages van ziekte en stress tijdens stedelijke en economische terugval. Deze bevindingen suggereren dat de 19e eeuwse suburbanisatie een negatief effect hadden op de luchtweggezondheid en het algemene welzijn, hoogstwaarschijnlijk als gevolg van verslechterde arbeidsomstandigheden en een beperkter voedingsaanbod.

Door het kader van stedelijk verval te verkennen, in plaats van de veel bestudeerde industriële welvaart, draagt dit onderzoek bij aan een breder begrip van de complexiteit van verstedelijking in bioarcheologisch onderzoek. Samen met Hoofdstuk 3 belicht Hoofdstuk 5 de diachrone complexiteit van urbanisatie en sociaaleconomische veranderingen, wat waardevolle inzichten oplevert met betrekking tot de langetermijneffecten op de volksgezondheid in Nederland gedurende verschillende historische situaties en economische systemen.

Hoofdstuk 6

Volgens klinisch onderzoek zijn kinderen bijzonder vatbaar voor luchtwegaandoeningen als gevolg van verschillende fysiologische en gedragsfactoren. Hoofdstuk 6 bestudeert deze vatbaarheid door chronische maxillaire sinusitis te analyseren onder niet-volwassenen uit 13 Nederlandse middeleeuwse en na-middeleeuwse vindplaatsen. Deze studie onderzoekt hoe toenemende urbanisatie, leefomgeving (landelijk versus stedelijk) en sociaaleconomische klasse de luchtweggezondheid van kinderen beïnvloedden. De resultaten tonen aan dat de kans om sinusitis te ontwikkelen bijna drie keer zo groot was voor na-middeleeuwse kinderen in verhouding tot hun vroegmiddeleeuwse leeftijdsgenoten. Na-middeleeuwse adolescenten werden het zwaarst getroffen, met een achttvoudig hoger risico om sinusitis te ontwikkelen.

Hoewel deze studie als doel had om de impact van urbanisatie te onderzoeken voor met name kinderen, weerspiegelt de verhoogde vatbaarheid van adolescenten waarschijnlijk hun blootstelling aan volwassen werk- en leefomstandigheden. Deze resultaten benadrukken de rol van maatschappelijke en tijdsgevoelige veranderingen in het behouden van luchtweggezondheid, in plaats van specifieke sociale of ecologische contexten.

Hoofdstuk 7 and 8

Tegenwoordig is tabaksgebruik een veelbeschreven risicofactor voor luchtwegaandoeningen, die aanzienlijk bijdraagt aan de prevalentie van aandoeningen als sinusitis, oorontsteking, longziekte en andere chronische luchtwegaandoeningen. Ondanks het belang ervan, blijft de impact die tabak had op vroegere bevolkingen tot nu toe ernstig onderbelicht in bioarcheologisch onderzoek. Om deze kloof te dichten, richt Hoofdstuk 7 zich op het osteologisch onderscheiden van rokers in vier diachronische skeletcollecties, wat nieuwe inzichten over de historische impact van tabaksgebruik met zich mee brengt. De bevindingen gaan in tegen het gebruikelijke historische narratief door aan te tonen dat tabaksgebruik de sociaaleconomische grenzen oversteeg en al voor 1630 CE op grote schaal populair was, in tegenstelling tot eerdere veronderstellingen op basis van schriftelijke en beeldende bronnen. Deze studie stelt ook dat roken niet uitsluitend een mannelijke gewoonte was, aangezien substantiële vrouwelijke deelname werd waargenomen binnen alle geanalyseerde na-middeleeuwse collecties.

