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Leprosy in medieval Denmark: exploring life histories through a multi-tissue and multi-isotopic approach

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Running title: Diet and mobility in medieval Danish leprosaria

Abstract

Objectives: By focusing on two Danish leprosaria (Næstved and Odense; 13th – 16th c. CE) and using diet and origin as proxies, we follow a multi-isotopic approach to reconstruct life histories of patients and investigate how leprosy affected both institutionalized individuals and the medieval Danish community as a whole.

Materials and Methods: We combine archaeology, historical sources, biological anthropology, isotopic analyses (δ13C, δ15N, δ34S, 87Sr/86Sr) and radiocarbon dating, and further analyze bones with different turnover rates (ribs and long bones).

Results: The δ13C, δ15N and δ34S results indicate a C3 terrestrial diet with small contributions of marine protein for leprosy patients and individuals from other medieval Danish sites. A similar diet is seen through time, between males and females, and patients with and without changes on facial bones. The isotopic comparison between ribs and long bones reveals no significant dietary change. The δ34S and 87Sr/86Sr...
results suggest that patients were local to the regions of the *leprosaria*. Moreover, the radiocarbon dates show a mere 50% agreement with the arm position dating method used in Denmark.

**Conclusions:** A local origin for the leprosy patients is in line with historical evidence, unlike the small dietary contribution of marine protein. Although only 10% of the analyzed individuals have rib/long bone offsets that undoubtedly show a dietary shift, the data appear to reveal a pattern for 25 individuals (out of 50), with elevated $\delta^{13}C$ and/or $\delta^{15}N$ values in the ribs compared to the long bones, which points towards a communal type of diet and reveals organizational aspects of the institution.

### 1. Introduction

Leprosy, an infectious disease that is caused by two bacteria (i.e. *Mycobacterium leprae* and *Mycobacterium lepromatosis*; Han *et al.*, 2009), primarily affects the skin and is linked to social isolation and stigmatization. However, it affects also the peripheral nerves, leading to dysfunction and paralysis of the extremities, as well as the eyes and the nasal tissues, causing blindness and breathing difficulties, respectively (Daniel, Ebenezer & Job, 1997; Shetty, 2016; Malaviya, 2016; Shah & Shah, 2016). Additionally, the involvement of bone tissues, with the characteristic changes on the facial bones (known as *Facies Leprosa* or *Rhinomaxillary Syndrome* (RMS); Møller-Christensen, 1961; Andersen & Manchester, 1992), provides the possibility to identify leprosy in archaeological populations using skeletal morphology. Today leprosy is mainly encountered in South-East Asia and Latin America (WHO, 2019), but, during the medieval period the disease was endemic across Europe.

The numerous leprosy hospitals (*leprosaria*) that were established in medieval Europe as a reaction to the disease represent the first evidence of large-scale institutionalization of diseased individuals (e.g. 46 in Denmark, Arentoft 1999:193; 320 in England, Rawcliffe, 2006:106; about 2000 in France, Vogelsang, 1965; >1000 in Germany, Schulze, 1986; Belker, 1988-1998; Belker-van den Heuvel, 2000-2006). The etymology of the Danish word for leprosy (*spedalskhed*), which refers to the hospitalization of the diseased (Ehlers, 1898:5), emphasizes further the association between leprosy and institutionalization. Modern scholars (cf. Brody, 1974; Grmek, 1989:171; Touati, 2000; Rawcliffe, 2007) have debated the purpose of leprosy hospitals, as well as the social stigmatization of leprosy sufferers during the medieval period. Nonetheless, a review of historical and archaeological sources (Brozou, 2018) demonstrates that medieval approaches to leprosy and leprosy sufferers were varied and dependent on socioeconomic, cultural and moral determinants that may differ both regionally and through time.

