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Urban Beings: A Bioarchaeological Approach to Socioeconomic Status, Cribra Orbitalia, Porotic Hyperostosis, Linear Enamel Hypoplasia, and Sinusitis in the Early-Modern Northern Low Countries (A.D. 1626–1850)

Maia Casna[a]* and Sarah A. Schrader[a]

[a]Faculty of Archaeology, Leiden University, Leiden, The Netherlands

*Correspondence to: Maia Casna, Faculty of Archaeology, Leiden University. Einsteinweg 2, 2333 CC Leiden, Netherlands.
E-mail: m.casna@arch.leidenuniv.nl

ABSTRACT Starting from the twelfth 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

Vanaf de 12e eeuw maakte Nederland grote sociaaleconomische veranderingen door. Verschillende steden groeiden in omvang en de industriële productie nam toe, waardoor de kloof tussen arm en rijk nog groter werd. Toegang tot bepaalde hulpbronnen (bijvoorbeeld voedsel, woonruimte, enz.) werd grotendeels afhankelijk van de sociaaleconomische status, waarbij de rijken zich veelal een betere levensstijl konden veroorloven dan de armen. Het doel van deze studie was om te bepalen of deze contrasterende ervaringen van het stadsleven de gezondheid van burgers hebben beïnvloedt. Om onze hypothese te testen dat armere burgers meer gezondheidsproblemen dan rijkere ondervonden, hebben we de aanwezigheid van niet-specifieke stressmarkers (d.w.z. cribra orbitalia, *porotic hyperostosis*, lineaire glazuurhypoplasie) en chronische maxillaire sinusitis in vier

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stedelijke bevolkingsgroepen, representatief voor verschillende sociaaleconomische statussen, onderzocht. De analyse van skeletresten liet statistisch significante verschillen zien in het voorkomen van cribra orbitalia tussen verschillende sociaaleconomische groepen. Bovendien werden er ook significante verschillen in het voorkomen van *porotic hyperostosis*, lineaire glazuurhypoplasie en sinusitis tussen de lage en middellage sociaaleconomische klassen waargenomen. Deze resultaten weerspiegelden de complexe relatie tussen sociaaleconomische status en gezondheid. Hoewel het leven in de stad duidelijk verschillend was haar diverse inwoners, hebben zij vergelijkbare gezondheidsproblemen ervaren. Factoren zoals arbeidsomstandigheden, beschikbaarheid van voedsel en culturele praktijken hebben waarschijnlijk een belangrijke rol gespeeld bij het vormgeven van de gezondheid van Nederlandse burgers. Aangezien onze bevindingen significante implicaties hebben voor het begrijpen van de complexe realiteit van het verstedelijkingsfenomeen, is meer onderzoek naar het voorkomen van de niet-specifieke stressmarkers in relatie tot sociaaleconomische status gerechtvaardigd.

Keywords: Stressindicatoren; sociale stratificatie; postmiddeleeuws

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 fourth millennium B.C., but it was only from the tenth century onward that the urbanization phenomenon became systematic, intensive, and, ultimately, global (Creekmore and 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 well-being. 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 health care, air pollution, and disease outbreaks (e.g., Rubin 2020; Simonton and Salmi 2019; Torres et al. 2019; Western and Bekvalac 2019).

In the past 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 and DeWitte 2020; Lewis 2016; Mays and 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 and DeWitte 2020; Edinborough and 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 and McIlvaine 2014:181). 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 and Rando 2020; Reitsema and McIlvaine 2014; Seckler 1980; Stuart-MacAdam 1995). For example, when looking at rates of enamel hypoplasia, cribra orbitalia, and osteoperiostitis in the Late Shang dynasty in China (1250–1046 B.C.), 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 health care, etc.). However, Betsinger and DeWitte (2017) observed how the same skeletal indicators did not significantly change with increasing urbanization in Polish medieval cemeteries (ca. A.D. 950–1250). In addition, Lewis (1999, 2002) investigated linear enamel hypoplasia and cribra orbitalia in several British urban and rural medieval and post-medieval sites (A.D. 850–1859) 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. A.D. 450–1500) 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-Niedbała and Łukasik 2016).

