The impact of socioeconomic status on rickets prevalence in the post-medieval Netherlands

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Cover Figure: Children affected by rickets, showing bending deformities of the legs (Holick, 2004, p. 1679S, fig. 2).

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Chapter 1: Introduction and research questions

"It is in the narrow alleys, the haunts and playgrounds of the children of the poor, that this exclusion of sunlight is at its worst, and it is there that the victims of rickets are to be found in abundance." (Palm, 1890).

It was already by the end of the 19th century that the medical community became aware of the lack of sunlight as one of the most important causes of rickets. The disease has been much talked about throughout history as a plethora of written sources can attest. The first description corresponding to the now known manifestations of the disease, dates to the Roman period, the 1st century AD (Brickley & Mays, 2019, p. 540; Jackson, 1988, p. 38). However, rickets is mostly known from the clinical treatises of the first half of the 17th century where descriptions of swollen joints, crooked legs and bigger heads are accepted as the first definite mentions of the disease (Chesney, 2012, p. 3; Glisson et al., 1650, p10-11; Lawson, 1922, p. 262; Veselka et al., 2021, p. 41). Coined "The English Disease", rickets was witnessed in children in England where an epidemic took place during the early 1600s. Most importantly, rickets has been primarily associated with the Industrial Revolution where along with urbanization and industrialization, its prevalence grew rapidly. The creation of overcrowded, air polluted and sunless cities meant that in Northern Europe and North America the prevalence of the disease could be as high as 75% to 98% (Chesney, 2001, p. 145: Steinbock, 1993, p. 979).

Rickets refers to the diseases witnessed in subadults stemming from a vitamin D deficiency and can therefore be classified as a metabolic disease (Brickley & Mays, 2019, p. 540). An insufficient input of either ultraviolet radiation, introduced by the sun, or of foods rich in vitamin D, will lead to an effective vitamin D deficiency resulting in an impaired mineralization of bone during growth (Brickley et al., 2014, p. 48; Mays et al., 2006, p. 362). Latitude and the amount of sunlight a particular region receives are important factors that affect the amount of synthesized vitamin D in the skin. However, recent research indicates that socioeconomic and cultural factors can be the most decisive causes in the development of a deficiency (Mays et al., 2018, p. 485; Mithal, 2009, p. 1811-1815). Densely populated urban centers, socioeconomic status, clothing style, gender roles, cultural and religious practices can negatively influence sunlight exposure. Furthermore, diet may also be subjected to various variables relating to the socioeconomic and cultural environment.

Vitamin D deficiency was rampant in Britain's industrialized cities, where a confluence of biocultural factors limited peoples access to sunlight (Chesney, 2012, p. 4). The development of factory work led to long working hours indoors. Furthermore, the subsequent employment opportunities attracted people to the cities leading to overcrowded and densely populated cities. The industrialization process was fueled by coal therefore, highly polluting the urban environment and further restricting exposure to UVB radiation (Chesney, 2012, p. 4). This high prevalence of rickets in 17th to 20th century Britain has led to a geographical concentration of research in the United Kingdom (Brickley et al., 2017, p. 421-422). Well-studied sites include Spitalfields (London), Broadgate (London) and Birmingham (Mays et al., 2006, p. 362; Pinashi et al., 2006, p. 372). Furthermore, rickets was generally considered rare before the Industrial Revolution (Mays et al., 2006, p. 362). However recently, more and more research has focused on different areas and time periods, disproving this traditional view (Mays et al., 2018; p. 484; Ventades et al., 2020, p. 245; Veselka et al., 2015, p. 665).

The Netherlands did not experience an Industrial Revolution similar to the one that took place in the United Kingdom. The rise of an intense factory system, high level atmospheric pollution and rapid urban expansion, were not characteristic to the post-medieval Netherlands (Chesney, 2012, p. 4; Veselka et al., 2019, p. 72; Wintle, 2000, p. 14). It was from 1850 onwards, when systematic economic growth was sustained leading to modern society (Wintle, 2000, p. 83). However, the 17th to 19th centuries mark an important period in the Netherlands where society underwent significant changes. This period signals the transition from medieval to industrialized society. Processes of population growth, urbanization and migration, but also economic developments (e.g., task specialization, intensification, etc.) had an impact on the daily life and sociocultural practices in Dutch towns (Brickley et al., 2014, p. 49; Veselka, 2019, p. 7). These changes in the environment interacted with the health of the population and influenced their vitamin D status as lifestyle changes could have impacted sunlight exposure. Considerably less research has been done in the Netherlands. Recently, studies of post-medieval populations in the Netherlands have shown significant rates of rickets prevalence in both rural and urban contexts (Veselka et al., 2015, p. 665; Veselka et al., 2021, p. 43-46). Therefore, further research adding onto and elaborating these insights is needed.

The aim of this research is to study the prevalence of rickets during the post-medieval period of the 17th to 19th centuries in the Netherlands and thereby to gain insight into how the socioeconomic context and the changes in lifestyle that accompanied this period, impacted the health of these communities. For this purpose, two populations respectively coming from the urban centers of Arnhem and Zwolle dating to the late 17th century to the early 19th century have been selected. A paleopathological analysis of rickets prevalence will be carried out in order to research whether differences in socioeconomic status had an effect on the prevalence of rickets in post-medieval Dutch populations. Both populations vary in socioeconomic status with Arnhem's population consisting of the lowest social class and the Zwolle population primarily being made up of the middle to upper class. The socioeconomic status of Zwolle's population is inferred from a combination of archival data, detailing the occupations of the deceased, and their burial location in the church, which constitutes the most expensive burial place. For Arnhem, social class was estimated based on the burial location as no archival data was available (van Oosten, 2019, p. 158). The graves of the Arnhem population were situated in the cheapest and most undesirable part of the cemetery, where the poorest members of society got buried (van Oosten, 2019, p. 155). In these varying classes of society different environmental stressors might have played possibly influencing rickets prevalence.

The following question will be asked during this research:

"Does socioeconomic status impact the prevalence of rickets in *post-medieval Dutch populations?"*

Additionally, to gain an elaborate insight into the research problem, the following sub questions will be explored:

Which factors, susceptible to socioeconomic status, impacted the development of rickets in these post-medieval Dutch communities?

How do these results of Zwolle and Arnhem fit within the broader context of the Netherlands?

Multiple studies have focused on the links between rickets and social, cultural and economic parameters (Chesney, 2012; Mays et al., 2006; Mithal et al., 2009; Pinashi et al., 2006). This biocultural approach has broadened our understanding of the complex etiology of this disease. However, some traditional assumptions still persist. Rickets has been commonly linked to low socioeconomic class (Chesney, 2012, p. 4). Traditionally, it has been assumed that the living circumstances of poor people made them considerably more susceptible to developing rickets than high-status populations (Veselka, 2019, p. 20). In the Netherlands, researchers have explained a low prevalence of rickets because of high socioeconomic status among other factors, in the populations of Alkmaar, Delft and Leiden (Baetsen, 2001, p. 58; Maat et al., 1984, p. 140-148). However, some regional studies carried out in Rennaissance Italy, where rickets was detected in the children of the Medici, and post-medieval Gouda have brought a new perspective (Giuffra et al., 2015, p. 608). In the Dutch city of Gouda, rickets was prevalent in high status individuals buried inside the St. John's church during the 17^{th} to 19^{th} centuries (Veselka et al., 2021, p. 47; Veselka, 2019, p. 20). The question can be raised whether socioeconomic status influences the prevalence of rickets and if low status is as determinant as previously assumed. In a recent study by Veselka et al. (2021, p. 41), ten Dutch populations from both rural and urban sites, dating to the 17^{th} to 19^{th} centuries were analyzed. The links between different biocultural factors, including settlement size and socioeconomic status, and vitamin D deficiency were studied. This study forms one of the first steps in the Netherlands to study the complicated relationship between status and rickets prevalence. However, further research is needed since the impact of socioeconomic status on the disease remains difficult to establish.

In this study an elaborate analysis of rickets prevalence in the two Dutch cities Arnhem and Zwolle will be carried out to gain an in-depth understanding of the interaction between socioeconomic status and possible vitamin D deficiency in children. This will be done by adopting a life-course approach where it will be considered which possible factors, related to the socioeconomic environment, were present in each life stage of subadults. Three important interlinked variables, urbanization, socioeconomic status and mother-child relationships will be explored to gain an understanding of the environment these subadults grew up in and whether it left them more vulnerable to developing rickets. The research presented here will contribute to our understanding of rickets development in the Netherlands but also to the broader debate about the impact of socioeconomic status on health. Since changes within this environment naturally impacted on people's lifestyles and consequently their health. The socioeconomic environment protected or left people vulnerable to nefarious outside stressors. Paleopathology therefore can be one of the main sources to study this interaction between environment and the people, especially of under-represented groups like women and children as historical sources are scarce.

In the first chapter, the disease rickets will be contextualized. Here the importance and role of vitamin D in the body together with the macroscopic lesions that can occur when rickets manifests itself, will be covered. Secondly, the etiology of vitamin D deficiency both biophysical factors such as latitude and availability of sunlight and socioeconomic factors such as status and economic occupation will be explored. Furthermore, in chapter 2 the politic and socioeconomic environment of the Netherlands, and more specifically Arnhem and Zwolle, during the 17th to 19th centuries will be analyzed. The aim of this historic research is to gather information of which possible practices and changes in lifestyle which could influence the vitamin D status, are present. In chapter 3, the archaeological populations analyzed in this thesis paired with the employed methodology will be described.

Subsequently, the results of the paleopathological research of the populations from Arnhem and Zwolle will be discussed in chapter 4. The objective will be to establish whether there is a difference in the prevalence of rickets between both populations and if this difference is related to socioeconomic status. In chapter 5, the results of the historical and the osteological research will be compiled to improve our understanding of the interaction between socioeconomic environment and vitamin D deficiency in two post-medieval communities from the Netherlands. The research will (a) contribute to our understanding of the vital period of the 17th to 19th centuries in Dutch history, (b) offer insight into the influence of the socioeconomic environment on health, (c) enable the testing of existing assumptions about the occurrence of vitamin D deficiency, and (d) expand knowledge about vitamin D deficiency beyond the known domain of the industrial period in the United Kingdom.

Chapter 2: The Disease rickets

Rickets has a long research history with many contributions leading to our understanding of the disease. From the first recognition of the manifestations of the disease to the realization that a lack of exposure to sunlight was at the root for example (Glisson et al., 1650, p. 10-11; Palm, 1890). Especially, the last 20 years paleopathological research of vitamin D deficiency has largely expanded in methodology and sources. A biocultural approach has been adopted where the interaction between the cultural context and biology is carefully considered (Brickley et al., 2014, p. 48). Another framework yielding results is the life course approach, since the disease manifests itself differently throughout the life course of an individual. During different phases of life (e.g., childhood, adolescence and adult life), varying factors might have contributed to a vitamin D deficiency. In this chapter, the disease rickets will be contextualized, based on decades of research that contributed to the field. In order to understand the complex interactions between rickets and the socioeconomic environment, the etiology of vitamin D deficiency needs to be understood. In the first part, the role of vitamin D in the body will be studied. Secondly, the etiology of vitamin D deficiency and more specifically the biological factors that play a role will be discussed. Subsequently, the macroscopic lesions that manifest in the skeleton will be described. Lastly, the link with the social environment will be covered.

2.1. Vitamin D and its use in the musculoskeletal system

Vitamin D is a vital pro-hormone in the human body since, unlike other vitamins, it has to undergo synthetization in order to play an active role (Brickley & Ives, 2008, p. 77-79; Holick, 2006, p. 2063-2064). Vitamin D commonly occurs in two forms that are obtained from different sources, vitamin D3 (cholecalciferol) and vitamin D2 (ergocalciferol). One source is sunlight. Vitamin D3 is formed in the skin when exposure to ultraviolet B (UVB) radiation causes 7-dehydrocholesterol, a type of cholesterol naturally present in the skin, to be transformed to pre-vitamin D3 (Brickley & Ives, 2008, p. 78; Holick, 2004, p. 1678; Holick, 2006, p. 2063-2064; Veselka, 2019, p. 13-14). Subsequently, preD3 will be converted to vitamin D3 under the influence of heat (fig. 1). Another source is diet. D3 can also be derived from animal dietary sources while vitamin D2 on the other hand can only be obtained through plants (Jones, 2018, p. 96). Vitamin D will then enter the blood circulation where it is transported to the liver, here vitamin D2 or D3 is converted to 25-hydroxyvitamin D [25(OH)D]. This conversion process will happen a second time in the kidneys where 25(OH)D is turned into 1,25-dihydroxyvitamin D [1,25(OH)2D], reaching the bioactive form of vitamin D (Holick, 2006, p. 2062-2064).

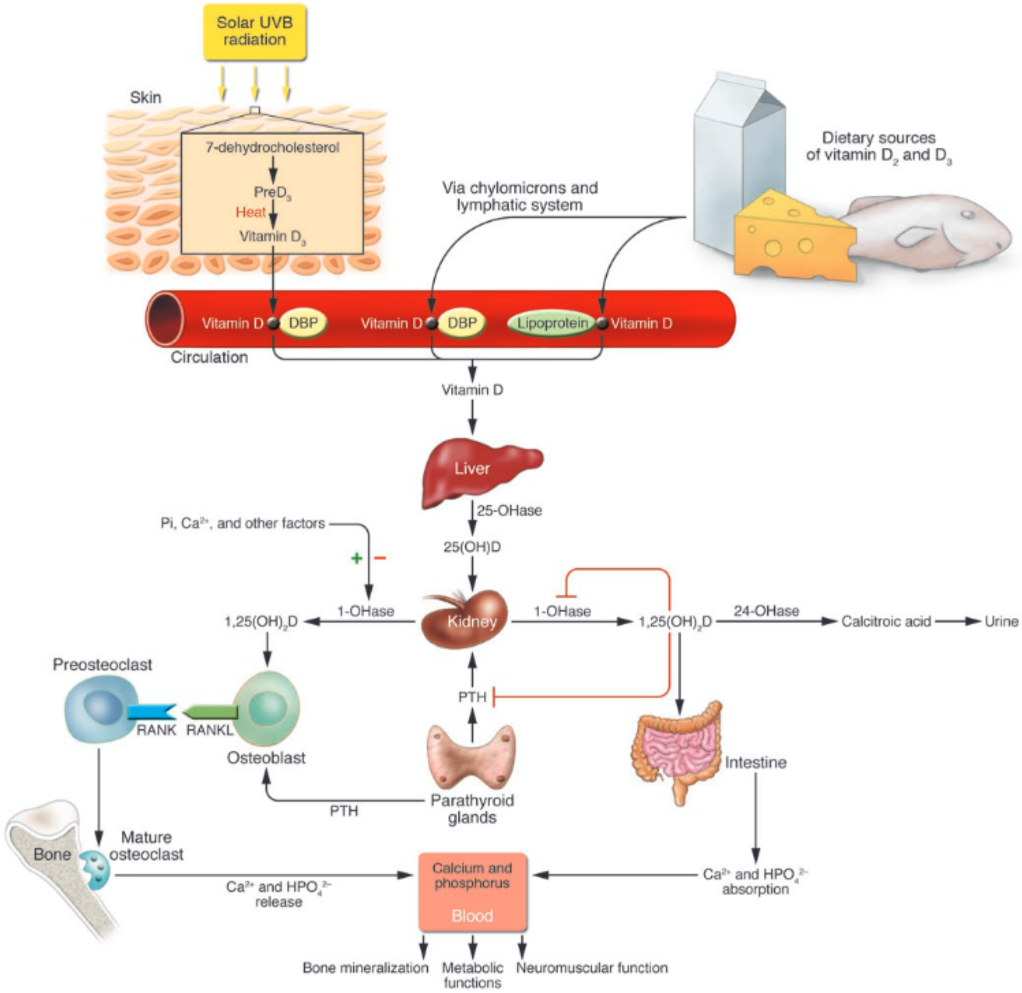

Figure 1: Schematic representation of the metabolism of vitamin D in the human body (Holick, 2006, p. 2064, fig.3).

Vitamin D plays an important role in various areas of the body, including intestinal functions, muscle functions and skeletal functions (Brickley & Ives, 2008, 79). More specifically, the hormone is essential for the regulation of calcium and phosphorus (fig.1). With calcium homeostasis being its primary role, vitamin D is crucial in the musculoskeletal system (Holick, 2006, p. 2062-2064; Holick & Chen, 2008, p. 1080S; Veselka, 2019, p. 14). Bones consist of an organic component, osteoid, that is mainly composed of collagen. The protein molecules will form elastic fibers. In order for bones to get their hardness and rigidity, the osteoid needs to be mineralized. During this process the bone matrix is filled with calcium phosphate, hydroxyapatite, causing the bones to be stiffened. A deficiency of vitamin D will lead to the reduced absorption of phosphorus and calcium causing an insufficient mineralization of the osteoid compartment leading to the bones being softer and weaker (Brickley & Ives, 2008, p. 75-76; Veselka, 2019, p. 14). When amounts of serum phosphorous and calcium are inadequate due to insufficient vitamin D, this will be corrected by the process of extracting calcium from the bones again, to release into the blood.

As a result, this increase in bone resorption will lead to osteopenia, a reduced bone density (Brickley & Ives, 2008, p. 75-76; Mays et al., 2006, p. 362; Veselka, 2019, p. 14; Waldron, 2009, p. 118-119).

Deficiency during an extended period of time will lead to impaired mineralization of new bone amid growth or remodeling. In case of a high deficiency of calcium, additionally secondary hyperparathyroidism can be caused (Brickley et al., 2014, p. 49; Holick, 2006, p. 2063-2066). An increase in the parathyroid hormone (PTH) leads to a decrease of phosphorus in the blood, exacerbating the general health of the bone more. The absence of enough of these minerals can in turn cause metabolic bone diseases. These are diseases that impede the natural metabolization process of bones (Waldron, 2009, p 118).

2.2. Vitamin D deficiency and its manifestations

A prolonged insufficient acquisition of vitamin D will lead to a vitamin D deficiency, defined by M. Brickley and R. Ives (2008, p. 78) as “a level of vitamin D at which pathological changes will occur”. When pathological changes in the skeleton occur due to an impaired mineralization of endochondral bone in subadults, the metabolic bone disease is referred to as rickets. Defects in mineralization of bone manifesting in adults, are in paleopathology referred to as osteomalacia (Brickley & Ives, 2008, p. 75; Brickley et al., 2014, 53). The main, but not only cause of rickets is a vitamin D deficiency (Holick, 2006, p. 2062-2063; Brickley & Ives, 2008, p. 87-88). Deficits of calcium and some rare genetic conditions interfering with the metabolism of phosphorus and calcium, or the synthesis of vitamin D can also lead to the development of rickets or osteomalacia. However, a common form of vitamin D deficiency in both past and modern populations is so-called “nutritional” rickets, referring to rickets caused by the insufficient input of ultraviolet B (UVB) radiation/sunlight or a deficient dietary intake of vitamin D (Brickley et al., 2020, p. 346).

Historically, exposure to ultraviolet radiation of the sun was the primary cause of vitamin D deficiency in the vast majority of cases (Mays et al., 2006, p. 362; Brickley & Mays, 2019, p. 540). The research objective of this thesis is to explore whether socioeconomic status has an impact on rickets prevalence, therefore only rickets will be discussed in the following chapters. Osteomalacia is referred to when vitamin D deficiency manifests in adults, hence it falls outside the scope of this study.

2.2.1. Factors influencing vitamin D deficiency

Geographic latitude impacts the amount of sunlight a region receives with areas close to the poles receiving less ultraviolet B radiation than low latitude zones (Brickley et al., 2014, 50; Brickley & Ives, 2008, p. 77-79). Additionally, factors such as seasonal variation and cloud cover influence the amount of sunlight exposure people can get in certain regions. The earth's ozone layer absorbs the majority of UVB radiation before it reaches our skin. High latitudes correlate with an increased zenith angle of the sun, thus increasing the distance the UVB radiation has to travel (Holick, 2006, p. 2062-2063; Brickley et al., 2014, p. 50; Brickley & Ives, 2008, p. 77-80). As a result, high latitudes receive significantly less UVB radiation than equatorial regions, especially during winter when the sun's zenith angle is at its largest. During the winter months from November until March, almost no vitamin D is produced under the influence of sunlight in Northern Europe. Studies show that approximately five to ten minutes of skin exposure to the sun per day is enough to synthesize an adequate amount of vitamin D (Holick, 2004, p. 1682S). Infants, if fully covered with the exception of their head, require at least two hours per week of exposure to the sun (Pettifor et al., 2018, p. 181).

Skin pigmentation can be another confounding factor of vitamin D deficiency, since melanin filters UVB rays and therefore can interfere with vitamin D synthetization (Brickley & Ives, 2008, p. 81-82; Pettifor et al., 2018, p. 181-182; WHO, 2004, p. 54). Research indicates how dark-skinned immigrants in Northern Europe and North America suffer from higher rates of nutritional rickets than lighter-skinned people. It is unlikely that a vitamin D insufficiency related to seasonal variation in availability of sunlight leads to the manifestation of rickets. However, if vitamin D insufficiency, which is defined by M. Brickley et al. (2014, p. 49) as "suboptimal vitamin D blood levels", maintains and becomes a deficiency, pathological lesions may follow (Brickley & Ives, 2008, 79-81).