The present study follows a multi-isotopic approach ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$, $^{87}Sr/^{86}Sr$) to investigate the diet and origin of leprosy patients from two medieval Danish *leprosaria* (Odense and Næstved). Rib and long bone samples from single leprosy patients were further analyzed ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$), in order to investigate whether, and to what extent, the diet of these individuals changed during the last few years of their life (when they were more likely residing in the leprosy hospital). Apart from the availability of foods, diet is further linked to social standing, and thus dietary reconstructions can provide information about the organization of past communities by revealing differences between sex, age or social groups (e.g. Kjellström, 2005; Yoder, 2012). The origin of leprosy patients from medieval Danish *leprosaria* is also of interest, since the hospitals had an obligation to receive infected individuals from the local communities that supported them economically (Richards, 1960), prioritizing perhaps local leprosy sufferers from those coming from further afield. This information, when interpreted within the archaeological context and in
relation to historical sources, adds to our knowledge on the lives of leprosy sufferers and on how society managed leprosy in medieval Denmark. In addition, radiocarbon dates from a subset of these individuals serve as a test of the validity of the arm position dating method, which is often used to date medieval burials in Denmark (e.g. Yoder, 2010; Turner, 2013; Duignan, 2015).

1.1. Diet in medieval Denmark and medieval leprosaria

Diet in medieval Denmark was primarily based on cereal grains (Boldsen, 2005; Yoder, 2010). The mild weather of the Medieval Warm period (8th – 13th c.), as well as agricultural and technological innovations (cf. Hybel, 2003:121; Hybel & Poulsen, 2007:202-204), set the foundations for a grain-based agriculture in early medieval Denmark. Preservation methods, such as drying, salting and smoking, were a common practice and allowed for meat and fish to be available all year (Kjersgaard, 1978:208; Arcini, 1999:44). Sheep, pigs and cattle provided the highest proportions of terrestrial protein, with cattle consumption increasing after the intensification of the production during the second half of the 14th century (Dyer, 1988b; Dyer, 1998:199; Woolgar 2006). Major marine fisheries of herring and cod made these two species widely available in northern Europe (Enghoff, 1996; Barrett et al., 2008; 2011; Barrett 2016). Based on the discovery of bones from small cods in medieval Danish sites, Enghoff (2016:153) suggests that cod probably constituted “a secondary catch obtained during herring fishing”, with both local and imported catches being reported. Freshwater fish were found in lakes and rivers (Garner 2002), but also in fishponds and fish farms. The latter are often mentioned in medieval Danish documents in relation to monasteries, as well as the aristocracy and royalty (Møller, 1953:52, 66; Hofmeister, 2016).

Regulation documents of medieval leprosy hospitals constitute the main sources of information regarding the types and amounts of foods consumed by leprosy patients. For example, at the leprosy hospital in Chartres in France, fish (mainly herring), was the main food consumed during the fasting days, while meat was available three times per week during the non-fasting periods (Laurioux, 2002:110). Furthermore, at the leprosy hospital at Sherburn in England meat and fish were, respectively, consumed three and four times every week, with bread and ale being served on a daily basis (Hutchinson, 1787:601-605 in Richards, 1977:125-127). To our knowledge, a royal decree from 1492 CE constitutes the only source regarding diet in medieval Danish leprosaria. According to the document, porridge, herring (or other type of fish) and beer were consumed daily by the leprosy patients from Næstved, while pork, beef, or just cabbages (depending on the availability) were provided during the meat days (Ehlers, 1898:79-80 in Richards, 1977:144). A regulation document from 1486 CE, mentions only yearly provisions of corn, butter, lambs, geese and hens that the leprosy patients from Svendborg were to share equally with the healthy individuals who lived in the leprosarium and cared for the sick (Ehlers, 1898:74-79 in Richards, 1977:142). Such detailed dietary accounts, which often provided alternatives in cases of need and/or food availability (e.g. Enköping leprosy hospital in Sweden; Richards, 1960; 1977:137), reveal the central role that diet played in the organization of medieval leprosy hospitals. Evidence of corruption, however, among the administrative bodies of the hospitals (e.g. in the Danish leprosy hospitals at Næstved and Svenborg, Richards, 1977:31) question the implementation of the regulations regarding the amounts and types of foods that were made available to leprosy patients.