The studies above represent only a small portion of the countless published bioarchaeological analyses on urbanization,[1] 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 health care are all commonly associated with urbanization, they usually impact lower socioeconomic classes more severely than upper ones (Liddle 2017; Tremblay and 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 (A.D. 1711–1857) 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 twelfth to the nineteenth 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 seventh–third centuries B.C. 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.

Urbanization, social stratification, and health in the Netherlands

While most European countries started their urbanization process by the end of the tenth century, Dutch cities only began forming from the twelfth century onward (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 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 financers 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 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 Countries[2] remained rigid until the second half of the nineteenth century and likely led people to experience the urban environment in very different ways (Wintle 2000). For example, in the early-modern period (ca. A.D. 1453–1800), taxes were notoriously high throughout the Low Countries and, although they were always based on each family's income, they were often miscalculated and

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

2. 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.

particularly hard to pay for the poorest socioeconomic classes (Lintsen and Thoben 2009). Historical sources suggest that, until at least the nineteenth century, most of the population suffered from a light but chronic form of malnutrition that, 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 health care to less wealthy citizens were well established already in the sixteenth 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 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 (A.D. 1626–1850) 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.

Materials

The skeletal collections used here originate from three major Dutch centers: Arnhem, Zwolle, and Eindhoven (Table 1; Fig. 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.

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 A.D. 1626 and 1829, when the cemetery was moved outside the city walls (Baetsen et al. 2018; Zielman and 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 and 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

Table 1. Skeletal Collections Included in This Study.

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

Figure 1. Map of the Netherlands showing the location of the sites under study. Image made by Maia Casna.

1997; Van Steen and 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 A.D. 1626 and 1829, 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 nineteenth century, making Arnhem almost as populated as other major Dutch centers (Lourens and 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 nineteenth century, when campaigns were launched to improve the workers' situation (van der Woud 2010; Wintle 2000).

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 and Clevis 2019).

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 ¾ of a guilder, while the price would have been half for a burial within the church cemetery (de Vries and Van der Woude 1997; Melssen 2013). In the seventeenth 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 and 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 and Baetsen 2020).

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 and Weterings-Korthorst 2013; Western and Bekvalac 2019).

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 percent; osteoarthritis appendicular: 39 percent) 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 inside and outside the church, as well as across age categories (Baetsen and Weterings-Korthorst 2013).

Methods

The total sample consisted of 252 adult individuals (i.e., age at death ≥20 years old) (Table 2, Table 3). Key features for including individuals in the total sample were orbital roofs, cranial vault, maxillary sinuses, and both upper and lower dentition. For inclusion in the sample, at least two among the features presented above were required to be >25 percent complete.

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 and 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 and Suchey (1990) and of the auricular surface (Lovejoy et al. 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 and Ubelaker (1994).

The presence of each lesion (i.e., cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary sinusitis) (Fig. 2) was macroscopically assessed for all skulls and noted as either "absent" or "present."

Cribra 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 cribra orbitalia remains highly debated (e.g., Brickley 2018; Cole and Waldron 2019; Rivera and Mirazón Lahr 2017; Rothschild et al. 2021; Walker et al. 2009). Most bioarchaeologists associate cribra 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 cribra 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

Table 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 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)