Voortbouwend op deze inzichten onderzoekt Hoofdstuk 8 of osteologisch-geïdentificeerde rokers kwetsbaarder waren dan niet-rokers voor luchtwegaandoeningen door ziektepatronen van chronische maxillaire sinusitis, middenoorontstekingen en longvliesontstekingen op individueel niveau te analyseren. In de minder geïndustrialiseerde gebieden bleken rokers vijf keer meer kans te hebben om sinusitis te ontwikkelen en drie keer meer kans te hebben om aan longvliesontsteking te lijden dan niet-rokers. Echter werden deze significante verschillen niet waargenomen in de meer geïndustrialiseerde omgevingen, wat suggereert dat aanvullende factoren als luchtvervuiling en slechte leef- of werkomstandigheden vermoedelijk de luchtweggezondheid verder deden verslechteren. Deze resultaten zijn uiterst belangrijk binnen het kader van dit onderzoek, omdat ze de wisselwerking tussen tabaksrook en omgevingsfactoren belichten en hierdoor kritische inzichten verschaffen in hoe verschillende leefomstandigheden vorm kunnen geven aan gezondheidsproblemen in zowel het verleden als het heden.

Hoofdstuk 9

Het laatste hoofdstuk van dit proefschrift blikt terug op de bijdragen die dit onderzoek levert aan ons begrip van de ingewikkelde relatie tussen luchtwegaandoeningen en ecologische, sociale en economische aspecten van historische Nederlandse populaties. Het benadrukt hoe veranderende leefsituaties (zoals toenemende/afnemende verstedelijking, sociaaleconomische ontwikkelingen en tabaksgebruik) de luchtweggezondheid in de loop van de tijd hebben gevormd, maar benadrukt ook de uitdaging in het uitlijnen van de verschillende risicofactoren die waarschijnlijk gelijktijdig en interactief van invloed waren binnen dezelfde omgevingen. Dit onderzoek biedt een uniek kader voor het begrijpen van ziektepatronen over het tijdbestek van

meer dan een millennium, waarbij de nadruk wordt gelegd op de complexiteit van menselijk gedrag en hun bijdragen aan het vormgeven van gezondheid. Tenslotte pleit deze studie voor meer interdisciplinaire, diepgaande en genuanceerde benaderingen voor het bestuderen van de effecten van historische urbanisatie op de menselijke gezondheid, met als doel een vollediger begrip van het verleden te verkrijgen en tegelijkertijd de hedendaagse gezondheidsproblemen beter aan te pakken.

Curriculum Vitae

Maia Casna was born on 10 August 1994 in Rovereto, Italy, at the edge of the Dolomites mountain range. Her research centers on the analysis of archaeological human skeletal remains to investigate aspects of daily life and disease, particularly in relation to historical urbanization processes.

Maia began her academic journey by obtaining a Bachelor's degree in Cultural Anthropology from the University of Bologna in 2017. She continued her studies at Leiden University, earning a Master's degree in Archaeological Science, *cum laude*, in 2019. Her Master's thesis focused on chronic maxillary sinusitis in two post-medieval populations from the Netherlands. In 2021, Maia was awarded the "PhD in the Humanities" grant offered by the Dutch Research Council (NWO) to advance her research on the impact of socioeconomic changes on the respiratory health of medieval and post-medieval Dutch populations, with findings presented in this dissertation.

Maia has authored and co-authored several peer-reviewed articles in leading scientific journals, contributing to the field of paleopathology with a particular emphasis on respiratory diseases. Her publications include studies on the application of computed tomography to investigate sinusitis in skeletal remains, as well as research into the physiological response to infection of the middle ear canal. In addition to NWO, her work has received financial support from the British Association for Biological Anthropology and Osteoarchaeology (BABAO), the Stichting ter Financiering van Barge's Anthropologica, and the Stichting Nederlandse Museum voor Anthropologie en Praehistorie (SNMAP).

Maia has extensive fieldwork and laboratory experience. She has worked as an osteoarchaeologist in projects across Italy, Jordan, and the Netherlands, and has been a visiting researcher at the University of Salento (Italy), the University of Leicester (United Kingdom), and at Purdue University (United States of America). Throughout her career, Maia has received recognition for her work in the form of numerous awards, including the Incentive Prize from the Nederlandse Vereniging voor Fysische Anthropologie (NVFA) and an honorary mention for the Early Career Achievement Prize from the Oscar Montelius Foundation, awarded by the European Association of Archaeologists (EAA).