Diet can be another important source of vitamin D (Brickley et al., 2014, p. 51; Holick, 2006, p. 2065). Certain foods naturally contain vitamin D, primarily egg yolk and oily fish including mackerel, tuna, sardines and salmon (see table 1). Shiitake mushrooms are the only vegetables containing natural levels of vitamin D. In modern times, starting from 1930 certain foods have been artificially fortified with vitamin D. Table 1 shows how mainly dairy products like milk and butter, but also infant formula have been treated. Before fortification, only trace elements of vitamin D were present in cow's milk for example (Waters-Rist & Hoogland, 2018, p. 109). The most efficient way of reaching adequate levels of vitamin D remains exposure to sunlight, as 90% of the required level of vitamin D tends to come from dermal synthesis (Brickley & Ives, 2008, p. 84; Holick, 2004, p. 1681S). This was especially the case in historic populations before the fortification of foods.

A study on the two main sources of vitamin D, UVB exposure and dietary intake, showed that white adults that underwent the minimal amount of UVB radiation that is needed to get a slight reddening of the skin (1 MED), had comparable vitamin D levels to those that received an oral dose of vitamin D equivalent to 10 000-20 000 IU (Brickley & Ives, 2008, p. 84; Holick, 2004, p. 1681S). In general studies show that the impact of dietary sources on vitamin D deficiency is rather limited. Therefore, vitamin D rich diets, before the artificial radiation of food, would not be able to prevent the development of rickets in cases of inadequate sun exposure (Veselka et al., 2021, p. 46-47; Jones, 2018; Pettifor et al., 2018, p. 180).

Table 1: List of food sources containing vitamin D (Holick, 2006, p. 2065, table. 1).

Dietary sources of vitamin D

Source	Vitamin D content
Fortified milk	100 IU/8 oz
Fortified orange juice	100 IU/8 oz
Infant formulas	100 IU/8 oz
Fortified yogurts	100 IU/8 oz
Fortified butter	56 IU/3.5 oz
Fortified margarine	429 IU/3.5 oz
Fortified cheeses	100 IU/3 oz
Fortified breakfast cereals	~100 IU/serving
Egg yolk	~20 IU/yolk
Shiitake mushrooms, fresh	100 IU/3.5 oz
Tuna, canned	236 IU/3.5 oz
Mackerel, canned	~250 IU/3.5 oz
Sardines, canned	~300 IU/3.5 oz
Salmon, canned	~300–600 IU/3.5 oz
Salmon, fresh	~400–500 IU/3.5 oz
Shiitake mushrooms, sun-dried	1,600 IU/3.5 oz
Drisdol (vitamin D_2) liquid	8,000 IU/cc
Cod liver oil	400 IU/tsp

Another important aspect of diet in preventing rickets and osteomalacia is the intake of calcium and phosphorous as these minerals interact with vitamin D. In this context, phytic acid (phytate) should be considered as it will bind to calcium and can therefore reduce the absorption of calcium in the body (Brickley et al., 2014, p. 51; Brickley & Ives, 2008, p. 84; Veselka et al., 2015, p. 672). As a result, more vitamin D will be needed to balance the inadequate calcium levels. Diets rich in phytate, present in whole grains and soy-products, will interfere with the metabolism of calcium and vitamin D, increasing the chance of developing rickets.

Additionally, vegetarian diets when high in fiber will decrease the half-life of calcifediol (25(OH)D). Furthermore, the low consumption of protein can impair vitamin D synthesis and lead to insufficient levels of the vitamin when sun exposure is limited (Brickley & Ives, 2008, p. 84).

Lastly, infant diet should be considered since at this moment a lot of discussion persists on the links between breastfeeding, weaning and vitamin D deficiency (Brickley et al., 2014, p. 51). Starting *in utero*, vitamin D is transferred through the placenta to the fetus from the mother. At the time of birth, the passing of vitamin D from mother to fetus must have resulted in sufficient vitamin D storage to supply the infant for the first three to four months of its life (Brickley & Ives, 2008, p. 86; Lewis, 2018, p. 209; WHO, 2004, p. 48). After this point other sources of vitamin D are needed, which means exposure to sunlight in the period before the fortification of infant formula (Pettifor et al., 2018, p. 180). As a result, nutritional rickets is rare before the age of three to four months old. Vitamin D deficiency occurring during pregnancy will have ramifications for the unborn child, in this case the infant can be born with congenital rickets. Research has shown that maternal deficiency can have long-term effects on infant vitamin D levels. Postpartum, breast-fed infants are at risk of developing rickets since human milk only contains low levels of vitamin D (Brickley et al., 2014, p. 52; Lewis, 2018, p. 209; WHO, 2004, p. 48).

Additionally, weaning foods need to be considered. In the Netherlands infants were weaned to animal milk, most commonly non-pasteurized milk of cows, and paps made with grains (Veselka et al., 2015, p. 672; Waters-Rist & Hoogland, 2018, p. 107; Waters-Rist et al., 2022, p. 2). These foods lack vitamin D and calcium, furthermore the paps with grains are high in phytates. UVB radiation is therefore needed as the main source of vitamin D, however infants are often covered-up and fed inside. Infants are particularly susceptible to vitamin D deficiency because their rapid bone growth significantly increases their need for this vital nutrient. Rickets is the most common in infants younger than two years old, the highest prevalence tends to occur in individuals from three months to 18 months old as they are not yet independent from their parents and spend most of their time inside (Pettifor et al., 2018, p. 180; WHO, 2004, p. 48).

2.2.2. Skeletal manifestations of rickets

Pathological changes in the skeleton following a vitamin D deficiency can occur due to two processes. On the one hand, the reduced amount of calcium and phosphorous being absorbed which therefore leads to a lack of these minerals in the osteoid and cartilage, will result directly in skeletal changes (Brickley & Mays, 2019, p. 541; Brickley & Ives, 2008, p. 90). The impaired mineralization will particularly affect the areas of endochondral growth, e.g., where bone grows from cartilage like the growth plates of long bones and the costochondral rib junctions (fig. 2) (Brickley & Ives, 2008, p. 90; Holick, 2006, p. 2063).

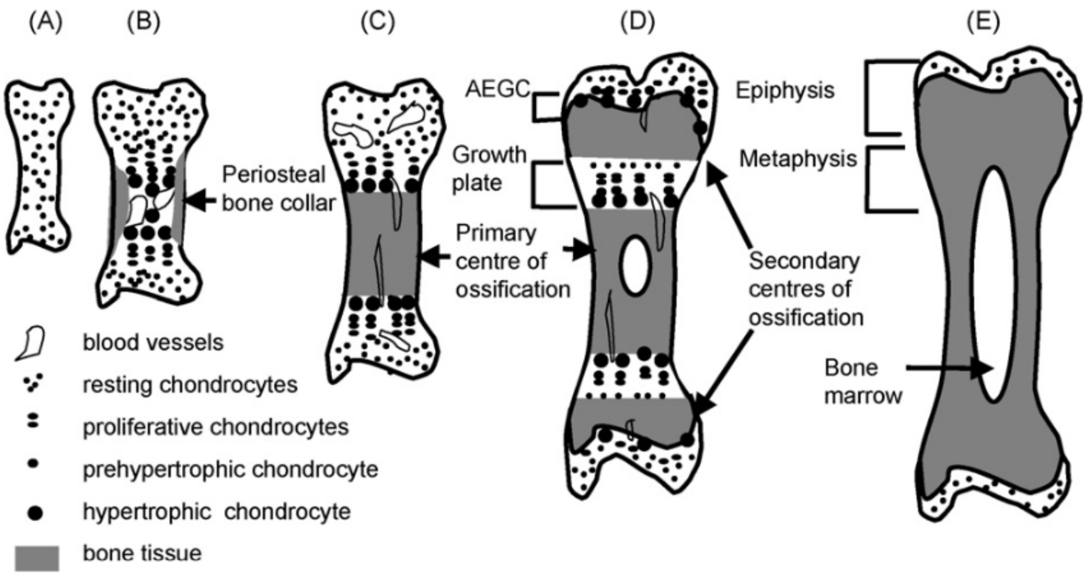

Figure 2: Schematic overview of the endochondral growth of bones (Mackie et al., 2008, p. 48, fig. 1).

In subadults these areas are rapidly growing, making them highly susceptible to disruption in cases where there is a vitamin D deficiency. Under normal circumstances, the cells in cartilage are structured orderly in zones illustrated in figure 3 by p, h and c (Brickley & Ives, 2008, p. 90; Mackie et al., 2008, p. 46-48). These cells, chondrocytes, follow a process of proliferation where the cartilage structure grows longitudinally (corresponds with zone p). Subsequently, a phase of hypertrophy where they grow in volume and eventually degenerate (zone h), in their wake letting in osteoblasts that will form bone in the structure, which will function as scaffolding (Brickley, Ives, 2008, 90; Mackie et al., 2008, 46-48). During vitamin D deficiency, this process will be impeded as mineralization is needed for chondrocytes to die and to finalize the transition into bone. As a result, the cartilage will continue to grow in a disorganized manner and osteoblasts will be obstructed (fig.3b). Poor mineralization will weaken the bone since the osteoid cannot be strengthened by minerals and will grow deformed (Brickley & Ives, 2008, p. 92).

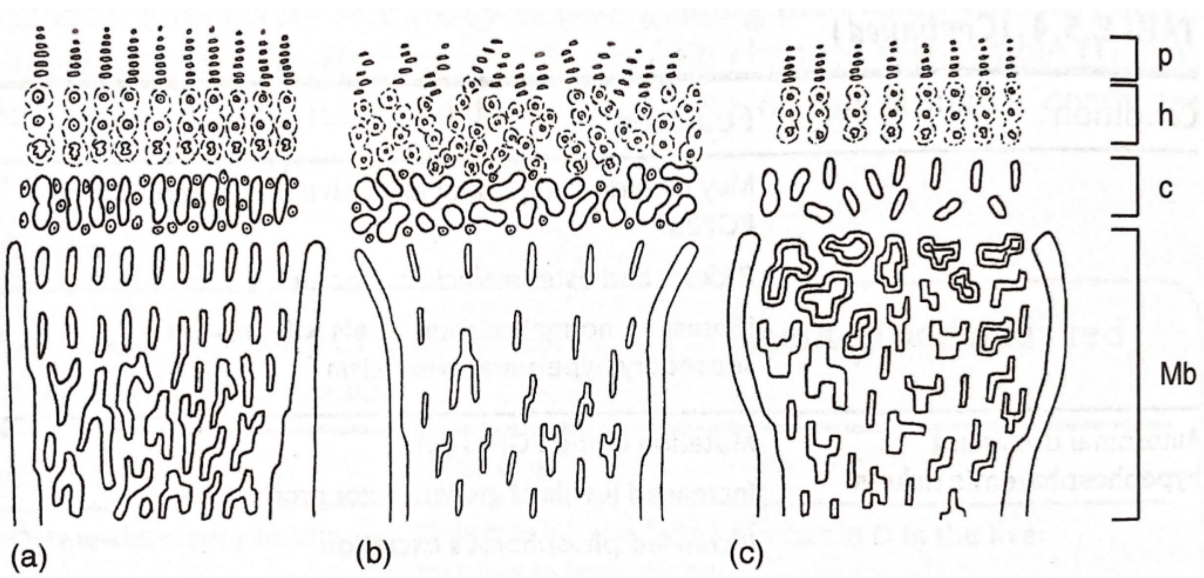

Figure 3: Schematic representation of normal endochondral growth (a) and pathological changes during early onset of rickets (b) and healing of rickets (c). The different zones of cartilage structure are indicated with p for proliferating, h for hypertrophy and c for cartilage mineralization, Mb refers to mineralized bone (Brickley & Ives, 2008, p. 90, fig.5.6.).

The other process leading to pathological changes in rickets contains mechanical forces causing bone deformation. Activities like crawling and walking will put pressure on the weakened bones and the poorly organized cartilage structure of the epiphyses (Brickley & Ives, 2008, p. 90). In early stages these changes will start at the metaphyses and growth plates. Pressure on the impaired cartilage structure will cause flaring of the metaphyses and fraying of the growth plate margins (fig. 4). Especially the distal radius and ulna are commonly affected during the onset of the disease (Lewis, 2018, p. 210). Biomechanical deformity may also consist of concavity or “cupping” of the growth plate (Brickley & Mays, 2019, p. 541). If the deficiency prolongs and intensifies, swelling of the metaphysis and/or angulation of the growth plate may take place (Brickley & Ives, 2008, p. 91). This angulation is often expressed in either medial or lateral tilting (fig. 4). Porosity may be present on the growth plates, metaphyseal surface and cranium, mainly the ectocranial surface and the orbital roofs, indicating unmineralized osteoid (fig. 5) (Brickley & Ives, 2008, p.97-98; Brickley & Mays, 2019, p. 541).

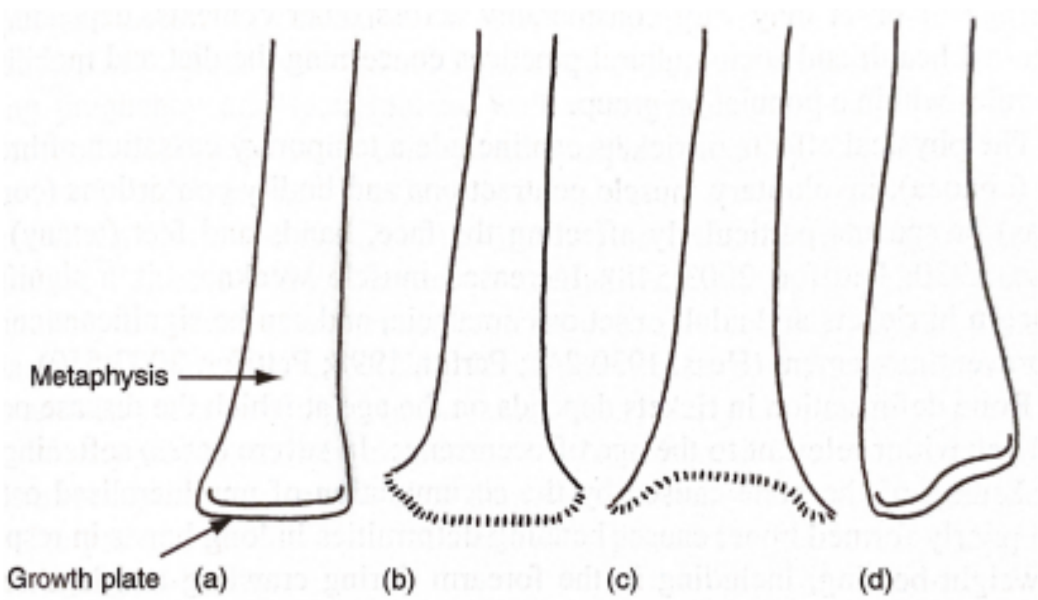

Figure 4: Visualization of growth plate deformities in an immature radius (Brickley & Ives, 2008, p. 91, fig.5.7).

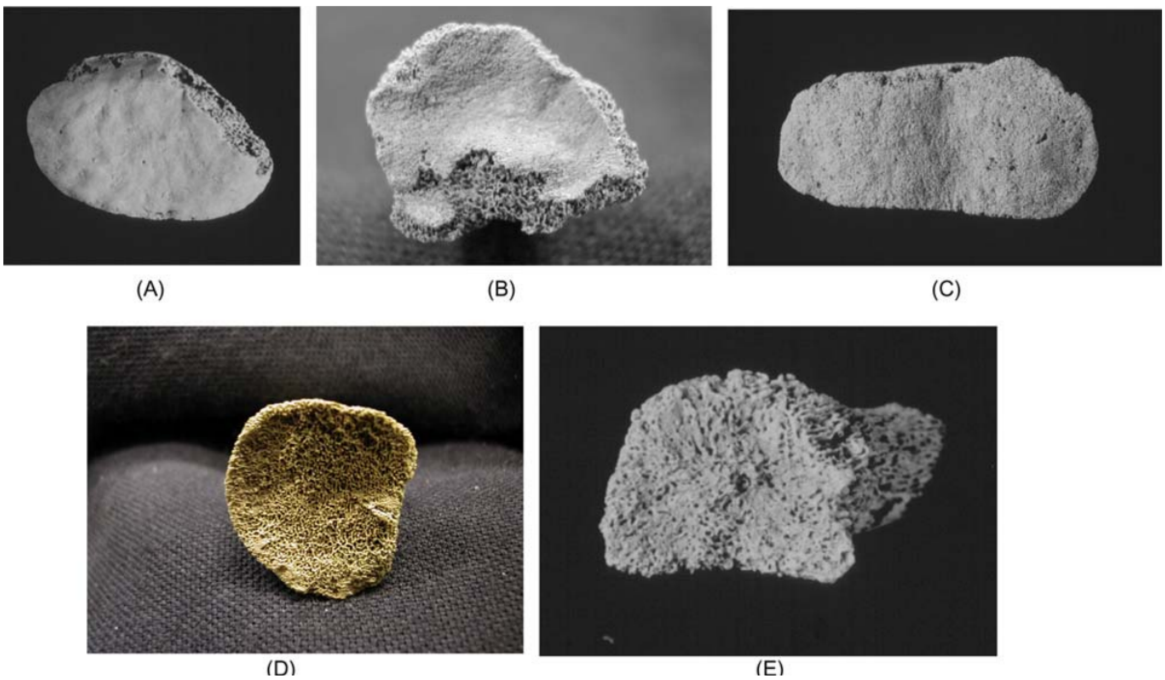

Figure 5: Evolution of growth plate morphology during rickets with (a) showing an unaffected growth plate, (b-c) showing slight roughening, (d) showing cupping and severe porosis of the growth plate and (e) showing severe roughening and deformity of the growth plate (Brickley & Mays, 2019, p. 542, fig. 15.18).

In infants, deformities of the skull may occur including craniotabes (softening of the cranium) on the occipital or parietals when areas of the bone become flattened where the infant rests its head. Furthermore, delayed closure of the fontanelles and enlargement of sutures may occur (Holick, 2006, p. 2064-2065). Additionally, mechanical forces can cause the mandibular ramus to angle medially and the condyles to bend (fig. 6) (Brickley & Ives, 2008, p. 103; Brickley & Mays, 2019, p. 541).

Figure 6: Medial bending of the right mandibular condyle (posterior view) (Brickley & Mays, 2019, p. 545, fig. 15.28).

A similar occurrence is witnessed in the ribs, namely in the costochondral junction. Here weakening of the formed bone and unmineralized osteoid will be expressed in flaring and cupping deformities of the costochondral rib ends (Lewis, 2018, p. 212; Brickley & Ives, 2008, p. 100). Enlargement or "beading" of the rib ends, so-called "rachitic rosary", may take place where osteoid compiles.

The most commonly known traits of rickets are undoubtedly bending deformities of the long bones caused by mechanical forces. When weight is carried on the weakened bone, it will start bending under the pressure (fig. 7). Bowing is most common in the lower limbs unless the individual was still crawling, in this case the arms could be affected. In the femur, an exaggeration of the anterior curvature is most frequently observed (Brickley & Ives, 2008, p. 102; Brickley & Mays, 2019, p. 541). Possible lesions affecting the femur specifically are *coxa vara*, which entails angulation of the neck, and flattening of the head. The tibia and fibula are generally affected by anterior or medial bending. Bending deformities can also occur in other bones like the sternum, sacrum, ribs, etc. (Brickley et al., 2018, p. 45; Brickley & Mays, 2019, p. 541). The pressure on the lower limbs can cause them to tilt inwards, so-called "knock-knees" (*genu valgum*) or outwards so-called "bowlegs" (*genu varum*) (Holick, 2006, p. 2064; Lewis, 2018, p. 210-212).

Lastly, the pelvis can be another commonly affected site of the skeleton. Mechanical deformities include abnormal curvature of the iliac crest, bending or flattening of the ilium (Brickley et al., 2014, p. 53; Ortner & Mays, 1998, p. 48-52; Lewis, 2018, p. 210). The ilium can also appear swollen and plump and/or experience growth retardation. *Protrusio acetabulae* can occur where the acetabulae are deeper than normal and protrude into the pelvic cavity.

Figure 7: Tibiae and fibulae of a subadult from Middenbeemster showing bending and metaphyseal deformities (Veselka et al., 2015, p. 669, fig. 3).

When adequate vitamin D levels are attained after a period of deficiency, the individual can overcome rickets. The osteoid that piled together during the active phase of the disease, will undergo mineralization causing the bones to thicken (Brickley et al., 2018, p. 44; Brickley & Ives, 2008, p. 98; Brickley & Mays, 2019, p. 541). Furthermore, porosity will be filled up with new bone during the phase of healing. Generally, the presence of porosity signals an active stage of the disease. One exception is porosity that is present in the concave surface of bowing long bones (Brickley & Ives, 2008, p. 98; Mays et al., 2006, p. 366). During healing, porous bone will be deposited in the concavity as a part of the remodeling process. It is possible that during remodeling manifestations of rickets get completely removed depending on the intensity of the disease. When residual lesions or lesions associated with healing are observed, it is classified as healed rickets.