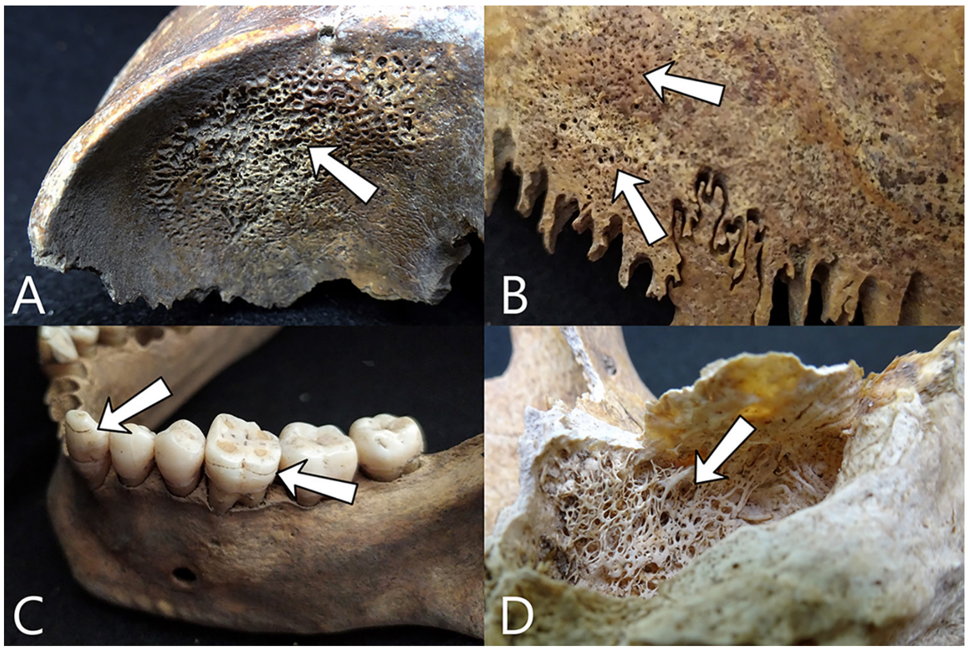

Figure 2. Examples of lesions observed in this research, respectively: (a) cribra orbitalia, (b) porotic hyperostosis, (c) linear enamel hypoplasia, and (d) chronic maxillary sinusitis in the form of "spicule-type bone formation," according to Boocock et al. (1995). Lesions are indicated by the white arrows. Photographs by Maia Casna.

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 and Brickley 2018; Ortner 2003; Ortner and 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 B_{12}–deficient diets. In fact, nutritional megaloblastic anemia (a form of macrocytic anemia caused by deficiencies of either vitamin B_{12} or B_9) can lead to marrow hyperplasia and, subsequently, to the associated porosity of the cranial vault (Walker et al. 2009). While vitamin B_9 is commonly found in a large variety of foods such as eggs and vegetables, vitamin B_{12} 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; King et al. 2002; Nunn 2001; 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 and 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, ø = 4 mm; view angle = 30°).[3] 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 and Feinstein 2000; Patel and Ferguson 2012).

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

Results

Figure 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), with Eindhoven inside the church reporting the highest prevalence rate. No other significant relationships were noted for the other lesions under study. In addition, differences were also investigated per site (Table 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 a statistically significant difference both between Zwolle and Eindhoven inside the church and between Zwolle and Arnhem.

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

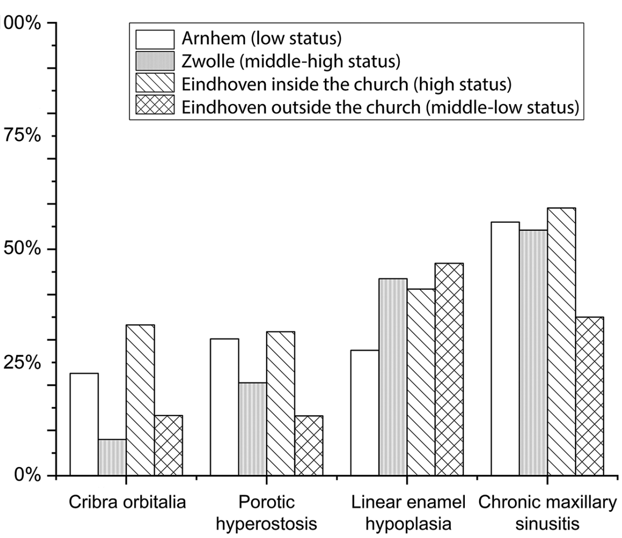

Figure 3. Prevalence of cribra orbitalia, porotic hyperostosis, linear enamel hypoplasia, and chronic maxillary sinusitis for all samples under study.

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

Table 4. Summary of Chi-Squared Test Results, per Site ($df = 3$).