Fish played an important role in medieval leprosy hospitals, due to their semi-monastic character that entailed adherence to the fasting rules with meat, eggs and dairy products being prohibited for almost
of a year’s duration (Dyer, 1988a; Mays, 1997; Müldner & Richards, 2005). Several regulation documents, which refer to the diet of leprosy patients, mention a high frequency of fish consumption per week and in relation to the fasting periods (e.g. c.f. Richards, 1977: 126, 137, 144). However, as diet was viewed as medication during the medieval period, English physicians favored not only fresh fish, but also poultry, pork, beef, eggs and fresh milk as beneficial foods for leprosy sufferers (Rawcliffe, 2006:213), while in the medieval leprosarium in Barcelona the therapeutic diet included mutton, chicken, sugar, dried fruit and nuts (Jáuregui, 2018). Furthermore, a progressive deviation from the fasting rules is evident throughout the medieval period, with an increase in the meat consumption (Jaritz, 1985; Harvey, 1995:40; Ervynck, 1997; Müldner & Richards, 2005; Serjeantson & Woolgar, 2006). Moreover, sick individuals that followed the monastic order of St. Benedict were often exempt from fasting in order to restore their health (Bond, 2017). Information regarding the connection of medieval Danish leprosy hospitals to monastic orders is scarce and not indicative of a specific order (Nielsen, 1879; Lindbæk & Stemmann 1906:111-112; Danmarks Kirker XII, 1940-1942:91; Kristensen & Poulsen, 2016:334). During the time of the operation of the leprosy hospitals, solely the orders of Benedictines, Dominicans and Franciscans were present in the areas of Næstved and Odense (Andersen, 1987:94, 97; Christensen, 1988:136, 137).

2. Materials and Methods

The skeletons with leprotic bone changes derive from cemeteries in Næstved and Odense, which are associated with two medieval Danish leprosy hospitals (Figure 1). Both hospitals were located outside the medieval borders of the towns, and functioned from around 1260 CE (Næstved, Møller-Christensen, 1954; Madsen, 1990:8) and 1270 CE (Odense, Nielsen, 1981; Arentoft, 1999:75) until their dissolution in 1542 CE (Michelsen, 1954; Hædorsdal, 1976). An isotopic baseline for the local area was generated by analyzing faunal samples from the site of Vilhelm Werners Plads in Odense, which dated to the time of operation of the leprosy hospitals. One lay (St. Alban’s church, Odense) and three monastic populations (St. Knud’s church, Odense; Carmelite Friary, Skælskør; St. Bendt’s church, Ringsted), which are contemporary and near to the leprosaria, were also analyzed for δ13C and δ15N values (a total of 140 rib samples from male and female adult individuals) (Figure 1). Table 1 presents in detail the number of samples and the analyses conducted for each site. Sampling was done using a low-speed drill, and bones with pathological lesions were avoided (cf. Katzenberg & Lovell, 1999; Olsen et al., 2014).

The sex of individuals from the two leprosaria was determined based on the morphological features of the pelvis and the skull (Phenice, 1969; Ferembach, Schwindezyk & Stoukal, 1980; Buikstra & Ubelaker, 1994; Loth & Henneberg, 1996). Bone changes related to RMS include: (a) atrophy of the anterior nasal spine, (b) recession of the alveolar process of the maxilla that initiates in the area of the prosthion and extends to involve the alveolar bone of the incisors and canines (with subsequent loss of these teeth), and (c) inflammatory changes of the nasal cavity, with pitting and/or perforation of the hard palate (oral and nasal surfaces), remodeling of the nasal aperture and maxillary sinusitis (Møller-Christensen, 1961:27-29; 1974; 1978:15; Andersen & Manchester, 1992; Manchester, 2016). Individuals from both leprosy hospitals were grouped either with or without RMS, based on the scoring system provided by Boldsen and Freund (2006) and Boldsen (2007). The presence of at least one area with a score of 1 or 2 was considered adequate for an individual to be included in the with RMS group (Table S1). The selection of samples from the two leprosaria aimed to include a similar number of males and females, as well as individuals with and without RMS.
Collagen was extracted at the Moesgaard Archaeo-Science Laboratory at Aarhus University (Denmark) using the protocol outlined in Richards and Hedges (1999), with the addition of ultrafiltration prior to lyophilization, as described by Brown, Nelson, Vogel and Southon (1988). Samples were analyzed at Iso-Analytical Ltd. (Crewe, UK) and at the Aarhus AMS Centre (AARAMS), Aarhus University for δ¹³C and δ¹⁵N values, and at the Department of Earth and Planetary Sciences (EPS), University of Tennessee (USA) for δ³⁴S values. Based on replicate measurements of internal and international standards, the analytical error (1 SD) was determined to be 0.1‰ (Iso-Analytical) and 0.2‰ (AARAMS) for δ¹³C, 0.1‰ (Iso-Analytical) and 0.3‰ (AARAMS) for δ¹⁵N and 1.2‰ for δ³⁴S. For the ¹⁴C analysis, collagen was extracted at AARAMS using a modification of the Longin method with ultrafiltration (Longin, 1971; Brown et al., 1988; Brock et al., 2013). The selection of the individuals was based on a method used widely in Denmark to date medieval graves (position of the arms in the grave). Strontium isotope analysis was performed at CREATI, Memorial University (St. John’s, Canada) on the enamel of canine teeth using laser ablation (LA) MC-ICP-MS (Multicollector Inductively Coupled Plasma Mass Spectrometry). All statistical tests were performed using IBM SPSS 26 for Windows 10. A detailed description of the methods is provided in the Supplementary information.