Traditionally, the estimation of rickets was mainly focused on the detection of bending deformities in adults and adolescents (Brickley & Ives, 2008, p. 97; Mays et al., 2006, p. 362). These were the most recognizable deformities when studying rickets. The last 25 years have seen significant progression in the paleopathological detection of (infantile) vitamin D deficiency (Brickley et al., 2014, p. 52; Mays et al., 2006, p. 362). More attention is being paid to the subtle alterations that can occur in the skeleton when the disease is active, particularly in infants. The study by Ortner and Mays (1998) of Wharram Percy in England, has been crucial in the description of skeletal manifestations that can aid in the diagnosis of rickets. In this publication ten features were established as being indicative of rickets, including cranial vault and orbital roof porosity, deformation of the mandibular ramus, flaring and porosity of costochondral rib ends, deformity of arm or leg bones, metaphyseal flaring of long bones and long bone thickening (Mays et al., 2006, p. 363; Ortner & Mays, 1998, p. 46).

The rise in paleopathological research of vitamin D deficiency over the past few years has resulted in an expansion of recognized deformities to diagnose rickets (Brickley et al., 2018, p. 43). These traits have been compiled and expanded in multiple studies (Brickley & Ives, 2008; Mays et al., 2006; Brickley & Morgan, 2023). In addition to the original ten features by Ortner and Mays in 1998, Brickley and Ives (2008, p.103-105) considered traits as deformation of the ribs, angulation of the ribs paired with a protruding sternum (so called pigeon-chested), swelling of the costochondral rib ends (so called rachitic rosary), kyphosis or scoliosis of the spine, concavity of the ilium, *protrusio acetabulae* caused by the anterior angulation and intrusion of the acetabulae into the pelvic cavity, to be diagnostic of rickets.

In this case, diagnostic means that multiple features need to be present in order to reliably diagnose rickets. Furthermore, some additional features were listed, that on their own are not sufficient for a diagnosis but can aid in the recognition of rickets. These include cranial deformities like parietal and frontal bossing and craniotabes (softening of the cranium), caries and enamel hypoplasia and angulation of the knees. (Brickley & Ives, 2008, p. 103-105; Yorifuji, et al., 2008, p. 1784). In most studies a variation of 10 to 16 of these macroscopic features are used to diagnose rickets (see table 2) (Brickley & Morgan, 2023, p. 3; Mays et al., 2006, p. 363; Mays et al., 2018, p. 487; Veselka et al., 2015, 667).

Table 2: List of macroscopic lesions often considered when diagnosing rickets (After Brickley & Morgan, 2023, p. 4, table 2).

Macroscopic lesions	Active/Healed
1. Cranial vault porosity. Arises as a result of impaired/defective mineralization	A
2. Orbital roof porosity Arises as a result of impaired/defective mineralization	A
3. Cranial vault thickening (arises when sufficient vitamin D becomes available to mineralize accumulated osteoid [Brickley et al., 2018, p. 44])	H
4. Deformed mandibular ramus (a biomechanical deformity)	
5. Rib bending deformity (a biomechanical deformity)	
6. Costo-chondral rib flaring (a combination of impaired/defective mineralization and biomechanical deformity). Note also reported in scurvy	
7. Costochondral rib porosity Arises as a result of impaired/defective mineralization	A
8. Ilium concavity (a biomechanical deformity)	
9. Bending deformity——Upper limb long-bones (a biomechanical deformity). Note bending deformities can arise in long bones for many other reasons	
10. Bending deformity——Lower limb long-bones (a biomechanical deformity). Note bending deformities can arise in long bones for many other reasons	
11. Long-bone metaphyseal flaring/cupping of ends. Note also reported in scurvy	
12. Long-bone general thickening (arises when sufficient vitamin D becomes available to mineralize accumulated osteoid [Brickley et al., 2018, p. 44])	H
13. Long-bone cortical (especially metaphyseal) porosity Arises as a result of impaired/ defective mineralization	A
14. Superior flattening femoral metaphysis	
15. Coxa vara (inferior angulation of the femoral head and neck)	
16. Porosis/roughening on bone underlying growth plates Arises as a result of impaired/ defective mineralization	A

In order to accurately diagnose rickets and not miss any manifestations whether in an early or progressed stage of the disease, it is important to pay close attention to the age of the individual and which mechanisms may lead to bone deformities. Cranial deformities for instance will be more common in infants that spend a lot of time lying down (Brickley et al., 2014, p. 54). Bending deformities of the lower limbs will only manifest themselves in individuals that are able to walk and carry their body weight on their legs. In infants, bending deformities of the arms can occur when they are crawling or in general bending and angulation can be caused by swaddling (Brickley & Ives, 2008, p. 92).

2.3. Link with the socioeconomic environment

The importance of exposure to sunlight and diet in the etiology of vitamin D deficiency has already been established, with biophysical factors such as age, latitude, seasonality and skin pigmentation being crucial (Brickley et al., 2014, p. 48). However, exposure to UVB radiation is also subjected to cultural variables (Jablonski & Chaplin, 2018, p. 54). Urbanization and the paired shift in lifestyle to the indoor environment have become major causes of the development of vitamin D deficiency.

Determinants such as densely built urban centers, socioeconomic status, clothing style, gender roles, and cultural and religious practices can influence sun exposure (Mays et al., 2018, p. 485; Mithal, 2009, p. 1811-1815). Recent research indicates that these sociocultural variables can be the most decisive in the etiology of the disease.

Within paleopathological research of vitamin D deficiency, two important frameworks should be considered. Firstly, a biocultural approach, propagated by Brickley et al. (2014), encompasses the complex interaction between biophysical and cultural variables in the development of vitamin D deficiency. Secondly, this framework should be considered in combination with a life course approach that can be defined as "the study of long-term effects on chronic disease risk of physical and social exposures during gestation, childhood, adolescence, young adulthood and later adult life. It includes studies of the biological, behavioral and psychosocial pathways that operate across an individual's life course, as well as across generations, to influence the development of chronic diseases." (Ben-Shlomo & Kuh, 2002, p. 285). While vitamin D deficiency is not a chronic disease per se, it can reoccur during an individual's life course and can furthermore increase susceptibility to other diseases like cancer, cardiovascular disease and multiple sclerosis (Holick, 2004, p. 1685S; Brickley et al., 2014, p. 48-49). A life course approach makes it possible to gain insight into the specific biocultural factors that influenced the disease during different stages of life as different determinants are at play *in utero* compared to late adulthood. Paleopathological research of vitamin D deficiency offers information about past societies and is particularly fruitful in the study of historically underrepresented groups like children and women.

In this theoretical framework, three important variables that are closely interlinked will be further elaborated, namely urbanization, socioeconomic status and mother-child relationships. Vitamin D deficiency can be closely linked with the urban context as increasing urbanization is paired with higher prevalence of rickets and osteomalacia (Veselka et al., 2021, p. 47; Brickley, 2017, p. 425). The creation of closely built and overcrowded cities meant less direct available sunlight (Holick, 2004, p. 1678). A study of different post-medieval communities in the Netherlands showed that rickets was two times more prevalent in subadults living in urban than in rural areas (Veselka et al., 2021, p. 47).

Socioeconomic status is closely connected to the urbanization process. Urban society required more social organization and stratification as differences between social classes grew. Additionally, economic diversification was higher in the cities resulting in more occupations that were spent inside compared to the countryside. The link between rickets prevalence and the socioeconomic environment of people has been made early on, as attested by Palm in 1890 when describing its occurrence predominantly in "the children of the poor". Lawson (1922) reported elaborately on the economic factors that had an influence on the manifestation of the disease. In particular, he emphasizes diet and the living conditions in post-medieval Britain, stating that the population density, overcrowding and the deficiency of light together with nutrition influences the frequency of rickets (Lawson, 1922, p. 335).

Important progress had been made in the English medical community during the 19th century regarding rickets (Steinbock, 1993, p. 978-979). The concentration of research in England resulted in rickets being named "the English disease". Since then, the disease was primarily linked with the Industrial Revolution in Northwestern Europe, as incidence in industrial towns could be as high as 89%. During this period, previously mentioned processes like demographic growth and urban expansion accelerated. Furthermore, pollution from the burning coal and wood, the spread of diseases, bad sanitation and living habits heavily impacted the health of people, especially of the poor (Brickley & Ives, 2008, p. 95; Holick, 2004, p. 1678). Child labor in factories and urban crafts lead to even less sun exposure in an already polluted environment (Brickley et al., 2014, p. 54-55).

Not only the lower social classes suffered from vitamin D deficiency. As mentioned in the introduction, some regional studies showed how vitamin D deficiency also affected some high-class populations. Cases of rickets were found in very high-status individuals from the Medici family in Florence. In the upper social classes in Renaissance Italy, fashion and social rules seemed to have played an important role (Giuffra et al., 2015, p. 621). Women were dressed in heavy clothing and wore heavy cosmetics, completely covering their skin when they were outside. Furthermore, pale skin was a status symbol leading to sun avoidant behavior. Vitamin D deficiency in mothers would have had repercussions for their young children (Brickley et al., 2014, 55-57; Giuffra et al., 2015, p. 620-621). On the one hand the infant is then born with inadequate levels of vitamin D and on the other hand, might be kept inside together with the mother. Additionally, cultural practices like swaddling and age of weaning are influenced by socioeconomic status and can compromise vitamin D levels.

In general, rickets can be the result of a complex interaction of biological, environmental, sociocultural and economic determinants that have influenced the individual's life course. Since socioeconomic status is an influential factor steering the lifestyle of people, it would therefore be fruitful to study its possible impact on rickets prevalence. Firstly, it needs to be established in which ways the socioeconomic landscape was shaped in the Netherlands and more importantly in Arnhem and Zwolle.

Chapter 3: The Netherlands in the 17th to 19th centuries

In order to study the impact of socioeconomic status on rickets prevalence in Dutch urban communities, the historical background during the 17th to 19th centuries needs to be understood. In the first part of this chapter, a historical analysis of important social and economic changes in the Netherlands during this period will be carried out. As mentioned in the introduction chapter, the Netherlands did not follow the same path to a modern economy as other Northwestern European countries like the United Kingdom did. The region did not experience an industrial revolution in the traditional sense. How its economy and society evolved will be explored here. The second part of the chapter will be focused on the two selected sites for comparison, Arnhem and Zwolle (fig. 8). The populations that were analyzed, and will be discussed later, were recovered from these two urban centers. The archaeological and available archival sources indicate that the sample from Arnhem was of low socioeconomic status while Zwolle's population belonged to a relatively high socioeconomic class. To fully understand the socioeconomic environment of these communities, the historic context of both cities will be analyzed in this part. First, general demographic and economic trends in each city will be described. Later the socioeconomic environment of poor people in Arnhem and well-off people in Zwolle will be discussed.

Figure 8: Map of the Netherlands showing the sites selected for analysis.

3.1. Socioeconomic context

The modern-day Netherlands consists of one of the most densely populated and urbanized areas in Europe with one of the highest life expectancies (Wintle, 2000, p. 7). This prosperity is the result of centuries of economic and social growth. Starting from the 13^{th} and 14^{th} centuries rapid urbanization processes took place throughout the country (Paping, 2014, p. 6). The development of various cities and towns was paired with growing economic specialization. The high economic output and standards of living made the Northern Low Countries by 1500, one of the most advanced regions within the continent (Alfani, Ryckbosch, 2016, p. 144). Especially the regions of Holland and Zeeland were characterized by a high urbanization rate where market-oriented economic activity was vital (Paping, 2014, p. 6-7). The inland areas of Overijssel (Zwolle) and Gelderland (Arnhem) were more predominantly rural with proto-industrial industries like textile production being crucial in urban centers.

During the 16^{th} century a period of political turmoil took place as the Northern Low Countries became steadily more unified and became the wealthiest area of the world in the 16^{th} century (Paping, 2014, p. 7-8). The following 17^{th} century is known as the Dutch Golden Age, a period of general economic and cultural prosperity (Paping, 2014, p. 8). The 17^{th} to 19^{th} centuries marks an interesting period in Dutch history. While a high level of urbanization and economic development took place already early on starting from 1400 onwards, the 18^{th} century especially marked a period of economic and demographic stagnation with a period of de-urbanization (Paping, 2014, p. 1). Where almost half of the Dutch population lived in towns by 1700, the number decreased to 37% in the middle of the 19^{th} century. The Golden Age of the 17^{th} century ended when a crisis occurred during the 60s and 70s impacting the crafts and industries negatively within the towns (de Vries & van der Woude, 1995, p. 776-783; Paping, 2014, p. 7-8). Losses also hit the trading and agricultural sectors. In general, an economic segmentation took place with higher unemployment rates and a concentration of wealth among a select few leading to an ever-growing inequality rate during the late 17^{th} to mid-19^{th} century in the Northern Low Countries. Instead of an industrialization process bringing the Dutch economy to a higher level, as witnessed in neighboring countries during the 19^{th} century, an economic decline took place (Wintle, 2000, p. 14, p. 69-72). An Industrial Revolution motored by iron and coal like in Britain, did not occur in the Netherlands. Regardless of this economic stagnation, the Netherlands remained one of the richest and economically advanced countries in the world with a competitive agricultural, trade and transport sector. In general, the 18^{th} and early 19^{th} centuries can be situated between two peaks of prosperity during the Dutch Golden Age and the onset of modern economic growth from the 1850s onwards (Wintle, 2000, p. 83).

These developments in the economy are mirrored in the Dutch demography (Wintle, 2000, p. 7-8). After a steady increase comes to a halt around 1700, the 18th century marks a recession in demographic growth (fig. 9). In the early 19th century, the population level starts to grow again and from the 1870s onwards a steep increase of the Dutch population takes place. Interesting when considering health and disease of populations, are the death rates. The 19th century up until the 70s marks a period of very high mortality and especially infant mortality, where around one in five deaths occurred below one year old. It was only after ages five to ten that mortality rates improved for children (ten Hove, 2005, p. 409-410; Wintle, 2000, p. 12).

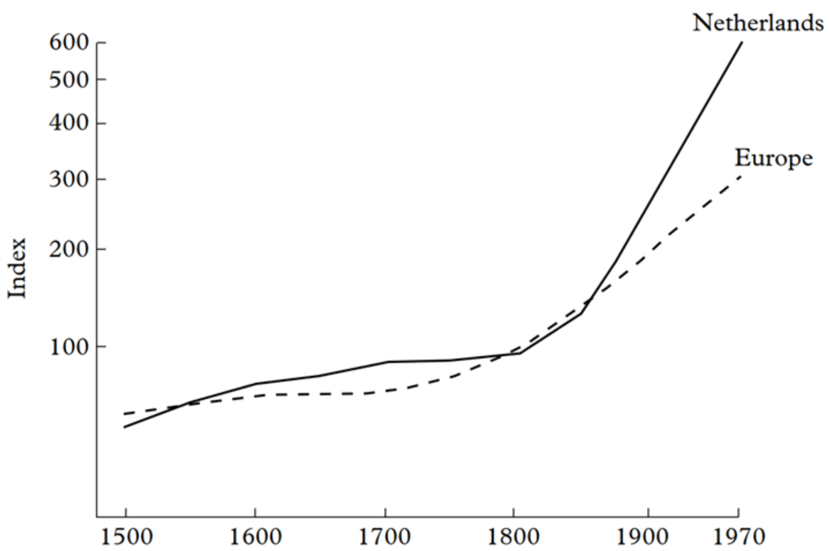

Figure 9: Evolution of the Dutch population compared to the European population from 1500-1970. The x-axis indicates the time period, the y-axis represents the (relative) population size with index (1800=100) meaning that the population in 1800 is baselined to 100 (Wintle, 2000, p. 8, fig. I.1).

These macroeconomic and political evolutions had a profound impact on the socioeconomic environment of the population. Society in the post-medieval Netherlands was stratified on a high level with at the top the elite consisting of high-level civil servants/military and industrial employers, followed by the middle class of low-level servants, supervisors, foremen, the self-employed and the skilled workers. At the bottom the laborers, the unemployed and the homeless are found (Alfani & Ryckbosch, 2016, p. 143; Van Bavel & Kok, 2004, p. 128). This bottom half of society was mainly made up of unskilled and lowly educated laborers working in textile production, distilleries, the army, etc. The poorest of the poor consisted of the unemployed and the possession-less (de Vries & van der Woude, 1995, p. 647-649). Downward mobility in these groups was especially high and dependent on years of shortage, war and unemployment but also disease and disabilities. During the second half of the 18th century and certainly from 1870 onwards- the cost of living hiked up significantly while the wages remained stagnant leading to a general pauperization of these lowest social groups. The crisis of international trade and urban industries during the late 18th and early 19th century impacted the proletariat strongly. It is estimated that around 50% of the population in Dutch towns was made up of these two groups.

The middle class could be further divided in different groups with the low-level shopkeepers and craftsmen at the bottom, followed by the group of teachers, specialized shopkeepers, smiths, butchers, tailors, shoemakers, etc. (de Vries & van der Woude, 1995, p. 649-650). Even higher, making up maximum 20% of society, successful bakers, butchers, smiths, grocers, skippers, officers, etc. were found. Lastly, included in the elite group are the upper middle class, which was made up of merchants, manufacturers, lawyers, doctors, entrepreneurs, pensioners, etc. and the patricians consisting of the high-level civil servants and industrialists.

These professional titles signify the male workforce, but the often-anonymous work of women and children cannot be overlooked. Little is known about the female workforce in Dutch preindustrial towns (de Vries & van der Woude, 1995, p. 689-690). Where official sources offer information about the vocation of men making it possible to analyze productivity, competition and the evolution of wages, they almost completely omit women and children. The most important source of employment for women were the preindustrial crafts, notably the production of textiles where women took part in various parts of the production process (de Vries & van der Woude, 1995, p. 691-694). Marital status influenced the occupation of women. Young and unmarried women were often employed as household staff, working as maids, housekeepers and governesses. Married women could be found working along their husbands as shopkeepers, grocers, tailors, bakers, butchers but also as spinsters, teachers, etc. Archival data like tax registers sometimes reference women with a function like elite women being listed as pensioners, i.e. living of bank interest (Dekker & Carlson, 1998, p. 167). In addition to their paid labor, women also carried out the bulk of unpaid labor consisting of housework, raising children and caregiving for ill and disabled relatives (de Vries & van der Woude, 1995, p. 690).

While child labor has been commonly linked to industrialization and the 19th century factories, it was already omnipresent on a large scale in the post-medieval crafts and in agriculture (de Vries & van der Woude, 1995, p. 689-699; van Nederveen Meerkerk & Schmidt, 2008, p. 717-718). The Dutch Republic reached an impressive economic growth already early on, resulting in a high demand for labor. This demand was met with wage labor, mainly by the children of the poor or orphans. They were predominantly employed in the labor-intensive export industries like the production of textiles and paper, but also pin-making and pipe-making for example. Leiden was infamous for its child labor in the textile industry, where thousands of orphans and children of poor families worked. Some were as young as six years old (van Nederveen Meerkerk & Schmidt, 2008, p. 720).

The contribution of children to the family income was crucial for survival. Among the poorest during the 17th century, 70% of children in Delft and 85% of children in Zwolle were put to work in the industrial sector (de Vries & van der Woude, 1995, p. 689-699; van der Vlis, 2001, p. 188; van Nederveen Meerkerk, Schmidt, 2008, p. 720). When during the late 18th century, the economy stagnated and unemployment plagued the lowest social classes, workhouses were created to aid poor families.

Differences can be attested in child labor depending on two parameters in general: social class and gender (fig. 10). During the 17th and 18th centuries, orphans and the children of the poor started working in the industries from a younger age, varying from six to nine years old (van Nederveen Meerkerk & Schmidt, 2008, p. 721-729). Exceptionally, historic sources indicate children could start working even younger. They were mainly employed in the high-demanding industries and crafts, their working days encompassing 10 to 14 hours. The gender division in these groups of young children was relatively limited (van Nederveen Meerkerk & Schmidt, 2008, p. 723-725). The majority were employed in low-skilled occupations in the textile industry, button-making and pipe-making. From the age of 14 and onwards a variety of occupations became available for boys, while girls' options remained limited to low-skilled jobs. Children of a higher social background entered the workforce at around 12 to 14 years of age. For boys this commonly entailed vocational training (van Nederveen Meerkerk & Schmidt, 2008, p. 731-732). Girls however, performed low skilled jobs that prepared them for married life like spinning, knitting or helping in the household or a trade.

Child labour in early modern times: a model

	From age 3 to 6	***From age 12 to 14***	
	Boys and Girls	*Boys*	*Girls*
Poor children	• *wage labour* • *sometimes a little general education*	• *wage labour* • *occasionally voca-tional education*	• *wage labour* • *household labour inside or outside the house*
Orphans	• *possibly tasks in orphanage* • *general education* • *sometimes wage labour*	• *vocational education* • *occasionally wage labour*	• *wage labour* • *household labour inside or outside the house*
Children of craftsmen/ shopkeepers etc.	• *possibly helping at home* • *general education* • *no wage labour*	• *vocational education*	• *sometimes wage labour* • *helping in trade, shop or household*

Figure 10: Model on child labor in the Dutch Republic from 1600-1800 (van Nederveen Meerkerk & Schmidt, 2008, p. 731, fig. 1).