	Cribra Orbitalia[†]				Porotic Hyperostosis				Linear Enamel Hypoplasia				Chronic Maxillary Sinusitis			
	N	*n* (%)	χ^2	*p*	*N*	*n* (%)	χ^2	*p*	*N*	*n* (%)	χ^2	*p*	*N*	*n* (%)	χ^2	*p*
Arnhem	106	24 (22.6)			106	32 (30.2)			94	26 (27.7)			109	61 (56.0)		
Zwolle	83	7 (8.4)			83	17 (20.5)			62	27 (43.5)			83	45 (54.2)		
Eindhoven, inside the church	18	6 (33.3)	10.352	0.013*	22	7 (31.8)	5.859	0.119	17	7 (41.2)	6.138	0.105	22	13 (59.1)	5.914	0.116
Eindhoven, outside the church	30	4 (13.3)			38	5 (13.2)			32	15 (46.9)			40	14 (35.0)		

N = total of individuals with observable feature; *n* = total of individuals showing lesions.
[†]Fisher's exact test.
*Statistically significant at 95 percent confidence level.

Table 5. Summary of Chi-Squared Test Results, per Site ($df = 1$).

	Eindhoven, Inside the Church	Eindhoven, Outside the Church	Arnhem	Zwolle
Cribra orbitalia				
Eindhoven, inside the church		[†]$p = 0.145$	[†]$p = 0.374$	[†]$p = 0.011$*
Eindhoven, outside the church			$\chi^2 = 1.239$, $p = 0.266$	[†]$p = 0.479$
Arnhem				$\chi^2 = 6.853$, $p = 0.009$**
Porotic hyperostosis				
Eindhoven, inside the church		[†]$p = 0.102$	$\chi^2 = .023$, $p = 0.880$	$\chi^2 = 1.267$, $p = 0.260$
Eindhoven, outside the church			$\chi^2 = 4.249$, $p = 0.039$*	$\chi^2 = .940$, $p = 0.332$
Arnhem				$\chi^2 = 2.284$, $p = 0.131$
Linear enamel hypoplasia				
Eindhoven, inside the church		$\chi^2 = .146$, $p = 0.703$	$\chi^2 = 1.259$, $p = 0.262$	$\chi^2 = .031$, $p = 0.861$
Eindhoven, outside the church			$\chi^2 = 4.016$, $p = 0.045$*	$\chi^2 = .094$, $p = 0.759$
Arnhem				$\chi^2 = 4.204$, $p = 0.004$**
Chronic maxillary sinusitis				
Eindhoven, inside the church		$\chi^2 = 3.351$, $p = 0.067$	$\chi^2 = .073$, $p = 0.787$	$\chi^2 = .167$, $p = 0.683$
Eindhoven, outside the church			$\chi^2 = 5.144$, $p = 0.023$*	$\chi^2 = 3.994$, $p = 0.046$*
Arnhem				$\chi^2 = .058$, $p = 0.809$

[†]Fisher's exact test (two-tailed *p*-value).
*Statistically significant at 95 percent confidence level.
**Statistically significant at 99 percent confidence level.

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 health care, 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 eighteenth 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).[4] 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 eighteenth and nineteenth 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 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 and Stojanowski 2015; O'Donnell and 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 and Stojanowski 2015; Wright and Chew 1998). Unfortunately, overcoming the mortality bias in bioarchaeology has been challenging so far (DeWitte and 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 percent and 60 percent. 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 eighteenth- to nineteenth-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 percent difference in frequencies between the two populations (Eindhoven outside the church: 35.0 percent; Eindhoven inside the church: 59.1 percent). 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;

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

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 and 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 percent). 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 a matter of debate and has been linked to anemia, vitamin deficiencies, and 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 percent) compared to the other sites under study (Eindhoven outside the church: 13.3 percent; Zwolle: 8.4 percent), 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 percent) 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 and Stojanowski 2015; Godde and Hens 2021; McFadden and 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 percent; rickets: 2.0 percent) and Eindhoven (scurvy: 0.5 percent; rickets: 5.3 percent), suggesting that these populations were indeed familiar with nutrient deficiencies regardless of their status (Aten 1992b; Baetsen and 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 health care, 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 subadult 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 and 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 non-stationarity in Dutch samples. Analysis of different samples could therefore help evaluate how migration might have shaped the health patterns of urban populations.

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.

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Supplemental Information

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.

Table S1; Figure S1 [https://journals.upress.ufl.edu/bioarchaeology/article/view/1939/2289]: demographic structure of the skeletal assemblages analyzed in this study.

Conflict of Interest

The authors have no conflict of interest to declare.

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