3. Results

3.1. Stable isotope ratio analyses (δ¹³C, δ¹⁵N and δ³⁴S)

Almost all human and animal samples yielded good quality collagen based on the established quality criteria involving C/N, %C, %N, collagen yield, %S, C/S and N/S (DeNiro, 1985; van Klinken, 1999; Nehlich & Richards, 2009). Two animal samples (MOS 1995 and 1996) had %S, C/S and N/S ratios outside the accepted ranges (respectively: 0.15% to 0.35%, 600 ± 300 and 200 ± 100), and thus their δ³⁴S values were not interpreted. Furthermore, three fish samples (MOS 1977, 1976 and 1992) had acceptable atomic C/N, but lower %C and %N values than the range proposed by van Klinken (1999). Nevertheless, since these were greater than 13% for carbon and 4.8% for nitrogen (Ambrose, 1990; Fuller et al., 2020), we included them in our discussion. All isotope data generated, along with collagen quality criteria, are provided in Tables S3-S10.

3.1.1. Faunal samples

The mean ± standard deviation (SD) of δ¹³C and δ¹⁵N values for Bos taurus (cattle; δ¹³C: -22.0 ± 0.3‰, δ¹⁵N: 6.3 ± 1.2‰), Ovis vel Capra (sheep/goat; δ¹³C: -22.4 ± 0.2‰, δ¹⁵N: 8.9 ± 1.0‰), Sus scrofa domesticus (pig; δ¹³C: -22.2 ± 0.2‰, δ¹⁵N: 8.4 ± 0.9‰) and Gallus gallus domesticus (chicken; δ¹³C: -20.6 ± 0.5‰, δ¹⁵N: 9.9 ± 1.8‰) reflect terrestrial C₃-based diets for these animals. The chickens have higher δ¹³C and δ¹⁵N values with greater ranges than the other three taxonomic groups, reflecting perhaps the consumption of human food scraps (Müldner & Richards, 2007).

Marine fish (Pleuronectidae and Gadidae – among which three samples identified as Melanogrammus aeglefinus and one as Gadus morhua) have higher δ¹³C values (Pleuronectidae: -13.2‰, Gadus morhua: -10.9‰, mean ± SD: Gadidae: -11.8 ± 2.6‰, Melanogrammus aeglefinus: -13.7 ± 0.7‰) than the terrestrial animals, and similar to those obtained on cod samples from the western Baltic/Kattegat, southern North Sea and Northeast Atlantic (Orton et al., 2011). The δ¹⁵N values between the different marine taxa indicate
differences in trophic level, with fish from the gadid family having elevated values compared to those of the Pleuronectidae (Pleuronectidae: 7.6‰, Gadus morhua: 12.5‰, mean ± SD: Gadidae: 12.4 ± 2.0‰, Melanogrammus aeglefinus: 14.5 ± 0.8‰). Regarding the Gadidae fish, and based on both δ13C and δ15N values, it is possible that haddock (Melanogrammus aeglefinus) was imported from either the Northeast Atlantic or Arctic Norway, while other gadids may have been caught locally (Orton, et al. 2011; Barrett et al., 2011).