When narrowing it down, it can be concluded that women and children contributed heavily to the family income. Regardless, they earned significantly less and had a lower social status in society. Divisions by social class and gender started early in childhood, strongly impacting the life-course of individuals. Social inequality had a massive impact on the health of the people (Haines, 2004, p. 249). Often the worsening of health correlates with the decrease of socioeconomic status. The deterioration of health was influenced by urbanization accompanied by densely packed buildings and unsanitary living conditions especially for the poor, growing commercialization and proletarianization – the appropriation of the means of production by a small group- leading to laborers being completely dependent on income, rising inequality, etc. (Alfani, Ryckbosch, 2016, p. 152; Haines, 2004, p. 249). The 17th to 19th centuries encompasses an interesting period in Dutch history spanning periods of social and economic prosperity and decline.

3.2. Arnhem

During the preindustrial period, Arnhem was a provincial town of medium size (Potjer, 2009, p. 17-24). The 18th century author Jan Wagenaar estimated that the town counted approximately 1100 to 1200 houses. Already by the 17th century, the open space in Arnhem was limited as the area within the city walls was densely built. For centuries the population level of Arnhem had remained constant (Vredenberg, 2009, p. 45). By 1818 a population increase took place that accelerated rapidly from 1850 onwards, making Arnhem the fastest growing town of its time within the Netherlands. This increase can be attributed to the construction of the '*Rhijnspoorweg'* in 1845, a railway connecting Arnhem with Amsterdam (Vredenberg, 2009, p. 35). In combination with the various large construction projects organized by the municipality, this expansion of the town's infrastructure generated new employment opportunities, attracting laborers to move to Arnhem (Vredenberg, 2009, p. 52). Consequently, these infrastructure works lead to a slight industrialization of Arnhem as more and more factories were built. Regardless of this, Arnhem still lagged behind due to the industrial component of its economy remaining rather insignificant by the middle of the 19th century (Klep, 2009, p. 141-144).

Arnhem's economy was during the 17th and 18th centuries primarily dependent on agriculture. During the 17th century, the town experienced turbulent times (Klep, 2009, p. 117). The connectivity of Arnhem was significantly impaired as a result of the Eighty Years War and the silting up of the Rhine. The export industries and trade were deeply affected, consequently leading to a strong dependency on agriculture. The majority of capital was owned by the city's elites, mainly consisting of landowners and city officials, who barely invested in the industries that were essential for job creation. The majority of the population was made up of laborers living in poverty and insecurity (Klep, 2009, p. 135). Workers could not rely on a stable employment opportunity and had to jump from one job to another out of necessity.

These jobs were mainly in agriculture or construction on a day contract and as seamstress, spinstress, tobacco spinner, etc. The 17th and 18th centuries marked a period of strong social stratification (Klep, 2009, p. 117-118). The poor were mainly dependent on the goodwill of the elite, since there was almost no involvement of the government. This goodwill had significantly declined in comparison to the Middle Ages and the economic developments resulted in a strong division between the rich and the poor.

Examining the evolution of rye prices offers insight into the economic situation in Arnhem during the 17th to 19th centuries (fig. 11). The price of rye was fundamental for the city's population (Klep, 2009, p. 119-120). Low prices were beneficial to Arnhem's working class, enabling them to divert money for other necessities like soap, clothes and shoes . Conversely, when prices were high, the majority of their wage went on food and survival.

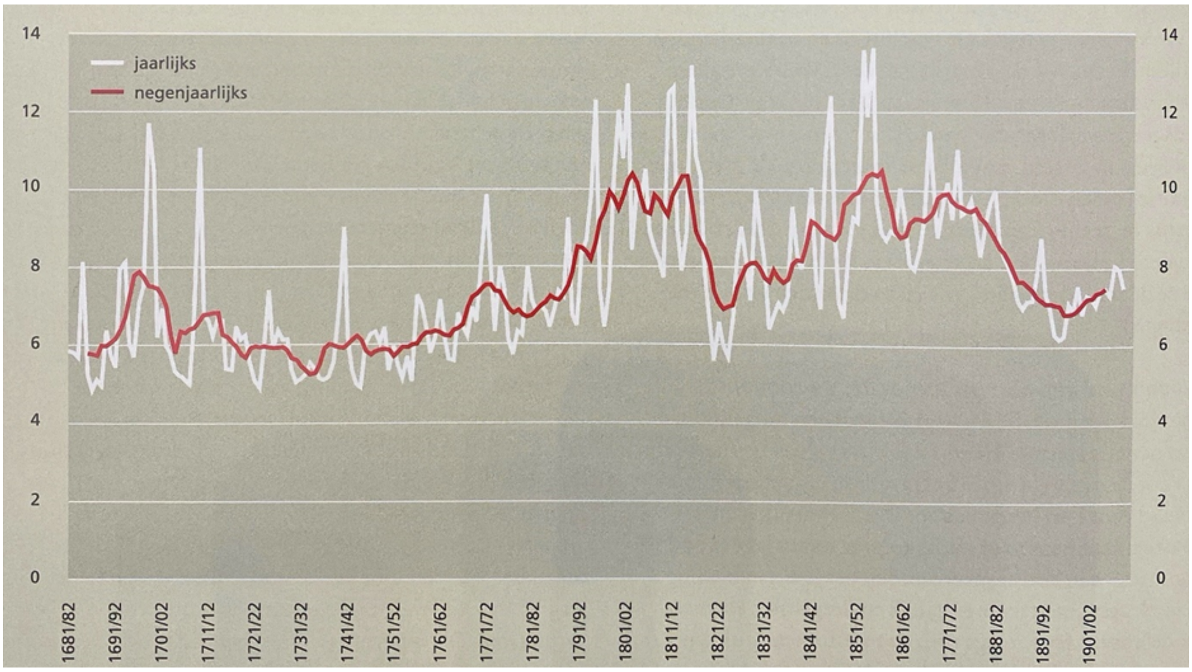

Figure 11: Evolution in rye prices from 1683-1909 in Arnhem (yearly average in white and nine-yearly average in red) (Klep, 2009, p. 120).

During the first half of the 18th century, the prices were low for an extended period of time causing trouble in the agricultural sector. With Arnhem being an agrarian center, this resulted in widespread poverty and unemployment among both farmers and laborers (Klep, 2009, p. 119-120). The situation changed in the last quarter of the 18th century to the early 19th century when a steep rise in the price of rye occurred. Thus, leading to a profitable period for farmers and landowners fueling the growth of the industries. However, the majority of the population suffered from stagnant wages resulting in an increase in poverty among the working class. It is only from the late 19th century that workers start to experience some prosperity when rye prices decreased and the wages started to rise (Klep, 2009, p. 152). Certainly, up until then the contribution of the whole family to the family income was essential. Both women and children -from a young age- worked to provide for the family.

An examination of the social and economic developments showed how omnipresent poverty was amid the lower social classes during the 17th to 19th centuries in Arnhem. The working-class population experienced appalling conditions, living in expensive single room houses in small and hidden alleyways where daylight barely protruded (Klep, 2009, p. 98-100; p. 152-153). The living conditions in these houses were extremely unsanitary, no plumbing was present, and the disposition of feces happened in the streets. The alleys contained no drainage system and with heavy rainfall waste water would run into the houses. In these neighborhoods potable water was hard to find as most bodies of water were contaminated. All of this facilitated the outbreak and spread of diseases, namely smallpox and cholera. During this period, the government did not provide any protection or was actively involved and the poor were mainly left on their own (Klep, 2009, p. 98-100).

3.3. Zwolle

Zwolle was one of the three capital cities of the province of Overijssel (ten Hove, 2005, p. 264; p. 20). The town was beneficially situated between the rivers *Ijssel* and *Vecht* and profited greatly from its trading connections with Amsterdam and Germany (ten Hove, 2004, p. 280). This resulted in a prospering city with a population of around 11.000 to 13.000 inhabitants during the second half of the 17th century (ten Hove, 2004, p. 290-292). Fluctuations in the number of inhabitants during this century were mainly caused by a high mortality rate due to epidemics of infectious diseases like the plague, typhus and smallpox and a high migration rate. The labor market and higher chances of employment were the most likely pull factors of migration, which mainly consisted of the lower classes. This is evident from the rise in demand for small single room houses. Another important demographic variable is birth rate, however it is unlikely that the number of births was able to compensate for the number of deaths.

During the 18th century Zwolle's population level remained stagnant with around 12.000 inhabitants (ten Hove, 2005, p.364). From 1830 onwards the population started to increase again and by the mid-19th century an increase of 45% took place compared to the previous century with Zwolle now counting 17.710 inhabitants (ten Hove, 2005, p. 409-410). This rise in the population level was mainly due to an excess of births while migration to the city was limited. Child mortality remained high, one in five infants did not survive their first year of life and it was only from the age of ten years onwards that children's chances of survival became less uncertain.

Economically, Zwolle benefited immensely from its strategic position as a transit point for long-distance trade between the province of Holland and Germany. (ten Hove, 2004, p. 280-282). Moreover, the regional market played an important role with the largest guild of the city consisting of retailers and shop owners. However, more employment opportunities were found in the local industries of the city (ten Hove, 2004, p. 284-285). In this sector as well, the guilds retained an important position during the 17th century, uniting most artisans like bakers, weavers, tailors and shoemakers and smiths. This unification provided more political power and an enhancement of their social status. The manufacturing of linen was one of the most important industries in Zwolle (ten Hove, 2004, p. 287). The weaving process was mainly carried out at home by women and children. During the first half of the 18th century, more than half of the male household heads were employed in the local industries while 9% worked in agriculture (ten Hove, 2005, p. 353).

By the middle of the 18th century the economy became stagnant and started to fall back in the second half. The long-distance trade transiting in Zwolle decreased which had a profound effect on everyone employed in the trade and seafaring sector (ten Hove, 2005, p. 359-361). Landowners were spared but the economic turmoil affected the general population significantly. In the 1770s multiple failed harvests lead to food shortages and the unemployment rate rose, leading to more and more people falling into poverty (ten Hove, 2005, p. 376-378). This turbulent economic situation continued into the 19th century. The trade routes between Germany and Holland with Zwolle as a transiting point had completely collapsed causing a further decay of the city's trading and exporting sectors. (ten Hove, 2005, p. 415-419). The disappearance of international trade was paired with the booming of regional market trade. During the 18th and early 19th centuries, the industries and crafts remained stagnant and were dominated by small businesses. The textile, button-making and paper producing industries suffered immensely due to international competition (ten Hove, 2005, p. 419-421). Many businesses struggled to make ends meet and no new industries nor factories settled in Zwolle by the middle of the 19th century. Unemployment was rampant and widespread pauperization took place, causing a further deterioration of the quality of life (ten Hove, 2005, p. 422-423). Around 10% of the city's inhabitants were dependent on poor relief in 1820. An analysis of the housing situation shows that the majority of people lived in small, often single-roomed houses (ten Hove, 2005, p. 293). These functioned as combined living- and working rooms for the whole family. Sometimes people even lived underground in basements they rented.

Even though from the late 18th century Zwolle's economy went through turbulent times, many people were also spared from pauperization. The higher social classes faced a different reality. This is visible in the archaeological record for example, where the amount of people being buried inside the church, a marker of high social status, increased during this period (van

Oosten, 2019, p. 158). The well-off could be found living in nicer houses with multiple rooms, situated in the main streets of the city, offering impressive views to visitors of the town. Entrepreneurs often lived in houses bordering their shops or workshops, sometimes renting out single rooms to poor families (ten Hove, 2005, p. 292-296). Post-medieval society was characterized by high inequality rates offering sharp contrasts in quality of life.

In general, this historic contextualization shows a vastly different lived reality between people from high and low socioeconomic classes. These differences in their environment might have led to different factors influencing their vitamin D intake, both through dermal synthesis or through diet. It will be studied in the following part, if these varying lifestyles, influenced by socioeconomic status, resulted in different rates of rickets prevalence between classes. Paleopathological analysis can contribute to our understanding of the lived experiences of people. For this purpose, two populations from varying social status from Arnhem and Zwolle will be analyzed. The archaeological context of these populations will be focused upon in the next chapter.

Chapter 4: Materials and Methods

In this chapter, the two populations selected for a comparative analysis will be discussed. As mentioned in the introduction, these sites consist of Zwolle, a high-status population, and Arnhem, a population with a low social status. After having gained more background information on the historical context of both cities and the Netherlands in general, the archaeological context will now be discussed. In a first part, the sample will be contextualized by giving background information of both cemeteries. Furthermore, the sampling strategy with the chosen selection criteria will be detailed. In the second part of this chapter, the methods employed during the paleopathological analysis will be discussed. The analysis consisted of two main parts: age-at-death analysis and an analysis of the presence of rickets. The used aging methods and criteria for rickets diagnosis will be discussed in this part. Finally, the chosen statistical analyses will be argued.

4.1. The sample

4.1.1. Arnhem

Starting in 2017, excavations were carried out in the grounds of the cemetery north of the Eusebius Church in the historical center of Arnhem (Zielman & Baetsen, 2020, p. 3; p. 83). Within the cemetery, three clusters of burials could be distinguished. Around the tower of the church 22 graves were found. Furthermore, a street called the '*kerkstraat'* runs perpendicular to the cemetery and divides a zone of four graves to the west and of 621 graves to the east (fig. 12). In total 647 graves containing 659 primary burials were excavated. (Zielman & Baetsen, 2020, p. 83). When considering the chronology, two periods of burials were distinguished by the researchers. The first period started approximately around 1350 and ended around 1650 when the plague epidemic took place and the cemetery was closed (Zielman & Baetsen, 2020, p. 101). After 1650 the cemetery was used again until 1829 when the last individual was buried there.

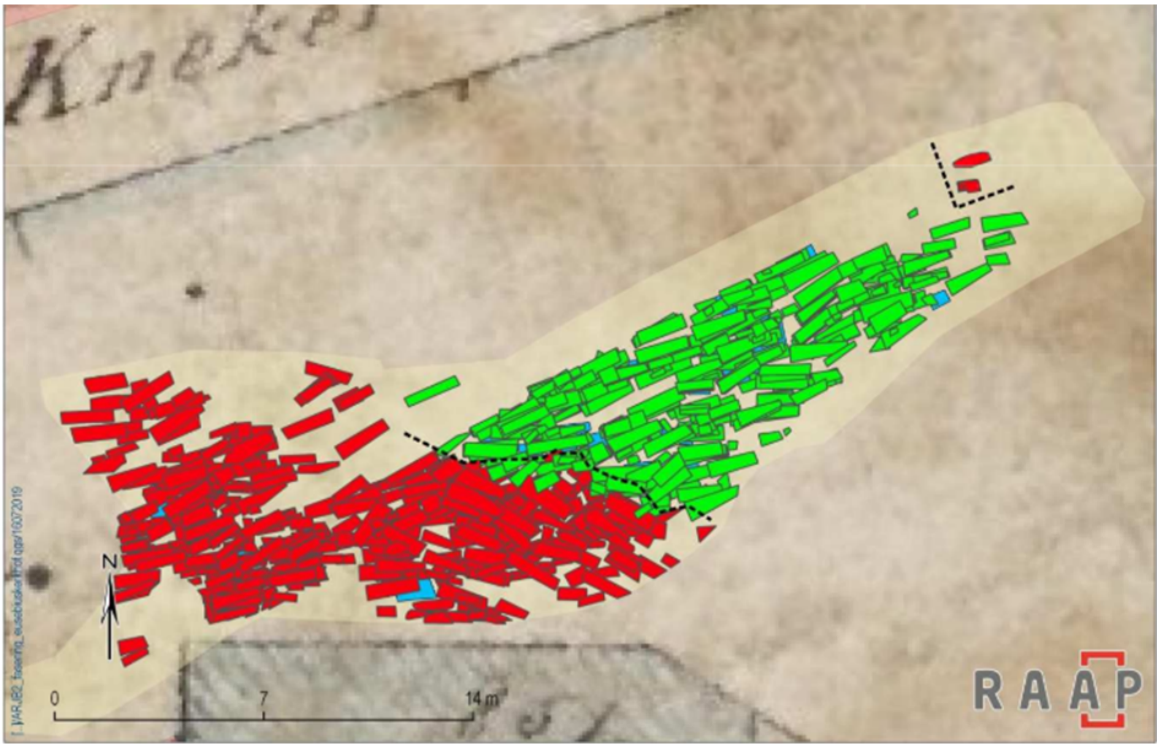

Figure 12: Chronology of the graves east of the '*Kerkstraat'* in the Eusebius Church' cemetery, the graves indicated in red date from the period 1350-1829 AD and the graves indicated in green date from 1650-1829 (After Zielman & Baetsen, 2020, p.100, fig. 63).

Extensive cemetery research carried out in the Netherlands has shown that the location of graves can offer information about the social status of the individuals buried there (Van Genabeek, 2018, p. 174, van Oosten, 2019, p.155). A combination of both historical and archaeological sources indicates that the north side of the church was the least favored position by the people. It was often referred to as the "cold" or the "cursed" side, since the sun would never shine upon these graves (Grolman, 1923, p. 388; van Oosten, 2019, p. 155). This phenomenon is witnessed in the St John's churchyard in 's-Hertogenbosch during the 18th and 19th centuries (Portegies, 1999, p. 178-185; van Oosten, 2019, p. 161). Within the churchyard, the southside of the church was the most prestigious. This was reflected in the price as it was three times more expensive to be buried in the south than in the northeast. Historical sources also attest to the existence of this belief in the province of Drenthe (van Oosten, 2019, 156; Grolman, 1923, p. 388).

The studied population of the Old Cemetery of the Eusebius Church in Arnhem was excavated from the northern part of the cemetery. This burial location suggests that the graves housed individuals of low socioeconomic status (Baetsen & Zielman, 2020, p. 687). Archival data confirmed that some of the people buried in the cemetery of the Eusebius church were of the lowest social status. The death records of Arnhem from the middle of the 18th century show that if the individual did not have the means to afford a burial, the Eusebius Church would offer support.

In this case they were referred to as 'Diaconate death' (Baetsen & Zielman, 2020, p. 686; Geldersarchief, DTB-register 0176/180, p. 47). Another sign of a lower social status of the buried is the layout of the cemetery. The burials in the northern section of the cemetery are characterized by a more haphazard layout of the burial grounds and the frequent superposition of graves, as seen in fig. 12. This pattern is also found in other Dutch cemeteries. The excavation of the northern side of the St John's churchyard in 's-Hertogenbosch has shown that up to five individuals could be buried on top of each other as a result of the lower price of these plots (Van Genabeek, 2018, p. 174, van Oosten, 2019, p. 162). In some areas there were even communal graves where multiple burials were placed in one pit, probably reserved for the poorest of society.

In this thesis, burial location is used as the main reliable indicator of socioeconomic status in the Arnhem population. Based on the location of these graves in the north end of the cemetery combined with the results of the conducted historic research of Arnhem's economic context, it is assumed that this population belonged to the lower class consisting of unskilled laborers.

For this research the Arnhem sample was defined based on a few important factors. Firstly, the individuals needed to be in storage at the laboratory for Human Osteoarchaeology of Leiden University to be accessible. Of the 659 burials, 511 individuals were loaned to the osteology laboratory for further research (Baetsen & Baetsen, 2020, p. 362). Secondly, the sample was limited to subadults based on the research questions. Analysis has indicated that around 159 of these 511 individuals were subadults, meaning they were below the age of 18 years old when they passed (see infra). Furthermore, while the occupation period of the cemetery stretches from 1350 to 1829, the focus of this study will be on the post-medieval period. In order to carry out an accurate comparative analysis, the subadults from the second period of the cemetery dating from 1650-1829 will be included. In order to accurately diagnose rickets, a certain preservation rate was needed. These selection criteria are further elaborated on in 3.1.3. After elimination, the Arnhem sample contained 53 individuals in total.

4.1.2. Zwolle

In 1987-1988 excavations took place in the church the "*Broerenkerk*" ("Brother's church") in Zwolle as new renovations were threatening the graves located in the church and their archaeological context (Aten, 2002, p. 13). The excavation trenches spanned the whole ground plan, covering the three construction phases of the church (fig. 13). The different research areas were primarily chosen based on the location of the tombstones (Aten, 2002, p. 17). During this field campaign 168 graves were excavated of a total of 559 graves present in the church (Aten, 2002, p. 22-23). It resulted in the detection of 529 individuals and more than 500 human remains that could not be tied to a specific individual.

This commingling of remains occurred when graves were cleaned out for new generations (Aten, 2002, p. 29). Each grave contained three layers of burials with more or less one individual (Aten, 2002, p. 24-25). When a grave was cleaned out, the resulting human remains were brought to an ossuary or buried collectively below the grave.

Since the focus of this study is an analysis of the possible effects of socioeconomic status on rickets prevalence, the status of the Zwolle sample had to be established. The importance of the location of burial and its link with social status has already been discussed, namely within the churchyard. The most prestigious burial location however was in the church itself, showing that the population of Zwolle buried in the *Broerenkerk* was of a high socioeconomic status, especially compared to the Arnhem population (van Oosten, 2019, p. 158). Another important indicator of status in the Zwolle sample is archival data. The archives show the occupation of deceased adults buried in the church. Two main societal groups can be distinguished, on one hand the middle to higher middle class including captains, second lieutenants, teachers, carpenters, smiths, bakers, shop owners, handmaidens, etc. And on the other hand, the upper class consisting of pensioners, merchants and officials. Showing the population buried here were self-employed/skilled workers likely belonging to the middle class of Dutch society and a subset belonging to the elites of the city (Van Bavel, Kok, 2004, p. 128).

The existence of a death register stemming from the period of 1819-1828 made it possible to identify certain individuals, adding to the importance of the excavation (Aten, 2002, p. 13). After the identification process, the 529 individuals were divided in two groups (Aten, 2002, p. 29). One containing the 141 individuals from the period 1819-1829 that were identified based on the death register. A second group of 388 individuals that were broadly dated based on stratigraphy to a period stemming from 1675 to 1819. A third group consists of the commingled remains of around 500 more individuals possibly spanning the whole period of the 17th century until 1828.

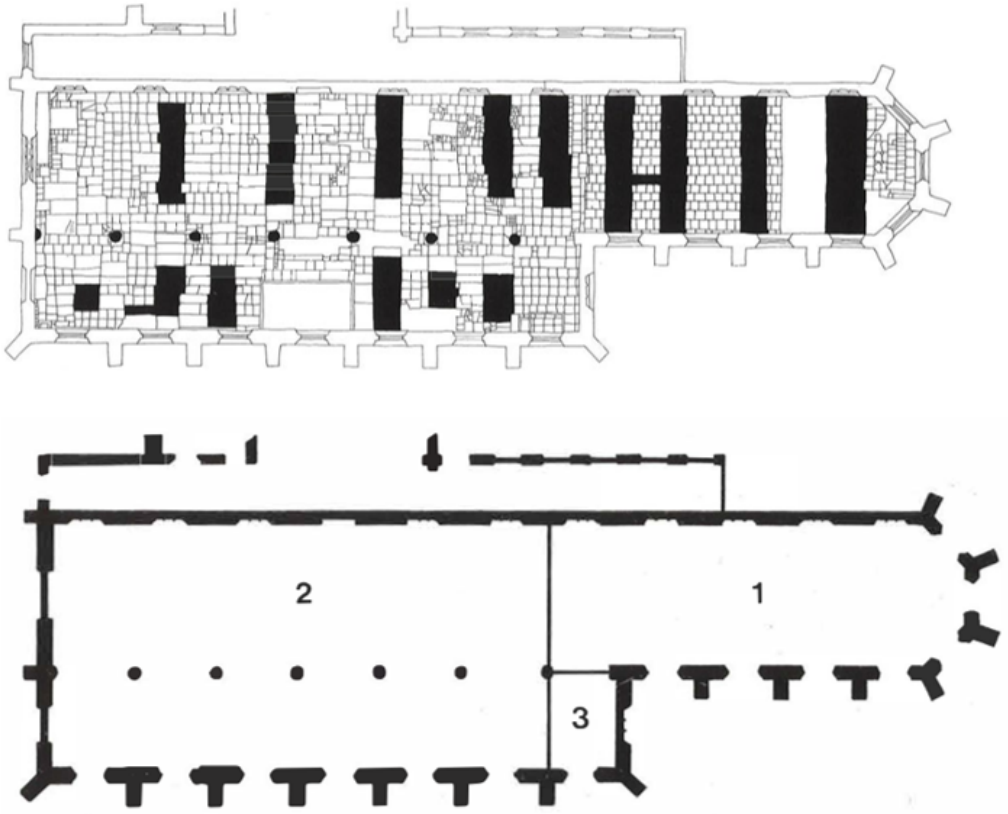

Figure 13: Ground plan of the *Broerenkerk* showing the trenches in black (top) and the 3 construction phases (bottom) (After Aten, 2002, p. 14-16).

The collection available in storage at the laboratory for Human Osteoarchaeology of Leiden University stems mainly from the first group of individuals identified based on the death register from the period 1819-1829. Around 73 subadults were present in this collection. The selection process was just like in Arnhem based on availability of the collection, age and preservation, which will be further elaborated in this chapter. After excluding individuals that were not available for the paleopathological analysis of rickets, the sample included 30 individuals.

4.1.3. Selection criteria

Not every individual from the cemetery samples was available for the analysis of rickets. Therefore selection criteria ware employed to create a sample including every individual that could be analyzed for the disease. The first important criterium was age. Rickets is a childhood disease that rarely develops before the age of 4 months (Brickley & Mays, 2019, p. 541; Maiyegun et al., 2002). Therefore, individuals below four months old were excluded from the study. It is possible that rickets appears in infants below this mark and is the result of vitamin D deficiency in the mother. Since vitamin D levels of the fetus *in utero* are dependent on the mother, it is possible that babies are born with neonatal rickets (Levene, 1991; Patterson &

Ayoub, 2015, p. 793). These congenital conditions are rare and therefore not likely to be detected in the archaeological record.

It is expected that manifestations of rickets in the skeleton are due to the inadequate production of vitamin D in the skin influenced by exposure to the sun and by insufficient diets to a lesser extent (Brickley et al., 2014, p. 48, Ortner & Mays, 1998, p. 46; Veselka, 2019, p. 14-19). Since rickets occurs as a result of vitamin D deficiency in childhood, adults were excluded. The upper age limit is set at 18 years old to only include subadults in the sample.

The second important criterium is the preservation of bones. Within paleopathology preservation has always been a key aspect of research methodology. Traditionally, efforts were often concentrated on well preserved skeletons as it was assumed that more information could be gathered from these individuals (Brickley et al., 2014, p. 52-54). However, pathologies often result in deterioration of the skeleton. When suffering from a vitamin D deficiency, skeletons are more susceptible to poor preservation as difficulties with the mineralization of osteoid arise. A study of a post-medieval population from St. Martin's in the UK (Brickley et al., 2006) has shown individuals with vitamin D deficiency also had a worse preservation. Therefore, it is important to not only include well preserved skeletons in paleopathological studies in order to get an accurate representation of the disease within a population. Common manifestations of the disease can be obscured by or hard to distinguish from post-depositional processes (Mays et al., 2006, p. 362-363).

For this study a selection was made based on preservation to make sure that an accurate recording of the presence of vitamin D deficiency was possible. Since the disease generally affects the long bones, the presence of the upper or lower limbs depending on age, was a deciding including factor in the study. For individuals younger or equal to two years old there had to be a minimum of one femur or one humerus present. This age category covers the period where infants are crawling and learning to walk. As a result, mechanical forces are more likely to affect the arm bones and the femur.

For all individuals older than two years old there had to be at minimum one femur or tibia present. After the age of two years it was assumed that every individual was walking and as a result the lower limbs would be most likely to be affected by bending deformities. Especially the femur and tibia seem to be the most indicative bones in the lower leg based on a study of a British population from Birmingham in the 19th century (Mays et al., 2006, p. 362). In this British population bending deformities were three times more common in the lower limbs than in the upper limbs. The fibula was the least likely to be affected and both the femur and tibia showed similar rates. In addition, metaphyseal flaring was the most likely to occur in the femur and the tibia (Mays, et al., 2006, p. 365).

When looking at the individual bones, all stages of preservation were as much included as possible to gain the most accurate representation of reality. Generally, a high rate of preservation is necessary to be able to distinguish lesions (Mays et al., 2006, p. 363). Difficulties arise when growth plates and metaphyses are (almost) completely eroded or large parts of the bones are not preserved. In some individuals the bones were too damaged by taphonomic processes to gather any information. When this was the case for all long bones that were present, they were excluded from the study. In total, 83 individuals met the criteria and were included in the sample.

4.2. Methods

The following part will detail the methodologies used in this study to carry out the age-at-death estimation and rickets analysis.

4.2.1. Estimation of the age at death

First, the age at death of each individual was estimated using a combination of methods that are based on the development of the skeleton. The main methods for ageing subadults as accurately as possible are based on dental development. The following three methods were used:

- Demirjian et al. (1973) for age assessment based on development of deciduous teeth.
- Moorrees et al. (1963) and Harris and Buck (2002) for age assessment based on development of permanent teeth.
- AlQahtani et al. (2010) method for age assessment based on dental eruption.

When individuals had one or more deciduous teeth, these were analyzed using the method established by Demirjian *et al*. (1973). By comparing each tooth with the dental formation stages established in this method, the age of the individual can be estimated. Additionally, the permanent teeth of every individual were also assigned a formation stage based on the method of Moorrees et al. (1963) adapted by Harris and Buck (2002). Lastly, the results of all teeth of each individual were combined and compared to a dental eruption chart developed by AlQahtani et al. (2010) to age the individual. The overall age estimates from each method were combined to come to the final age estimate for each subadult. See appendix 1 for all charts used for age estimation based on dental development during this study.

In case of poor preservation resulting in the teeth being unobservable, a combination of the following methods was used to determine age at death:

- Measurements of bones: Maresh (1970) for length of long bones, Black and Scheuer (1996) for the clavicle length and Molleson and Cox (1993) for the ilium length.
- The stage of bone fusion: Schaefer et al. (2009)

First, all the bones of an individual that were available for age estimation (e.g., long bones, clavicle and the ilium) and were preserved, were measured. These measurements were then compared to the measurements from reference collections carried out by Maresh (1970), Black and Scheuer (1996) and Molleson and Cox (1993). Additionally, the same bones, if their state of preservation allowed it, were analyzed for their stage of fusion.

The individual age of each subadult in the sample was registered, in addition the individuals were assigned to age categories of one year starting from the category "4mo-1yr old" until "18yrs old" (see appendix 1). These age categories were used to facilitate a better overview and an accurate comparison to other studies done in the Netherlands. Other frequently used divisions in bioarchaeology, that will be used in the following chapters, are: infant (birth-2yrs), child (3-6yrs), juvenile (7-12yrs), adolescent (13-17yrs). As previously mentioned, individuals younger than four months old and older than 18 years old were excluded from the sample.

4.2.2 Estimation of rickets

After the age-at-death assessment, a subsequent macroscopical examination for the presence of rickets was carried out within the samples from Arnhem and Zwolle. When analyzing individuals for rickets, it is important to not only focus on the most recognizable deformities like bending of the long bones but also to carefully consider more subtle alterations. Otherwise, the risk of missing, for example, milder forms or infantile rickets grows. For this reason, a diagnosis will be based on multiple features. One feature alone cannot be considered a diagnostic trait of rickets, however combined they make a tentative diagnosis possible. Differences in severity of the disease and age of the individual result in variation of the expression of lesions and in variation of the bones affected (Brickley & Ives, 2008, p. 99).

In this thesis the selection of the analyzed features was based on the criteria established in leading studies by Ortner and Mays (1998, p. 40) and expanded by Brickley and Ives (2008, 103-105). Furthermore, they were streamlined with the criteria employed in the studies by Veselka, Hoogland and Waters-Rist (2015) and Veselka, Brickley and Waters-Rist (2021) that focused on rickets prevalence in the Netherlands. This way a more accurate comparison of the results of Arnhem and Zwolle with other cities in the Netherlands could be carried out.

The following 14 pathological lesions were studied in the populations from Zwolle and Arnhem (see table 3). Some traits were grouped together for more clarity. Long bone growth plate deformities correspond to porosity, cupping deformities and fraying bone margins of the growth plate. Long bone metaphyseal deformities include flaring and swelling but also porosity and irregularity of the cortex. Pelvis deformation circumscribes concavity of the ilium and previously mentioned *protrusio acetabula.* Lastly, cranium abnormalities include craniotabes, frontal and parietal bossing, delayed closure of fontanelles and thinning.

Table 3: List of macroscopic features used to assess rickets.

Macroscopic features of Rickets	
Cranial vault porosity	Long bone metaphyseal deformities
Orbital roof porosity	Bending of upper limbs
Angulation of ramus	Bending of lower limbs
Flared/thickened costo-chondral ends of ribs	Thickening of long bones
Cortex of costo-chondral ends of ribs irregular and porous	Angulation of neck femur (*coxa vara*)
Long bone growth plate deformities	Pelvis deformation
Cranium abnormalities	Long bone concave curvature porosity

A scoring form was created for every individual where the presence of each lesion was recorded either as present, absent or unobservable (see appendix 1). Features were considered unobservable if the state of preservation had made it impossible to observe said feature. In order to diagnose rickets at least three features had to be recorded as present or, in case of a bending deformity one other feature had to be present, conforming to Veselka, Hoogland and Waters-Rist (2015). It was important to move away the focus from only bending deformities to be able to register all forms of vitamin D deficiency, especially the mild ones. Furthermore, in case of infantile rickets the expression of the disease can be more subtle and oftentimes bending deformities of the long bones would not have been able to develop yet.

This method was set in place to detect all variations of rickets as robustly as possible and to make comparison of the results with other studies from within the Netherlands possible. However, a case-by-case approach was also employed as not all features carry the same weight. Some lesions can be attributed to a plethora of disease, for example orbital roof porosity is considered a non-specific stress marker. If in one case, three features are present, but they consist of only porous lesions, for example cranial vault porosity, orbital roof porosity and porosity of long bone metaphyses, this individual cannot be diagnosed with rickets.

4.2.3. Statistical analysis

The results of the data collection were compiled in a database and subjugated to statistical analysis. However firstly, after registration the crude prevalence of rickets was calculated for each population by using the following formula:

$p = n/N \times 100$

In this case p is the prevalence, n is the number of individuals where rickets has been diagnosed and N amounts to the total number of examined individuals of the population (Keiding, 1991, p. 371; Waldron, 1994). In order to make an analysis between populations more accurate age-specific rates were looked at for comparison. Since the crude prevalence of the disease is influenced by age, the prevalence of rickets was calculated for each age group to exclude the erroneous factor of age. Subsequently, the results per age group were compared between both sites.

In order to assess whether a relationship exists between prevalence of rickets and socioeconomic status a statistical analysis was carried out. Socioeconomic status as a variable was based on which site the individuals came from. Rickets prevalence is based on the number of individuals that were diagnosed with rickets. A Pearson's $\chi 2$ -test for independence was employed to see if differences in rickets prevalence between Arnhem and Zwolle were statistically significant. This way it was tested whether the variables status and rickets prevalence were independent of each other or whether there was an association (Peacock & Peacock, 2011, p. 262, 274). The test compares the observed frequencies of the variables to the expected frequencies under the assumption that there is no association. If the observed and the expected frequencies differ significantly, an association exists between the two variables (Peacock & Peacock, 2011, p. 262). The test will calculate the p-value to determine the strength of the association. If the p-value is lower than 0.05, the association is statistically significant. In short, the relationship between socioeconomic status and rickets prevalence will be considered statistically significant if the p-value is below 0.05. The statistical tests were carried out in the Spyder programming application by writing a code in the Python language.

4.2.4. Ethical considerations

In this study, the human remains of two communities were analyzed in order to gain insight into their lived experiences and the way they interacted with their environment. With the act of handling human remains should always come a careful consideration of ethical concerns. Every skeleton represents a once living person, therefore it is important to safeguard the human integrity of all human remains, both physical and personal (Kreissl Lonfat et al., 2015, p. 1176-1177). During the paleopathological analysis, the physical integrity of each individual was protected by handling the remains with respect and by minimizing possible harm. The human remains were studied in the protective environment of the osteological laboratory and only handled with the purpose of scientific progress. Furthermore, every analysis conducted was non-destructive.

Ethical considerations do not only apply during analysis but also after when for example reproducing the results. The skeletal manifestations of rickets were recorded with photographs specifically for the purpose of this thesis. These images were not spread or shared in any other way. Furthermore, the communities studied in this thesis stem from relatively recent times, as a result it is possible that living relatives exist. Out of respect, all individuals are anonymized in the following description of the results and the discussion.

Chapter 5: Results

The results of the analyses conducted on the archaeological samples from Arnhem and Zwolle will be detailed in this chapter. The first sub-chapter will entail the results of the age-at-death analysis and rickets analysis, so the age distribution of the affected individuals both populations can be studied. Knowing the age distribution of the affected individuals will then enable the study of environmental factors that may have influenced their vitamin D status. Furthermore, the results of the statistical analysis of the possible relationship between rickets prevalence and socioeconomic status will be described. In the second part of this chapter, the individuals affected with skeletal manifestations of rickets in both samples will be described.

5.1. Age distribution and rickets prevalence

5.1.1. Arnhem

The Arnhem sample contained 53 individuals varying from 4 months to 17 years old. Figure 14 shows a graph detailing the age distribution of the studied subadults and the number of individuals affected with rickets per age category. All age groups were represented in the sample with one exception, no individuals of 10 years old were detected. In total 18 subadults (34%) were below two years old (infants) around their time of death. Table 4 presents the number of individuals with rickets and the prevalence of the disease in the different age categories. In total four cases of rickets were recorded in the Arnhem sample, resulting in a crude rickets prevalence of 7.6%.

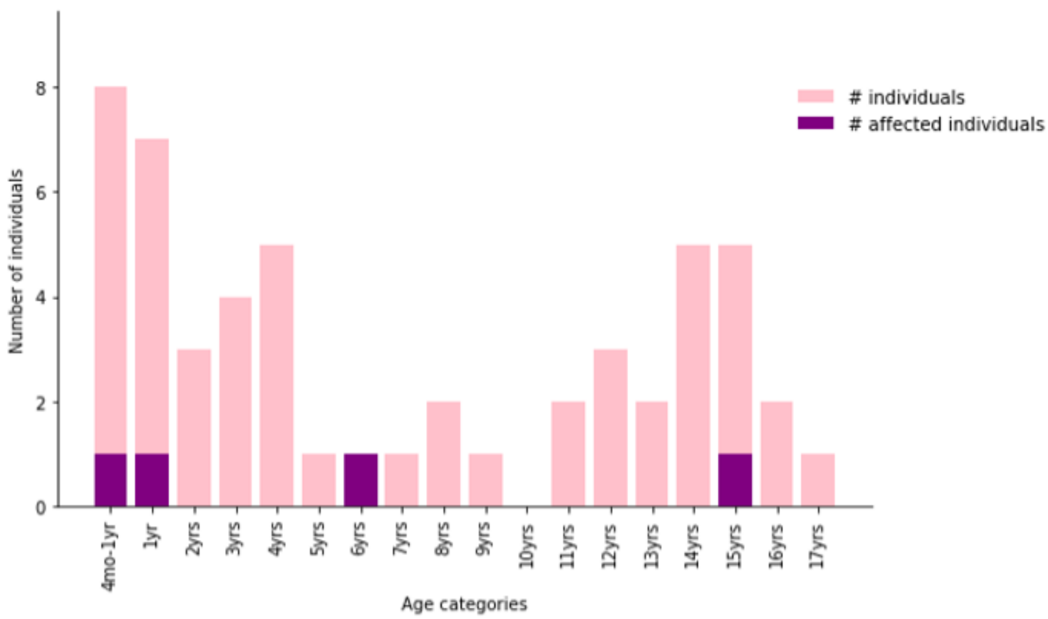

Figure 14: Number of individuals affected with rickets per age category in Arnhem.

Table 4: Rickets prevalence in four age groups from Arnhem.

Age category	Number of individuals examined	Number of individuals with rickets	Prevalence
4mo-1yr	8	1	12,5%
1yr	7	1	14%
6yrs	1	1	100%
15yrs	5	1	20%

5.1.2. Zwolle

The Zwolle sample consists of 30 individuals ranging from four months to 14 years +- 2yrs old. Figure 15 shows the age distribution of the Zwolle sample. Compared to Arnhem, the share of infants was substantially larger in Zwolle with 22 subadults, or 73% of the sample, being around two years old or younger. When considering rickets, four cases of rickets were detected and categorized with a 'yes' in the Zwolle sample. One other individual was diagnosed with a possible case of rickets. The prevalence of rickets for each age group where the disease was diagnosed is presented in table 5. The crude prevalence of rickets in the sample from Zwolle is 16.7%.

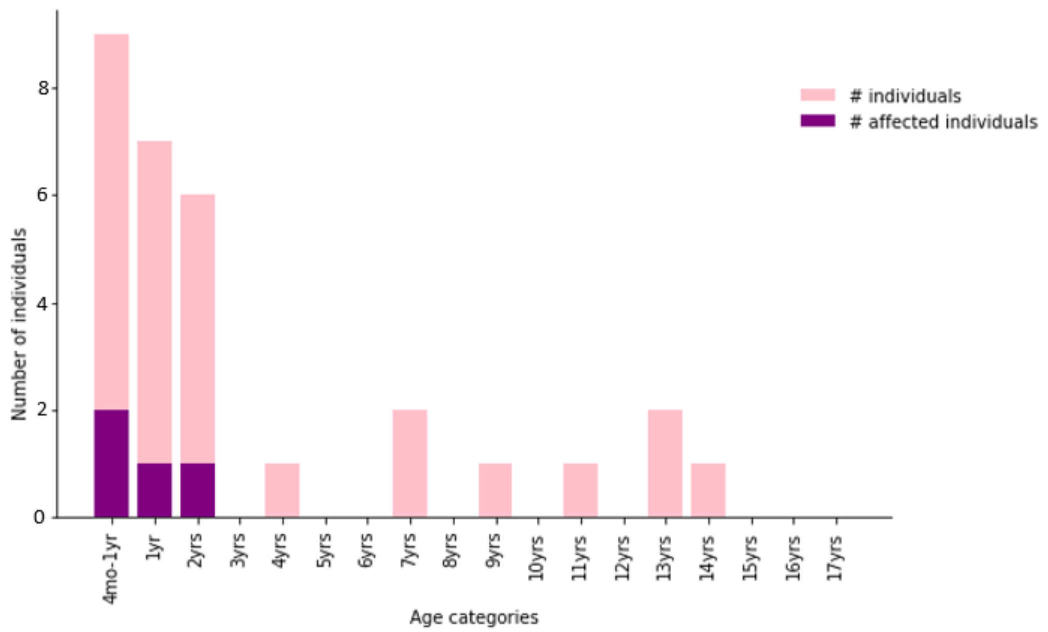

Figure 15: Number of individuals affected with rickets per age category in Zwolle.