Freshwater taxa have typical low δ13C values (Esox lucius: -27.5‰, Cyprinidae: -25.6‰), even though a wide range in δ13C may be observed for this group, due to the influence of different carbon sources in freshwater ecosystems (Fuller, Müldner, Van Neer, Ervynck & Richards, 2012b; Guiry, 2019). Furthermore, the wild birds have similar δ15N values (Anser sp.: 6.3‰, Cygnus sp.: 6.5‰), indicating a similar trophic level, but different δ13C values (Anser sp.: -22.3‰, Cygnus sp.: -15.9‰) that may reflect the input of marine protein in the diet of the swan (Cygnus sp.). Finally, one sample of the taxon Felis catus (cat) has δ13C (-21.3‰) and δ15N (9.8‰) values that indicate a terrestrial diet, while three samples of Canis familiaris (dog) have mean ± SD δ13C (-19.8 ± 0.7‰) and δ15N (11.2 ± 1.1‰) values that reveal a diet similar to the diet of the humans from the two leprosaria (see 3.1.2 and Figure 2).

Sulphur isotope values were obtained from 13 animal samples that belong to the following taxa: Anser sp., Bos taurus, Canis familiaris, Capra/Ovis, Felis catus, Gallus g. domesticus and Sus s. domesticus, and have a δ34S value range between +5 and +15.5‰ (see Figures 5 and 6). All animals, except for two (Anser sp. and Bos Taurus) have δ34S values greater than +10‰. While the elevated δ34S values could reflect the consumption of food scraps that include marine protein for the dog, cat and chicken, the δ34S values of sheep/goats, pigs and cattle could suggest a sea-spray effect. This is perhaps supported by the slightly lower δ34S values reported for other terrestrial animals from the Baltic region (Linderholm, Fornander, Eriksson, Mörth & Lidén, 2014; Etu-Sihvola et al., 2019). No samples represented the freshwater ecosystem and only one was marine, due to the large amount of collagen needed for δ34S analysis (~ 5 mg). Although the %S, C/S and N/S values are within the range suggested by Nehlich and Richards (2009) for fish samples, a δ34S value was not generated. This was also the case for two terrestrial samples (Sus s. domesticus; MOS 1996, Gallus g. domesticus; MOS 1995), the latter of which has %S, C/S and N/S values outside the acceptable range.

**3.1.2. Human samples**

The rib mean ± SD δ13C and δ15N values of the leprosy patients from both Odense and Næstved indicate a C3 terrestrial diet with a small contribution of marine protein (δ13C: Odense: -19.7 ± 0.5‰, Næstved: -19.9 ± 0.4‰; δ15N values: Odense: 12.0 ± 0.6‰, Næstved: 11.8 ± 0.6‰), which is similar between male and female leprosy patients, as well as between individuals with and without RMS (Tables 2 and 3). All 43 individuals (rib samples) that were analysed for δ34S values have similar δ34S results to the majority of the animals (between +10‰ and +14‰), indicating a diet based mainly on terrestrial protein. Furthermore, male and female leprosy patients have similar mean ± SD δ34S values (males: 12.1 ± 0.7‰, females: 12.3 ± 0.8‰). The same dietary picture for the leprosy patients from Odense is also shown by the isotope values of long bone samples (mean ± SD: δ13C: -19.9 ± 0.6‰; δ15N: 11.8 ± 0.8‰; δ34S: 12.8 ± 0.9‰). The δ13C and δ15N values of individuals from other medieval Danish sites also reveal a similar diet in
contemporary, non-leprosy populations (Table 4). The results of the statistical comparisons that were performed are presented in Table S11.

3.2. Radiocarbon dating

The AMS radiocarbon dates are presented in Table S12. A simple Bayesian phase model is constructed to estimate the onset and termination of the two cemeteries (Odense and Naestved) altogether (Table S12, Figure 3). The output calibrated age ranges from Bayesian phase model are then used to test the statistical agreement with the expected arm position ages by combining the individual $^{14}$C modelled age ranges and the expected arm position age. If the combination of these age intervals fails, then $^{14}$C age and arm position age are in not in agreement. Agreement between the radiocarbon and arm position date ranges is only found for 50% of the $^{14}$C-dated individuals. This indicates that the arm position dating method is not always accurate, yielding both older and younger date ranges. By discussing different factors that might lead to the rearrangement of the arms during and/or after burial, Gilchrist and Sloane (2005) have already suggested the invalidity of this method for dating medieval burials in Britain.