Table 5: Rickets prevalence in three age groups from Zwolle.

Age category	Number of individuals examined	Number of individuals with rickets	Prevalence
4mo-1yr	9	2	22%
1yr	7	1	14%
2yrs*	6	2	33%

*Including the one possible case of rickets

5.2. Rickets prevalence and socioeconomic status

To establish whether a statistically significant relationship exists between the prevalence of rickets and socioeconomic status, a Pearson's $\chi 2$ -test for independence was carried out.

When considering the crude prevalence which was 16.67% in Zwolle and 7.55% in Arnhem, no statistically significant association exists in rickets prevalence between Arnhem and Zwolle ($\chi 2=2.61$, $p=0.27$). However, there is variation in the results as Zwolle has more than double the crude prevalence of Arnhem. Interestingly, more individuals were affected by the disease in the high-status population of Zwolle than in the low-status population of Arnhem. This trend is continued in the age group of '4mo-1yr' olds with 22% versus 12.5%. The majority of cases fall into this age category, that makes up 33% of all individuals affected with rickets. For one-year olds the same prevalence is registered between populations, while for the two-year olds Zwolle has a prevalence of 33% compared to 0% in Arnhem. The prevalence of rickets in infants (i.e. subadults around or below two years old) was also calculated since incidence of the disease tends to be highest in these age groups, resulting in a rickets prevalence of 11.1% for Arnhem and of 22.7% in Zwolle. It has to be noted that 77.78% of all individuals affected by the disease are infants from 4months to around 2 years old. The other age groups are not directly eligible for comparison since the categories of 6yrs and 15yrs are not represented in Zwolle.

5.3. Description of rickets cases

5.3.1. Arnhem

V0556

Individual V0556 was an adolescent of around 15yrs +- 2yrs old. Manifestations of rickets were detected on the lower limbs and the pelvis. Both the left and right femur are affected, with flared and swollen proximal and distal metaphyses. Especially, the neck of the right femur shows marked swelling with microporosity on the superior surface running to the inferior surface of the proximal metaphysis. Furthermore, the head is less medially inclined and angled more to the anterior side (fig. 16). The same phenomenon is witnessed on the left femur where the head is angled more anteriorly paired with slight *coxa vara* (fig. 16). The two tibiae display swelling and flaring of the proximal metaphyses paired with medial bending from the midshaft to the proximal metaphysis causing the tibial plateau to be angled laterally. Additionally, the fibulae show slight medial bending at the midshaft area. The features on both os coxae consist of thickening of the ilia with exaggerated medio-lateral curvature. There is a deformity of both acetabulae as they are angled more anteriorly than usual (fig. 17).

Moreover, the lunate surface is more flattened and the acetabular fossae are slightly deeper than normal. This is especially the case in the left os coxa, causing it to protrude into the pelvic cavity, this deformity is known as *protrusio acetabulae*.

Figure 16: (a) Both femora of individual V0556, especially note the flaring and swelling of the proximal metaphyses and the *coxa vara*. (b) the right femur of individual V0556 (left) compared to a non-rickets femur (right), the angulation and deformity of the neck are notable. (Photographs by Emma Vereecken).

Figure 17: (a) Left ox coxa of individual V0556 (right) with thickening of the ilium and exaggerated medio-lateral curvature. The arrow points to the *protrusion acetabulae* into the pelvic cavity, this area is notably less concave than in the non-rickets example (left). (b) Close-up of the deformity of the acetabulum of the right os coxa of individual V0556. (Photographs by Emma Vereecken).

V0821

Individual V0821 is an infant of 9mo +- 3mo old. Features of rickets were slight cranial vault porosity in the form of patches of irregular porous bone formation on the frontal bone, paired with slight *cribra orbitalia* in the right socket. Considering the long bones, the right femur showed flaring of the distal metaphysis and some slight porosity of the cortex around the growth plate. Both tibiae had flared proximal metaphyses with the right tibia showing very slight medial bending on the proximal portion of the shaft near the proximal metaphysis. The bending is subtle, but the bone exhibits an exaggerated curvature compared to the left tibia (fig. 18). These lesions indicate an active but probably early/mild stage of the disease.

Figure 18: Lower limbs of individual V0821 showing flaring of the distal metaphysis of the right femur and of the proximal metaphyses of the tibiae. The arrow indicates the slight medial bending of the right tibia. (Photograph by Emma Vereecken).

V1112

Individual V1112 was around 6yrs +- 0.5yr old at the time of its death. Only the right femur displayed lesions of rickets. Some porosis was present on the neck portion of the bone. Furthermore, there was anterior bending of the mid shaft to the proximal part of the shaft of the right femur (fig. 19). In the concave surface of the bending shaft, new porous bone had formed on the subperiosteal surface (fig. 20). This feature is associated with healed cases of the disease (Mays et al., 2006, p. 366).

Figure 19: Right femur of individual V1112 displaying anterior bending. (Photograph by Emma Vereecken).

Figure 20: Right femur of individual V1112 with the posterior side up. The arrows indicate the new porous bone formation on the concave side. (Photographs by Emma Vereecken).

V1777

Lastly, individual V1777 is around 1.5yrs ± 2mo old. The infant's ribs were strongly affected with flaring, pitting and fraying margins of the costochondral ends (fig. 21). The cortex of the sternal ends was irregular and porous. This individual also displayed strong deformities of the growth plates of the long bones. The left humerus was affected by extreme roughening of the proximal growth plate paired with porosis and extreme pitting. The proximal metaphysis was flared and swollen with fraying metaphyseal margins. The growth plates of both radii were marked by severe flaring of the distal growth plate, fraying margins and extreme roughness (porosis and pitting) (fig. 22). Heavy flaring and swelling of the distal metaphysis occurred while the cortex was irregular and porous. Both tibiae showed severe roughening of the distal growth plate (porosis and pitting). Furthermore, angulation of the distal growth plates occurred during severe deficiency, leading them to be tilted medially (fig. 22) (Brickley & Ives, 2008, p. 91). Additionally, the proximal and distal metaphyses were swollen.

Figure 21: Left ribs of individual V1777 showing signs of rickets like flaring, pitting and porosity of the cortex. (Photograph by Emma Vereecken).

Figure 22: (a) Both tibiae of individual V1777 showing angulation of the distal growth plate. (b) Left radius of individual V1777 displaying growth plate deformity (anterior side up). (Photographs by Emma Vereecken).

4.3.2. Zwolle

007

Individual 007 from Zwolle was around 2yrs ± 1yr old. The manifestations of rickets consist of strong deformities of the costochondral rib ends, including enlargement of the ends by fraying and swelling, but also cupping of the junction and an irregular and porous cortex (fig. 25). Both humeri showed fraying of the metaphyseal margins and marked porosis and roughening with slight cupping of the proximal growth plates (fig.23). The proximal and distal metaphyses of the humeri were swollen and had an irregular and porous cortex. Both the left and the right humerus showed lateral bending, which was more pronounced in the proximal part of the diaphysis. Frayed metaphyseal margins along with marked porosis and cupping of the growth plate were also attested in the right distal radius and ulna. Furthermore, the right radius had a flared and swollen distal metaphysis with a porous cortex (fig. 23). A slight latero-posterior bend of the central diaphysis was present. The left radius and ulna, along with the lower limbs of this individual were not preserved. Additionally, marked deformities of both the ilia were registered. The bones were plump and displayed an abnormal medial curvature (fig. 24; 25). Severe porosity was present on the iliac crest of both ilia. Lastly, slight *cribra orbitalia* in the left and right sockets could be remarked.

Figure 23: Upper limbs of individual 007. Note the lateral bending, metaphyseal swelling and growth plate deformities of the humeri. (Photograph by Emma Vereecken).

Figure 24: Left and right ilium of individual 007. (Photograph by Emma Vereecken).

Figure 25: (a) Left ilium of individual 007 showing abnormal curvature. (b) Left ribs of individual 007 displaying costochondral end deformities. (Photograph by Emma Vereecken).

103

This individual was an infant of 5mo ± 2mo old at the time of its death. Identification based on archival data was not possible. Features of rickets were visible in the costochondral rib ends with flaring and fraying, cupping of the junction and porosity of the cortex. The long bones were affected by growth plate and metaphyseal deformities. The left proximal humerus displayed slight flaring and porosity of the metaphysis. Porosis and cupping deformities were present on the proximal growth plate. The proximal and distal metaphyses of both ulnae were marked by high levels of porosity. The distal ulnar growth plates contained cupping deformities with slightly fraying metaphyseal margins. The two radii showed similar features of rickets, an irregular and porous cortex of both metaphyses with slight flaring of the distal metaphysis, and cupping of the distal radial growth plates with fraying metaphyseal margins. When considering the lower limbs, both femora displayed slight flaring of the distal and proximal metahphyses with fraying margins (fig. 26). Porosity of the cortex is present on the distal metaphysis and the neck of the femur. The proximal and distal growth plates were irregular and roughened, marked by porous lesions and cupping deformities. Additionally, the proximal end of the left tibia showed flaring of the metaphysis along with porosity and cupping lesions on the growth plate.

Figure 26: Lower limbs of individual 103. Note the flaring of the metaphyses. (Photograph by Emma Vereecken).

279

Individual 279 was 1yr ± 0.5mo old. The post-mortem damage of the skeleton, especially of the cortex and growth plates, is severe. However, features of rickets could still be analyzed. Firstly, cranial vault porosity was present in the form of irregular porous bone formation on the ectocranial surface of the occipital and parietal bones (fig. 27). The ribs displayed deformities of the costochondral ends including flaring and fraying of the ends with cupping of the junction. The cortex of the sternal ends was irregular and porous.

The two radii were heavily impacted by the disease in their proximal and distal ends. The margins of the junction between the distal growth plate and the metaphysis were fraying of both radii. The distal growth plates themselves were coarsened by severe porosity and cupping deformities. In the case of the right radius, the growth plate showed a slight medial angulation. The proximal growth plate of the right radius was no longer smooth, but finely grained and rougher. The distal metaphyses of the left and right radius showed severe flaring and widening (fig. 27). Likewise, the distal metaphysis of the right ulna was flared. The distal growth plates of both femora were badly affected by taphonomy, fraying of the metaphyseal junction could still be observed in both bones. The distal metaphysis of the right femur was flared. Lastly the proximal metaphysis of the right tibia showed some slight flaring and fraying of the metaphyseal junction. These lesions indicate an active stage of the disease.

Figure 27: (a) Occipital bone of individual 279 showing porous bone formation on the ectocranial surface. (b) Both radii of individual 279 displaying marked flaring of the distal metaphyses. (Photographs by Emma Vereecken).

314

314 was an infant of around 6mo ± 5mo old around its death. Age estimation was based on post-cranial measurements since no teeth were preserved nor was any archival data available. Varius features of rickets were documented on individual 314 indicating an active stage of the disease, starting with serious deformation of the ribs. Rachitic rosary consisting of swelling – also called beading- of the costochondral ends and cupping of the junctions, could be documented. Furthermore, some ribs showed marked flaring of their sternal ends. The cortex of the costochondral ends was irregular with marked porosis, including both micro- and macroporosity.

Additionally, the long bones exhibited strong deformities of the proximal and distal ends. Both humeri were affected by flaring and swelling of the proximal metaphysis, paired with fraying margins of the metaphyseal junction (fig. 28). The cortex around the distal metaphyses was porous. The proximal growth plates of the left and right humerus were highly porous, including macro pores with a circumference of more than 1mm, and had a velvety texture (fig. 29). The surface was rugged with cupping deformities. The two ulnae and the right radius were marked by both micro and macroporosity of the cortex around the proximal and distal metaphyses, sometimes including pores with a diameter of 1 to 2 mm. The distal metaphyses were flared, swollen and the margins were fraying. The distal growth plates of both ulnae and the right radius showcased the same deformities as the humeri, where the original morphology was almost completely gone.

When considering the lower limbs, both femora displayed marked porosis of the cortex covering the proximal and distal metaphyses. *Coxa vara* in the form of acute angulation of the neck of both femora was present (fig. 28). Marked flaring occurred in the distal metaphysis of the left femur, especially towards the medial side enhancing the medial curvature of the bone. The right femur had a distal metaphysis showing flaring and marked swelling. The growth plates were strongly deformed due to the disease. The proximal metaphyses of the left and right femur showcased severe flattening and depression of the head. The original morphology had made place for a severely roughened growth plate with marked micro- and macroporosity on the head and the lesser trochanteric surface. Additionally, the distal growth plates of both femora were seriously modified, the plates were severely roughened with micro- and macroporosity and cupping deformities (fig. 29). Furthermore, the distal growth plates of the two femora displayed a lateral tilt, paired with a posterior angulation of the right femoral growth plate (fig. 28). Lastly, both tibiae exhibited a porous cortex that covered the proximal and distal metaphyses. The proximal growth plates of both bones displayed micro- and macroporosity paired with cupping deformities all over the plates, as seen in the other long bones.

The distal ends of the tibiae showed flaring and swelling with fraying margins (fig. 28). Their distal growth plates exhibited wide swept porosity and cupping deformities, in addition abnormal medial tilting was witnessed. This medial angulation paired with the lateral tilting of the distal epiphyses of the femora resulted in *genu valgum* or so called “knock-knees” (fig. 28).

Figure 28: (a) Lower limbs of individual 314 showing serious deformities of the epiphyses. (b) Upper limbs of individual 314. (Photographs by Emma Vereecken).

Figure 29: Detailed pictures showing (a) the deformities of the proximal growth plate of the right humerus and b) the deformation of the distal growth plate of the left femur. (Photographs by Emma Vereecken).

possible case of rickets. The lesions witnessed were still faint and possibly indicate an early onset of the disease. However, certainty couldn't be reached since the preservation of the skeleton was relatively poor. Features of rickets manifested were flaring and swelling of the costochondral rib end of the right fifth rib and flaring of the right sixth rib end. Other sternal ends of ribs were generally not preserved. When considering the long bones, the right radius was affected by porosity and starting cupping deformities of the distal growth plate, paired with fraying margins of the metaphyseal junction (fig. 30). The cortex was marked by micro- and macroporosity of the cortex around the proximal and distal metaphyses. Likewise, the right ulna displayed the same growth plate and metaphyseal deformities as the right radius. Lastly, the left ulna was affected by marked porosity of the metaphyseal cortex on both ends. The lower limbs were not preserved hence they couldn't be subjected to analysis.

This will be regarded as a possible case of rickets since the features are faint but present. The disease often manifests itself this way in young individuals/infants, with deformations of the growth plates, long bone metaphyses and ribs being common when suffering from rickets. Furthermore, a tentative diagnosis of rickets is often made based on the presence of a minimum of three features. However, the preservation of the skeleton was too fragmentary to form a definite diagnosis.

Figure 30: Right radius of individual 295 showing rachitic deformity of the distal growth plate. (Photograph by Emma Vereecken).

Chapter 6: Discussion

In this chapter the results from the data collection will be discussed. More specifically the prevalence of rickets in both Arnhem and Zwolle will be explored and situated within the broader context of the Netherlands during the 17th to 19th centuries.
Firstly, biocultural factors inherent to the urban environment that might have had an impact on the vitamin D status of the wider populace of Arnhem and Zwolle will be discussed. Secondly, the possible influence of socioeconomic status on rickets prevalence will be looked at by employing a life-course approach, meaning that different life stages with their own unique set of causes from infant to adolescent will be considered. These two sections cannot be completely separated since daily lives in the city will be determined by socioeconomic status.

6.1. Biocultural factors in an urban environment

The results show a relatively high prevalence of rickets in both populations from Arnhem (7.6%) and Zwolle (16.7%). These fit within the pattern of the disease observed in Dutch cities during the 18th to 19th century (see Table 6) (Maat et al., 2002, p. 15; Veselka et al., 2019, p. 73). A significant part of the Dutch urban population seemed to have suffered from vitamin D deficiency. Multiple studies refer to the urban environment and the effects of urbanization as an important inhibitor of vitamin D deficiency (Jablonski & Chaplin, 2018, p. 54; Mays et al., 2006, p. 362; Mays, et al. 2018; Veselka, 2019, p. 21).

Table 6: Overview of rickets prevalence in post-medieval Dutch urban and rural contexts. Data from: Maat et al., (2002) and Veselka et al., (2021).

Site	Number of subadults	Number of affected subadults	Rickets prevalence
Urban			
Arnhem	53	4	7.6%
Zwolle	30	5	16.7%
‘S hertogenbosch*	68	3	4.0%
Hattem	23	6	26.1%
Den Haag	44	12	27.3%
Rural			
Roosendaal	14	2	14.3%
Beemster	87	13	14.9%

*Only based on tibias, 7% residual rickets was observed

During the post-medieval period, vitamin D deficiency was a frequent occurrence in the industrialized cities of Northern Europe. Albeit the Netherlands did not undergo a traditional industrial revolution comparable to the United Kingdom, considerable industrialization and high intensity urbanization still occurred (Veselka et al., 2019, p. 72). Both Arnhem and Zwolle were highly developed and densely populated urban centers. Already by the 18th century, Arnhem was densely built with limited open space, Zwolle followed a similar development (Vredenberg, 2009, p. 45). These towns were formed by high-rise buildings in narrow streets and alleyways, with the exception of the opulent houses of merchants and officials located in the main streets of the cities (Klep, 2009, p. 98-100; p. 152-153; Ten Hove, 2005, p. 292-296). The majority of the populace lived in small single room houses, sometimes even in underground basements, further limiting the protrusion of sunlight.

Overcrowding both on the city level, with the creation of a densely built street pattern, and within the living spaces with one or multiple families living in close quarters, is an effect of urbanization that can directly impact vitamin D deficiency (e.g., restricting sunlight). However, together with the insufficient sanitation and pollution of the environment, overcrowding facilitated the spread of diseases possibly leading to the secondary development of rickets (Brickley & Ives, 2008, p. 95). This might have been the case in a medieval population from Wharram Percy where only active infantile rickets was diagnosed. This suggests that these infants died from another lethal cause while rickets was active, and before they had the chance to recover from the deficiency and start healing. Therefore, it is possible that these infants were suffering from other (fatal) diseases and “were kept indoors in dark smoky houses” (Ortner & Mays, 1998, p. 54). In Zwolle and Arnhem historical sources attest to the spread of infectious diseases like the plague, smallpox and typhus (Ten Hove, 2004, p. 290-292). For some individuals being kept inside might have resulted in secondary rickets. However, it is unlikely that all cases of rickets in Arnhem and Zwolle developed in a secondary context. Rickets was considerably more prevalent in these two cities and more spread out across the different age categories than in Wharram Percy (Ortner & Mays, 1998, p. 52-54; Veselka et al., 2015, p. 670-672).

Along with urbanization came economic diversification resulting in a broad scale of occupations carried out indoors. From work in the factories, urban industries and crafts to the extensive labor carried out at home, urban workers spend a significant amount of their time inside. This was also the case in Zwolle and Arnhem, where many people were employed in these sectors (Klep, 2009, p. 135; Ten Hove, 2004, p. 284-287). This would also have had ramifications for children and adolescents. They were often an important part of the workforce either engaged in wage labor or apprenticeships depending on their social background (van Nederveen Meerkerk & Schmidt, 2008, p. 731). It would also have influenced sun exposure of infants since a lot of the work of women, their primary caregivers, was centered inside the house (van Rijswijk-Clerkx, 1983, p. 30). Furthermore, in modern times infants particularly can be brought along to work by their parents in case a sitter cannot be found. It would not be unlikely that this also happened during the post-medieval period if no other form of childcare was available. In rural villages on the other hand, the primary occupations like cattle farming and agriculture happened outside, meaning more exposure to UVB radiation (Veselka et al., 2021, p. 47). From five years onwards, children in Dutch villages like in Middenbeemster would have started to work alongside their parents (Veselka et al., 2015, p. 672).

Another nefarious effect of urbanization and growing industrialization is atmospheric pollution. During the post-medieval period, Dutch cities heavily relied on peat as their primary source of fuel (Stol, 1998, p. 127-129; Pierik, 2023, p. 216; Zeeuw, 1987, p. 12). Peat played a crucial role in the energy infrastructure, serving not only local industries but also domestic households. This widespread use of peat must have contributed to the pollution levels in these urban areas. Therefore, possibly contributing to the development of vitamin D deficiency since air pollution has been proven to negatively affect vitamin D synthesis (Mousavie et al., 2019, p. 71). The pollutants will absorb UVB radiation before it reaches the skin hindering vitamin D metabolism (Chesney, 2012, p. 4). However, it is important to consider that Dutch post-medieval cities were markedly smaller and less industrialized and polluted than cities in England (Veselka et al., 2021, 47). Therefore, air pollution is not assumed to be a primary cause of the development of vitamin D deficiency in Arnhem and Zwolle.

Biocultural studies of vitamin D deficiency have mainly been focused on the industrial period. However, the relationship between vitamin D deficiency and urbanization can already be observed in the Roman period. In a population from Isola Sacra, dating to the 1st to 3rd centuries, a rickets prevalence of 7.5% was detected (Lockau et al., 2019, p. 1-5). The urban built-up environment consisting of apartment buildings paired with economic occupation and cultural practices negatively influenced this population's exposure to sunlight. It is likely that the urban environment including the architecture, economic occupations and sanitation, contributed to the prevalence of vitamin D deficiency in Arnhem and Zwolle. A study conducted by Veselka et al. (2021) in the post-medieval Netherlands showed that there was a significant relationship between settlement type and prevalence of vitamin D deficiency. The prevalence of rickets in subadults of the studied cities (Gouda, Rotterdam, Hattem, Den Haag, Rhenen) was twice as high as the prevalence of the disease in the rural areas (Beemster, Roosendaal, Silvolde, Noordwijkerhout). According to the authors this can be attributed to differences in occupation between villagers and town inhabitants, causing restricted sun exposure (Veselka et al., 2021, p. 41).

The results from Arnhem and Zwolle fit in the pattern that is witnessed throughout the Netherlands during this period (Table. 6). While settlement type can be linked to rickets prevalence, it is often a confluence of different variables leading to the development of a vitamin D deficiency. In the rural context of Beemster a rickets prevalence of 9.5% was observed (Veselka et al., 2015, p. 665). This considerable rate of rickets can be explained by the communities' cultural practices regarding infant care (e.g., swaddling for an extended period of time, weaning practices and clothing habits). A combination of settlement type, the physical environment, socioeconomical and sociocultural factors can lead to the restriction of access to sunlight causing rickets to manifest.

6.2. Socioeconomic status and rickets prevalence

In the previous section, possible effects of the urban environment on rickets prevalence have been discussed. Even though a division was made, socioeconomic status cannot be separated from urbanization and industrialization. The living standards, occupations and cultural practices of people are inherently influenced by their socioeconomic status in society. In reality all these factors are tightly intermingled. However, since the research objective of this thesis was to study the possible impact of socioeconomic status on rickets prevalence, it will be the focus of this part. The impact of status varies throughout an individual's life course; therefore the socioeconomic environment will be studied within different life stages.

6.2.1. Infants

In the sample 77.8% of all individuals with skeletal manifestations of rickets were infants. In Arnhem the prevalence of the disease within this group was 11.1% with two infants showing manifestations of rickets. The one-and-a-half-year-old (V1777) showed serious deformities, indicating a severe deficiency around the time of death. In Zwolle on the other hand, the prevalence was 22.8% in this group. All the five affected cases were below three years old and could be found in this group. It should be noted that 73% of the sample of subadults in Zwolle were infants. During this period, the infant mortality rate was high across the Netherlands (Wintle, 2000, p. 12; Ten Hove, 2005, p. 409-41). The reasons for this skew in Zwolle cannot be fully explained. There is an inherent bias in samples excavated from cemeteries. It is possible that older children and adolescents were more likely to be buried elsewhere, or that excavation methods introduced this bias for example.

While the difference in rickets prevalence between the two populations was not statistically significant, there's a notably higher prevalence in the high-status population of Zwolle. These infants seem to be twice as likely to suffer from rickets than their counterparts from a lower social background in Arnhem. When considering infant vitamin D deficiencies, both childcare practices and maternal deficiencies should be examined (Brickley et al., 2014, p. 57). Maternal levels of vitamin D will influence the infant during pregnancy and after birth through breast feeding (Lewis, 2018, p. 209). An infant born to a vitamin D deficient mother is at risk of developing rickets early on. Especially if they are not exposed to enough sunlight during the breastfeeding period.

Examining the life of mothers can offer a possible explanation for the high prevalence of rickets in infants, and especially in Zwolle where 22.8% of infants were affected by rickets. In his study of daily life in post-medieval Amsterdam, B. Pierik (2023) noticed that there was generally a division of time spend outdoors between women and men. Men would go further away from home for a longer period of time than women (Pierik, 2023, p. 35; p. 197). Women were at home more often and 4/5 of work by women was practiced inside. There was also a socioeconomic division with lower class women being more likely to perform work outside in the open air, like selling different products in the streets or on markets, and upper middle class/elite women being more secluded (Pierik, 2023, p. 108; p. 199-200). It is likely that the same trends existed in other urban centers in the Netherlands like Zwolle and Arnhem.

This would have had ramifications for the vitamin D levels of their children. Well-off Dutch women were assisted by a nurse and a maid in the first months after birth but were still heavily involved in childcare and housework. Infants were tightly swaddled for the first half year of their life, strongly restricting movement and exposure to sunlight (van Rijswijk-Clerkx, 1983, p. 36-39). After this phase, children spent a significant amount of time seated in a chair while the mother and/or maid worked inside the house. Toddlers were able to play inside where their caregivers could keep an eye on them. From the moment toddlers could walk, they were given a thick dress and hat made of cotton wool to wear to protect them while playing around (Leeuw, 1991, p. 75; van Rijswijk-Clerkx, 1983, p. 39). Nieuwenhuijs, a medical doctor living in Amsterdam during the early 19th century, wrote in his medical treatise how infants are kept too much indoors (Nieuwenhuijs, 1817, p. 228-230). Infants from a higher socioeconomic background therefore seemed to have spent a considerable portion of their life indoors. Not only the time spent inside but also the clothing and swaddling of upper-class infants seemed to have restricted sun exposure.

Reconstructing the life of poor infants is especially hard since historical sources and art barely mention them. However, the documentation by organizations providing poor relief in Zwolle offers information about poor mothers and their living circumstances (Bakker et al., 2006, p. 129; van Rijswijk-Clerkx, 1983, p. 37). Multiple families lived together in small rooms, helping each other with childcare and nursing.

Historical research showed that poor women in Dutch cities were engaged in more informal labor on a day-to-day basis and would spend more time working outside than their well-off counterparts (Pierik, 2023, p. 108; p. 199-200). It is likely that they brought along their infant, when no childcare was available, as is illustrated in this etch by Rembrandt (fig. 31). A mother is pictured carrying her child on her back when panhandling. The illustration shows the infant tightly swaddled and covered with a hat. While the infant is more exposed to UVB radiation this way, the occlusive layers of fabric have an adverse effect.

Figure 31: Etch depicting a panhandling family (Rijksmuseum Amsterdam, objectnr BI-1961-168-78, https://www.rijksmuseum.nl/nl/collectie/BI-1961-168-78).

Next to exposure to sunlight, infant diet should be considered when studying rickets. Multiple studies have shown that the diet alone cannot sustain sufficient vitamin D levels. However, the intake of food rich in vitamin D, in addition to UVB exposure, has proven fruitful in northern populations (Jablonski & Chaplin, 2018, p. 56). In the post-medieval Netherlands, a relatively short period of breastfeeding was the norm (Waters-Rist et al., 2022, p. 3). Dutch infants were breastfed until the age of one year old after which they were weaned. Breastmilk as a food source is low in vitamin D, certainly in vitamin D deficient mothers. During a period of breastfeeding that is mainly spent indoors, children will be at a high risk of developing rickets (Waters-Rist & Hoogland, 2018, p. 109).

The predominant weaning foods included animal milks, especially cow's milk, and porridge made from milk, grains and broth (Waters-Rist et al., 2022, p. 2-3). As a replacement of human milk, cow's milk is inferior since its levels of vitamin D are similar to breast milk but lacks in other important nutrients. Cow's milk contains less calcium than human milk and higher vitamin D levels are needed in cases of low calcium levels (Veselka et al., 2015, 672). Furthermore, the consumption of unpasteurized cow's milk by infants can lead to gastrointestinal infections further complicating the absorption of vitamin D (Waters-Rist & Hoogland, 2018, p. 95; p. 107).

In addition, Dutch weaning foods were high in phytic acid, found in grains used in porridges. Phytic acid hinders the absorption of calcium which can lead to deficiencies requiring a higher vitamin D intake (Graf, 1983, p. 851; Veselka et al., 2015, p. 672). It has been established that breastfeeding is better for overall infant health (Waters-Rist, Hoogland, 2018, 109). Breastfeeding, if both mother and child are sufficiently exposed to UVB radiation, is more beneficial regarding vitamin D status. There is no indication of a major difference in weaning foods between different social classes. However, some research in urban context has shown breastfeeding being more resorted to by the lowest social classes since it was cheaper than buying weaning foods (Waters-Rist, de Groot, Hoogland, 2022, 2). Breastfeeding and weaning practices might have influenced differences in rickets prevalence between Arnhem and Zwolle with the high-status population of Zwolle being more negatively affected.

6.2.2. Children and adolescents

After infancy, a switch appears to have occurred during childhood and adolescence. In Zwolle, no rickets could be observed from the age group of three years old and onwards. In Arnhem on the other hand the disease was witnessed in the 6yrs old and 15yrs old categories. It should be considered that, since the sample of 6yr olds from Arnhem consisted of one individual, the prevalence of rickets is 100% in this age category. However, an interesting result is the prevalence of 20% in the age group of 15-year-olds. The trend seems to indicate that rickets were more prevalent in adolescents than in infants in Arnhem. The opposite is true in Zwolle.

Children and adolescents had more freedom and independence from their parents than toddlers, making the lifestyle of the mother herself a less influential factor of vitamin D status. For children growing up in urban centers, the streets, squares and parks were their playground. Children from all classes of society played outdoors rather than inside the house (van Rijswijk-Clerkx, 1983, p. 39). It was around the age of seven that children of well-off parents moved further away from the proximity of their house. An etch from the 17th century shows children engaged in different games in 'Lange Voorhout' in The Hague (fig. 32). In the left corner two upper-class girls are depicted playing with dolls, accompanied by a maid carrying a baby. It seems that from the age of three years old, children in Zwolle of a higher socioeconomic status were less at risk of developing a vitamin D deficiency. Being able to play independently outside might have been an important factor in preventing rickets. Even though the clothing practices that were fashionable in the higher classes seem to have limited skin exposure to sunlight. Both boys and girls are dressed in occlusive clothing like long dresses and pants often accompanied by a hat (Leeuw, 1991, p. 75). This is visible in the etch where the two girls are dressed in elaborate dresses and the baby is tightly swaddled. However, spending sufficient amount of time outdoors will cancel out the adverse effects of occlusive clothing.

Figure 32: Etch depicting playing children playing in the "Lage Voorhout" in The Hague. Two upper-class girls and their maid are indicated by the black square (Rijksmuseum Amsterdam, objectnr. RP-P-OB-15.674, https://www.rijksmuseum.nl/nl/zoeken/objecten?q=Jan+hendriksz&p=1&ps=12&st=Objects&ii=2#/RP-P-OB-15.674,2).

Apart from playing outside, middleclass subadults would also enter the workforce during adolescence between the ages of 12 to 14 years (van Nederveen Meerkerk & Schmidt, 2008, 731). However, for well-off adolescents the focus was mainly on vocational training. This was predominantly the case for boys, who would start an apprenticeship in the vocation of their father. While these occupations must have also kept them inside, the working environment might not have been as strict as was the case with wage labor where workers were dependent on wages instead of training. Historical sources from Antwerp show how two apprentices were tasked with babysitting the children of their masters during their training and taking them outside to play (Pierik, 2023, p. 221).

While poor children would also have played outside in the street, children in the lowest social classes lived a completely different life (Bakker et al., 2006, p. 129). The concept of childhood was barely existent, children started working from a very young age to support the family, sometimes even from three to five years old (van Nederveen Meerkerk & Schmidt, 2008, p.

731). These were more of an exception and poor children generally entered the labor force around the age of six years old (van Nederveen Meerkerk & Schmidt, 2008, p. 721-722). The workhouses established during the economic stagnation from the late 18th century onwards, were seen as a way to keep poor children off the streets and for them not be a burden. Historical sources from Leiden and Tilburg show that it was common for working children, especially girls, to live in with their employer (van Nederveen Meerkerk & Schmidt, 2008, p. 726-727). In the 17th century 45% to 80% of children in Leiden's textile industry were housed by their employer. While this arrangement was beneficial for poor families, it also meant that children were directly near their place of work and did not have to travel through the city. Child labor would have been a factor contributing to developing a vitamin D deficiency by restricting time spent outside. In his book "*Fabriekskinderen"* or "Factory children" the 19th century author J.J. Cremer (1863) from Arnhem wrote about the appalling conditions children working in factories were exposed to. This rough environment would have been nefarious for their health in general.

Socioeconomic status would also have had an impact on the quality of the diet children and adolescents consumed. As a primary source of vitamin D, food does not suffice but in combination with dermal synthesis, it can help prevent the occurrence of rickets (Veselka et al., 2021, p. 47). A study of a rural community from Beemster has shown significant differences in diet between rachitic subadults and subadults not showing skeletal manifestations of rickets (Waters-Rist & Hoogland, 2018, p. 111). Subadults affected by rickets seemed to not have consumed as much animal protein like meat, fish and eggs that are rich in vitamin D. Non-rachitic subadults on the other hand seemed to have had access to high-trophic-level foods in this post-medieval farming community.

This might also have been the case in Arnhem and Zwolle with high status children and adolescents having been able to consume more animal protein and quality foods than the poor. A historical entry from a diary of a well-off 14-year-old child named Jan Pijnappel shows us what food was on the table in the early 19th century (Lintsen, 1992, p. 40; de Booy, 1978). His parents were in the butter and cheese trade, making them part of the upper-middle class. They seemed to consume meat once every day, either for lunch or for dinner. One lunch consisted of meat, cabbage, apples, potatoes and bread. In the evening, buttermilk and cereals were on the menu. This testimony shows the varied diet of children from the higher social classes which might have helped them sustain vitamin D levels, especially during the winter months when UVB radiation was limited (Waters-Rist & Hoogland, 2018, p. 111). Children from lower social classes generally could not afford to eat meat most of the time. Their diet consisted of cheap vegetables like cabbage, potatoes and grains of which rye was the most important (de Meere & Noordegraaf, 1977, p. 160). Sometimes animal proteins like tallow or milk were added.

It seems to be that the socioeconomic environment that influenced the occupation and the diet of children might have left them vulnerable to developing a vitamin D deficiency. Wage labor would have kept poor children from Arnhem indoors more than their better-off counterparts in Zwolle. Furthermore, the inadequate diet of the lower social classes might have aggravated a vitamin D deficiency and the absorption of nutrients.

6.3. Comparison with Dutch collections

The results for Arnhem and Zwolle align with the overall trend of the disease in the Netherlands. Namely, the prevalence of rickets is relatively high in Dutch cities during the 17th to 19th centuries. Table 7. contains the crude rickets prevalence rates in different cities with known socioeconomic status, studied earlier by Veselka, Brickley and Waters-Rist (2021) and Maat, Mastwijk and Jonker (2002). There is a strong variation in prevalence rates between the cities, with Zwolle and Arnhem constituting among the lowest rates of crude rickets prevalence. When considering socioeconomic status, no stand-out trend can be witnessed. High rickets prevalences can be found in both high- and low-status populations (table 7).

Table 7: Overview of rickets prevalence in post-medieval Dutch High and low SES urban contexts. Data from: Maat, Mastwijk, Jonker (2002) and Veselka, Brickley, Waters-Rist (2021).

Site	Number of subadults	Number of affected subadults	Rickets prevalence
Low SES			
Arnhem	53	4	7.6%
‘S hertogenbosch*	68	3	4.0%
Gouda 2	42	15	35.7%
Rhenen	19	10	52.6%
High SES			
Gouda 1	6	3	50%
Zwolle	30	5	16.7%

SES = socioeconomic status

* Only based on tibias, 7% residual rickets was observed

In their study, Veselka, Brickley and Waters-Rist (2021, p. 46) found no statistically significant relationship between socioeconomic status and rickets prevalence. These results are similar to the ones in Arnhem and Zwolle. However, an important caveat in this study is the inclusion of only one high-status population Gouda 1, which included only six subadults. The small sample size makes comparison with Zwolle or the low-status populations hard. Furthermore, the Gouda 1 population consisted of some elite/upper class members including the mayor’s family among others. The environment of these families was vastly different from the majority of people. The authors point out that the sociocultural practices these individuals engaged in, possibly were at the root of their lack of sunlight exposure (Veselka et al., 2021, p. 46). In Zwolle, the individuals from the 'Broerenkerk' (Brother's Church) did not belong to this small top of society and varied from upper class to middle class. The analysis of this population contributes to our knowledge about vitamin D deficiency in Dutch high-status populations. However, more of these populations need to be studied for vitamin D deficiency than is now the case.

The cities with a low socioeconomic status contained both the lowest and the highest prevalences of rickets from the studied cities. The results from 'S Hertogenbosch should be carefully considered since the diagnosis was based only on bending deformities of the tibia (Maat et al., 2002). To not miss cases of rickets it is important to take all bones in consideration, particularly for infants. However, Gouda 2 and Rhenen, have a markedly higher prevalence then Arnhem showing that considerable variation exists among low-status populations. Within different populations sociocultural and environmental factors will vary, irrespective of socioeconomic status. In Gouda 2 and Rhenen, rickets was highly prevalent in infants with rates of 45.0% and 42.9% respectively (Veselka et al., 2021, p. 46). In Arnhem, rickets was less common in this age group with a prevalence of 11.1%. These infants seem to have been more exposed to sunlight than in Gouda 2 and Rhenen. Possible causes can be differences in the mother-child relationship, in swaddling or clothing practices, infant diet, etc. that are not tied to social class.

In general, when comparing results in a broader context no direct link can be established between socioeconomic status of populations and rickets prevalence. Therefore, it cannot be assumed that rickets is more prevalent low-status individuals, as was traditionally the case. There is considerable variation between populations, even between those with comparable social class.

6.4. Limitations

The study of vitamin D deficiency as a result of sun avoidant behavior or inadequate diet can offer information about sociocultural and –economic practices of past societies. While the paleopathological study of human remains provides unique information about individuals and populations that are often unmentioned in historical sources, there are some limitations when using this study to infer information about cultures.

A first problem that is part of the osteological paradox, is the absence of lesions being used to infer whether an individual was healthy. It takes time for lesions to manifest in the skeleton (Siek, 2013, p. 92-93). In this case it is possible for individuals to be vitamin D deficient without developing skeletal lesions. Therefore, the assumption that subadults not showing signs of rickets, had sufficient vitamin D levels can lead to a misrepresentation of reality. In addition, the concept of heterogeneity in frailty should be considered (deWitte & Stojanowski, 2015, p. 399). Not every individual is as susceptible to certain stressors. Some individuals will unavoidably have been more 'frail'. Since not every individual has the same likelihood of dying within a specific age group. Some individuals in Arnhem and Zwolle that suffered from rickets but did show skeletal lesions of the disease after death, will be invisible to us. Lesions of rickets can disappear completely after remodeling, especially pathological alterations of the growth plates and metaphyses (Veselka et al., 2021, p. 47). Long bone bending is most commonly used to diagnose residual rickets and can still be visible in the skeleton for an extended period of time (Brickley et al. 2018, p. 44). However, bending deformities only occur in 10%-15% of individuals (Veselka et al., 2021, p. 47). Which means that a lot of cases will be missed.

Secondly, it should be considered that cemetery samples are inherently biased as they represent only a subset of the population. Already mentioned is the concept of heterogeneity in frailty that causes bias in samples (deWitte, Stojanowski, 2015, 406-407). Furthermore, not every individual will be buried in a cemetery, nor will they be discovered and excavated by archaeologists. Metabolic diseases like rickets will cause the bones to become frailer, making them less likely to preserve (Brickley, Ives, 2008, 13). Subadults in particular, can be harder to detect and be less likely to preserve. In order to diagnose rickets, individuals need to be sufficiently preserved to recognize the lesions. Conversely, these individuals are less likely to be preserved and included in the sample.

In the sample from Zwolle, considerably less individuals from the age group '3yrs" old and onwards, could be included in the sample. This can be the result of many different factors like for example: being buried in a different place, selection bias during excavation, worse preservation causing them either to not to be preserved at all or to not be included in the sample. Subsequently, this can cause problems when comparing rickets prevalence in children and adolescents between the two sites. It is possible that rickets was prevalent in subadults older than three years old in Zwolle, but that they were not included in the sample due to the above-mentioned reasons.

Furthermore, no lesions are pathognomic to rickets therefore identifying the disease can be hard. In order to accurately diagnose rickets, multiple diagnostic features need to be considered. Most of these lesions can also occur in other diseases causing the need for a differential diagnosis (Brickley & Ives, 2008, p. 103-105). The combination of multiple diagnostic features makes a tentative diagnosis possible (Mays et al., 2006, p. 363). Difficulty can arise when comparing different studies since inconsistencies exist in the methodology of researchers. Some studies only include adults or focus primarily on bending deformities and are at risk of missing manifestations of infantile rickets.

Lastly, when comparing results between studies of vitamin D deficiency, comparable datasets and streamlined methodologies are needed. Significant variation in sampling strategies, data collecting methods and reporting of results, complicate comparative analysis. There is considerable variation in the criteria used to diagnose rickets between different studies. This can lead to individuals being missed or excluded from samples. Additionally, comparisons between sites often rely on crude prevalence rates of rickets, which can be problematic because they do not take the influence of age in account. It should therefore be kept in mind that the interpretation of the results from Arnhem and Zwolle in the broader context of the Netherlands, was based on crude prevalences that do not paint a complete picture. Suggestions for further research will be specified in the following chapter.

Conclusion

Rickets has long been seen as a disease of narrow and polluted alleyways that made up industrialized cities. A disease of "the children of the poor" as Palm (1890) stated it. Research of vitamin D deficiency classically focused on the Industrial Revolution in big urban centers in Northwestern Europe. The Netherlands, however, did not experience a traditional industrial revolution. Its economy modernized already during the Dutch Golden Age and retained a high level until modern times (Veselka, 2019, p. 125; Wintle, 2000, p. 69). Nevertheless, the 17th to 19th centuries marks an interesting period of changes in the political, social and economic landscape that impacted the lifestyle of its population. Since dermal synthesis has been the primary source of vitamin D in historic populations, sun-avoidant lifestyles can lead to the development of rickets in subadults (Brickley & Mays, 2019, p. 540). Socioeconomic status has a considerable influence on people's lifestyles, therefore an in-depth analysis of its possible impact on vitamin D deficiency in the Netherlands was needed.

This study aimed to evaluate the relationship between socioeconomic status and rickets prevalence by analyzing sociocultural and economic practices that shaped the daily life of subadults and possibly protected or rendered them vulnerable to vitamin D deficiency. The cross-population comparison of Arnhem and Zwolle with differing socioeconomic status, can be fitted within the wider context of the Netherlands and contribute to the broader understanding of rickets in the region. The research was carried out to answer the question: "Does socioeconomic status impact the prevalence of rickets in post-medieval Dutch populations?". To get a further understanding of this complex interaction, a sub-objective was to assess which factors susceptible to socioeconomic status, impacted the development of rickets in these post-medieval Dutch communities. Lastly the question was raised how these results fit into the broader context of the Netherlands.

While there was no significant difference between rickets prevalence in the low-status population of Arnhem and the high-status population of Zwolle. The crude prevalence of rickets in Zwolle (16.7%) was more than double as high as it was in Arnhem (7.6%). It showed that subadults of the well-off class seemingly were more likely to suffer from rickets. This is especially the case for infants. Infancy is a high-risk period for the development of rickets and infants in the upper classes of Zwolle (22.8%) suffered twice as much from rickets than poor infants in Arnhem (11.1%). The lifestyle of the mother seemed to be a crucial factor at this life stage. A combination of economic factors such as high-status women working more inside the house with their infants compared to lower class women working more outside, and social factors such as the well-off class being more secluded from public space and restrictive clothing practices meant that high status infants were less exposed to the sun. Furthermore, the practice of swaddling and a diet poor in vitamin D likely had nefarious effects in the development of rickets in both populations.

From childhood onwards a different trend takes place, where now low-status individuals are more likely to suffer from rickets. In Arnhem, prevalence was as high as 20% in the age group of 15-year-olds. Child labor was rampant during this period and poor children entered the labor force at a very young age. Long working hours in the local industries and crafts restricted time spent outside, aiding in the development of vitamin D deficiency. High-status children faced a different reality with more free time to play outside as they would enter the workforce between the ages of 12 to 14. In these instances, it mostly involved vocational training which was less demanding than wage labor. Additionally, a better-quality diet with more meats and fish rendered them less vulnerable to vitamin D deficiency.

Socioeconomic status cannot be regarded on its own. The effects of the urban environment should also be considered. Multiple studies have shown that people living in urban centers are significantly more at risk of developing rickets than in rural areas (Mays et al., 2006, p. 362; Veselka, 2019, p. 21; Veselka et al., 2021, p. 45). High-rise buildings and narrow streets hindered the protrusion of sunlight. Overcrowding facilitated the spread of infectious diseases rendering people less resilient to metabolic disease. Importantly, urban populations worked more inside jobs compared to villagers spending more time working outdoors (Veselka et al., 2021, p. 41). These factors inherent to the urban environment affected both the poor and the wealthy living in the cities.

It can be concluded that the socioeconomic environment can contribute to the development of rickets. The living environment, occupation, social norms and cultural habits differ between socioeconomic classes and can strongly impact sunlight exposure. However, it does not seem to be a determinant of rickets prevalence in the populations of Arnhem and Zwolle. A diverse and complex confluence of circumstances are etiologically at the root of the disease. Although the causes of inadequate sun exposure can be different depending on socioeconomic status, they are numerous in all social classes of society and can lead to the same result. A relatively high prevalence of rickets was present in both populations. Even though less subadults suffered from a vitamin D deficiency in Arnhem, rickets was still prevalent in this poor socioeconomic environment. Additionally, the osteological paradox comes into play as even if we would assume the environment of a certain subgroup to be more beneficial in relation to rickets prevalence, not every individual within that group has the same chance of developing a deficiency and associated skeletal lesions. Heterogeneity of frailty applies to all social classes.

In the broader context of the Netherlands, Arnhem and Zwolle fit into the wider pattern of the disease, with higher rates in the urban centers, regardless of socioeconomic status (Veselka et al., 2021, p. 46). Contrary to earlier research done in the Netherlands, showing that rickets was more common in low-status populations, albeit not significant, this study shows a new perspective. Indicating that some high-status populations can be more vulnerable to developing rickets than some low-status populations. The research shows that low socioeconomic status does not automatically indicate a high prevalence of rickets and that different biocultural factors need to be carefully considered for each population. Moreover, the high-status populations that have been studied for rickets, were localized contexts with circumstances that apply to a small subset of people, e.g., the Medici family in Florence (Giuffra et al., 2015) and the mayor's family in Gouda (Veselka et al., 2021, p. 47). The results from Zwolle contribute to the wider understanding of rickets in high-class populations.

Further research is needed to gain more insight into the interaction between socioeconomic status and rickets prevalence. The last decade significant contributions have been made to explore this relationship within the framework of biocultural and life-course approaches. They have shown that traditional assumptions about rickets prevalence in different social classes should be questioned. Analysis of the Zwolle population has contributed to our knowledge of how rickets impacted this well-off community. However, certainly for the research of high-status populations, an expansion of sources is needed. Specifically for the Netherlands, more high-status populations from both rural and urban contexts need to be studied in order to come to broader conclusions about this interaction.

Furthermore, methodologies for rickets assessment need to be streamlined to facilitate accurate comparisons. Therefore, I suggest the use of a multiple-criteria-method, varying from 10 to 16 macroscopic features, to diagnose rickets. It is especially important to carefully examine infants since manifestations of rickets in these young individuals can be hard to detect. In addition, the study of osteomalacia and residual rickets in adults can help to improve our understanding of the impact of vitamin D deficiency on communities. Specifically for infants, the mother-child relationship is an important influence on their exposure to sunlight. Studying vitamin D deficiency in women and mothers can aid in the understanding of rickets incidence in infants. Moreover, socioeconomic status also has likely a profound effect on the lifestyle of adults, therefore including them in analyses might offer more information on the complex relationship between the socioeconomic environment and the prevalence of vitamin D deficiency.

Abstract

Rickets, a disease caused by vitamin D deficiency in subadults, has known a long research history. The primary causes of a deficiency are a lack of exposure to UVB radiation and an inadequate diet (Veselka et al., 2015, p. 665). While biophysical factors (e.g., latitude and skin color) play a role, recently more attention has been paid to sociocultural factors that may have contributed to the development of the disease (Brickley et al., 2014, p. 48). Socioeconomic status, cultural and religious practices could have impacted an individual's exposure to sunlight.

In this study, the possible impact of socioeconomic status on the prevalence of rickets in two post-medieval Dutch populations from Arnhem and Zwolle will be examined. The Netherlands underwent significant social and economic changes during the 17th to 19th centuries that may have influenced the health of its population. To explore this, a paleopathological analysis was conducted on skeletal remains from two urban populations: Arnhem, representing a low-status population, and Zwolle, representing a higher-status population. The study seeks to answer the research question: "Does socioeconomic status impact the prevalence of rickets in post-medieval Dutch populations?" Additionally, it explores which socioeconomic factors might have influenced the development of rickets and how these findings fit within the broader context of the Netherlands

In total 83 subadults were analyzed for rickets based on 14 macroscopic features. The results show a crude rickets prevalence of 7.6% in Arnhem and 16.7% in Zwolle. While the relationship between socioeconomic status and rickets prevalence was not statistically significant, rickets was more than twice as common in the higher-status population of Zwolle than in the lower-status population of Arnhem. This was particularly evident in infants. It is possible that factors influenced by socioeconomic status such as reduced outdoor activities for women, clothing practices and diet, contributed to this difference between both populations. Additionally, the effects of the urban environment like density of buildings, pollution, overcrowding and more indoor occupations likely influenced rickets prevalence in both populations.

It can be concluded that socioeconomic status is not a determinant of rickets prevalence in Arnhem and Zwolle, however it can influence the amount of sunlight exposure an individual gets. A confluence of different biocultural factors impacts the prevalence of rickets of which socioeconomic status can be one.

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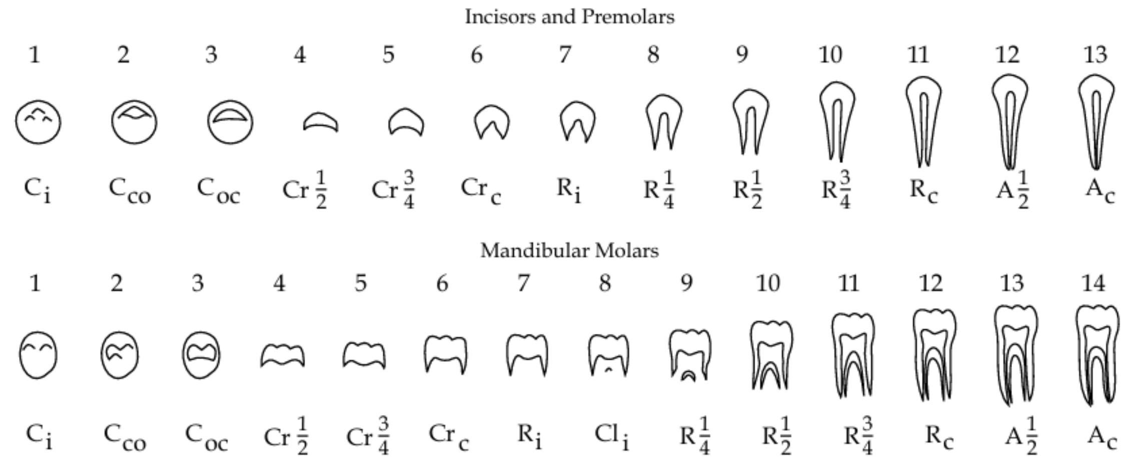
Appendix 1

The thesis dataset is available in its entirety here

Method for age assesment by Demirjian *et al*. (1973, p. 220-223, figs. 1&2):

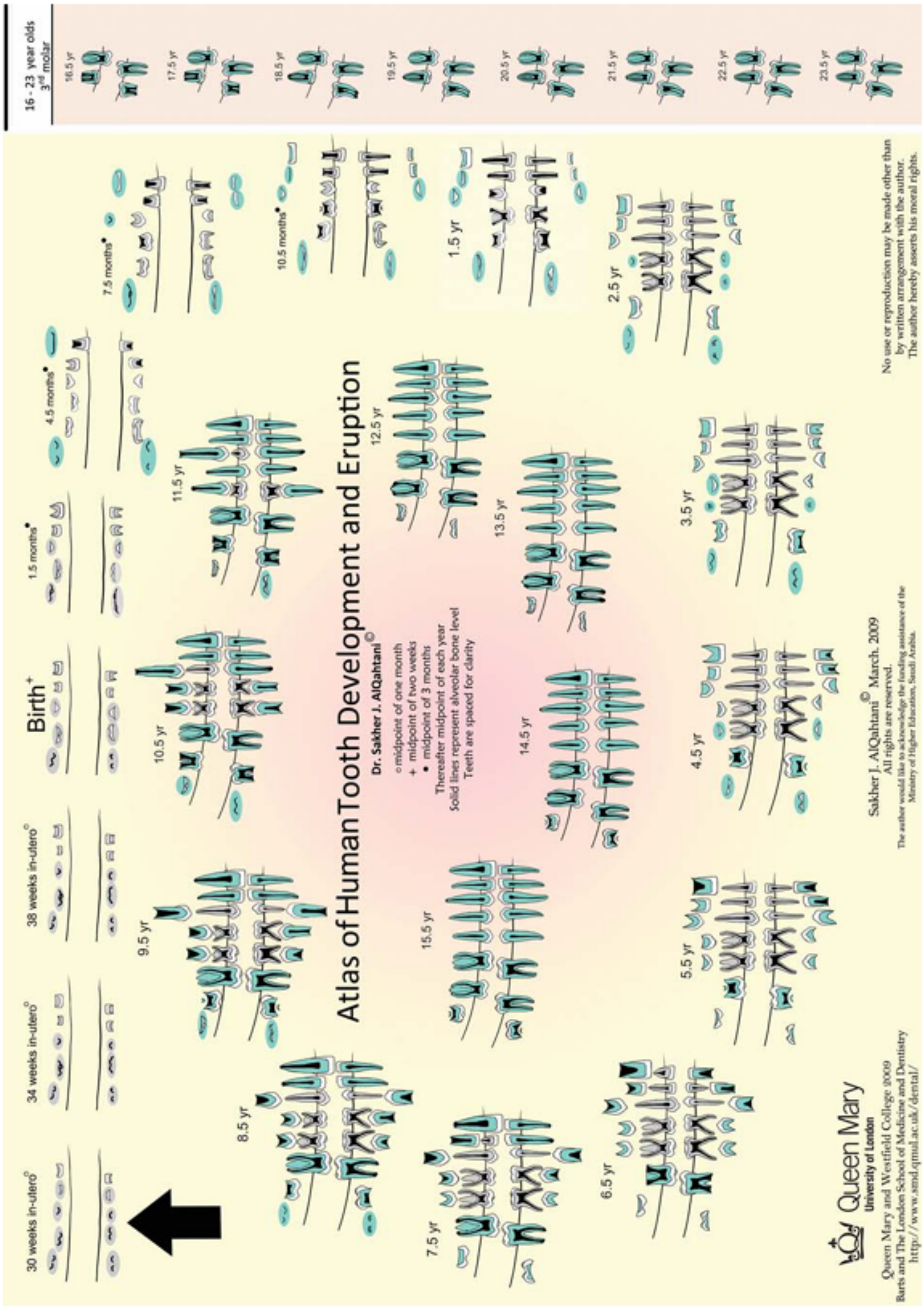
Definition of tooth formation stages	
A	Calcification of the cusp tips have initialized, however have not yet united in multiradicular teeth
B	Cusp tips unite to form a regularly outlined coronal surface
C	Crown formation extends towards cervical region; dentinal deposition and pulp chamber are observable
D	Crown formation is complete; pulp chamber is curved in uniradicular teeth and exhibits a trapezoidal form in molars
E	Walls of pulp chamber exhibit straight lines in uniradicular teeth; initial formation of radicular bifurcation in molars; root length is less than the crown height in all teeth
F	Walls of pulp chamber form isosceles triangles in uniradicular teeth; molar roots are more definite and funnel shaped; root length is equal to or greater than the crown height in all teeth
G	Root length is nearly complete; however its apical end remains open
H	Apical end of the root is closed; the periodontal membrane has a uniform width around the root and apex

Method by Harris and Buck (2002) modified from Moorrees et al. (1963, p. 17-18; figs. 1&2):



Grade	C $\bar{x}$	C sd	P1 $\bar{x}$	P1 sd	P2 $\bar{x}$	P2 sd	M1 $\bar{x}$	M1 sd	M2 $\bar{x}$	M2 sd	M3 $\bar{x}$	M3 sd
Girls												
C i	0.5	0.12	1.7	0.24	2.9	0.35	0.1	0.05	3.5	0.41	9.6	1.00
C co	0.7	0.15	2.2	0.28	3.5	0.40	0.2	0.09	3.8	0.43	10.1	1.05
C oc	1.2	0.18	2.9	0.35	4.1	0.47	0.7	0.14	4.3	0.49	10.7	1.11
Cr 1/2	1.9	0.25	3.5	0.41	4.7	0.53	1.0	0.17	4.8	0.54	11.3	1.17
Cr 3/4	2.9	0.35	4.2	0.49	5.3	0.59	1.4	0.20	5.4	0.59	11.7	1.20
Cr c	3.9	0.45	5.0	0.56	6.2	0.66	2.2	0.28	6.2	0.68	12.3	1.27
R i	4.7	0.52	5.7	0.63	6.7	0.73	2.6	0.32	7.0	0.75	12.9	1.32
R cl	•		•	•	•	•	3.5	0.41	7.8	0.83	13.5	1.39
R 1/4	5.3	0.57	6.5	0.69	7.5	0.79	4.6	0.52	9.1	0.96	14.9	1.53
R 1/2	7.1	0.75	8.1	0.86	8.7	0.92	5.1	0.57	9.8	1.01	15.8	1.62
R 3/4	8.3	0.88	8.8	0.97	10.0	1.05	5.5	0.60	10.5	1.09	16.4	1.67
R c	8.8	0.93	9.9	1.03	10.6	1.12	5.9	0.63	11.0	1.13	17.0	1.71
A 1/2	9.9	1.03	11.0	1.15	12.0	1.24	6.5	0.71	12.0	1.23	18.0	1.82
A c	11.3	1.18	12.1	1.26	13.6	1.40	8.0	0.85	13.8	1.43	20.1	2.01
Boys												
C i	0.5	0.11	1.8	0.24	3.0	0.37	0.0	0.09	3.7	0.42	9.2	0.98
C co	0.8	0.15	2.3	0.31	3.5	0.42	0.2	0.11	4.0	0.44	9.7	1.01
C oc	1.2	0.19	2.9	0.36	4.2	0.48	0.5	0.11	4.8	0.52	10.3	1.07
Cr 1/2	2.1	0.27	3.6	0.43	4.7	0.53	1.0	0.17	5.1	0.56	10.9	1.14
Cr 3/4	2.9	0.35	4.4	0.52	5.3	0.59	1.5	0.21	5.7	0.61	11.6	1.20
Cr c	4.0	0.46	5.2	0.58	6.2	0.69	2.1	0.29	6.5	0.69	12.0	1.24
R i	4.8	0.55	5.8	0.64	6.9	0.74	2.7	0.34	7.1	0.76	12.7	1.32
R cl	•	•	•	•	•	•	3.5	0.41	8.1	0.84	13.6	1.41
R 1/4	5.7	0.63	6.8	0.74	7.8	0.83	4.7	0.53	9.3	0.98	14.6	1.50
R 1/2	8.0	0.86	8.5	0.91	9.4	0.99	5.1	0.57	10.1	1.04	15.1	1.54
R 3/4	9.6	1.00	9.9	1.04	10.8	1.13	5.4	0.61	10.8	1.12	15.9	1.62
R c	10.2	1.06	10.3	1.09	11.5	1.21	5.8	0.64	11.3	1.16	16.3	1.67
A 1/2	11.8	1.23	11.9	1.24	12.7	1.30	6.9	0.75	12.2	1.25	17.6	1.79
A c	13.0	1.35	13.3	1.38	14.2	1.46	8.5	0.91	14.2	1.46	19.2	1.95

Method for age estimation based on dental eruption by AlQahtani et al. (2010, p. 485, fig. 6):



Scoring form rickets

Individual number:

Site: **Age Category:**

Macroscopic features of Rickets		
Cranium *Ortner, May (1998), 46 and Brickley, Ives (2008), 103	Cranial vault porosity (Layers of spiculated, irregular, porous bone formation) *during healing when osteoid is mineralized	
	Orbital roof porosity	
	Cranium abnormalities (Craniotabes, Frontal and parietal bossing, delayed closure of fontanelles, thinning)	
Mandible *Brickley, Ives (2008), 103	Angulation* of ramus (*medial)	
Ribs *Ortner, May (1998)	Flared/thickened costo-chondral ends of ribs	
	cortex of costo-chondral ends of ribs irregular and porous	
Long Bones *Ortner, May (1998), 46 and Brickley, Ives (2008), 103	Growth plate deformities (porosity, fraying bone margins, cupping deformities)	
	Metaphyses deformities (flaring and swelling, cortex irregular and porous)	
	Bending of upper limbs	
	Bending of lower limbs	
	Thickening of long bones	
	Long bone concave curvature porosity	
	Angulation of neck femur (*coxa vara*)	
Pelvis	Pelvis deformation	