3.3. $^{87}$Sr/$^{86}$Sr analysis

Table S15 summarizes the results of the strontium isotope analysis. All samples have acceptable mean $^{86}$Sr signal intensities to allow for appropriate corrections to the $^{87}$Sr/$^{86}$Sr data (Table S15; i.e. > 0.3 V, cf. Copeland et al., 2008). The resin had a maximum $^{86}$Sr signal of only 0.04 V (average = 0.003 V) and was only slightly higher than typical background $^{86}$Sr intensities on blanks during solution strontium analyses, indicating that it could not have been a source of strontium contamination. Furthermore, the $^{87}$Sr/$^{86}$Sr and $^{86}$Sr signal intensities of dentine are similar to those of the enamel, indicating the lack of diagenetic contamination. Data quality was assessed through monitoring the invariant $^{84}$Sr/$^{86}$Sr (0.05655 +/- 0.00014) and $^{88}$Sr/$^{85}$Rb. Several of the analyzed enamel samples with low strontium concentrations (i.e. $^{88}$Sr = <2 V) show $^{84}$Sr/$^{86}$Sr beyond these limits (samples 896, 936, 268, 265 and 6), while the enamel $^{86}$Sr/$^{85}$Rb ranged from 251 to 1548 indicating levels of $^{87}$Sr/$^{86}$Sr accuracy between 0.001 – 0.00008 (Yang et al., 2011). Due to the small range of $^{87}$Sr/$^{86}$Sr standard deviation (0.0011 – 0.0003) within each sample raster, individual measurements are not reported, while mean values are considered herein.

4. Discussion

4.1. Diet in medieval Danish leprosaria

According to the zooarchaeological evidence from the site of Vilhelm Werners Plads in Odense, the main animals consumed throughout the medieval period were cattle, sheep and pigs (Østergaard, 2016; 2018). Here, these animals have similar mean $\delta^{13}$C values, but different $\delta^{15}$N values, which may indicate different animal husbandry strategies (Fuller et al. 2012a). The $\delta^{15}$N mean value difference of almost one trophic level between cattle and sheep/goats has previously been reported for Roman and medieval Belgian sites by Müldner, Britton and Ervynck (2014), and may indicate different grazing environments, with
sheep/goats feeding on coastal plants that are influenced by sea-spray (Virginia & Delwiche, 1982) and soil salinity (Heaton, 1987), and thus have higher $\delta^{15}N$ values.

The humans from the two leprosy sites have mean $\delta^{13}C$ and $\delta^{15}N$ values that are elevated by 2-3‰ and 3.5‰, respectively, in relation to the mean values of the three domestic animal species, indicating that they constituted large components of the human diets (Bocherens & Drucker, 2003), while marine fish (mainly haddock) were also consumed, but in smaller quantities. The fish consumed by medieval individuals in Odense, and that we used for our baseline, does not have the low carbon isotope values recorded on marine fauna from the eastern Baltic or ‘Baltic Proper’ (Etu-Sihvola et al., 2019). Assuming that the samples we have collected are representative, this means that the endmembers of the marine trophic food webs exploited by the leprosy sufferers from Odense and Næstved are fully marine. Chicken were probably also part of the regular menu, but wild animals and freshwater fish were only a minor component. However, it should be noted that the sample numbers of wild animals and freshwater fish are limited (i.e. 2 of each). The statistical tests showed no difference in $\delta^{13}C$ and $\delta^{15}N$ values between Odense and Næstved leprosy hospitals (Table S11). The small dietary contribution of marine protein is true for both male and female leprosy patients, even though there is a statistically significant difference in $\delta^{13}C$ values between the two sexes at both sites, with male patients having slightly increased carbon isotope values (Table S11).

A terrestrial-based diet is further indicated by the sulphur isotope values of leprosy patients from the Odense leprosarium, which fall within the $\delta^{34}S$ value range of the domestic animals (sheep/goat, cattle, pig, chicken) (Figures 5 and 6). Generally, sulphur isotope values of terrestrial animals exhibit a wider range (0‰ to +10‰), which overlaps with the range of freshwater animals (−20‰ to +14‰), while marine animals range between +14‰ to +19‰ (Nehlich & Richards, 2009). Human values within this range, therefore, may reflect a significant dietary contribution of marine protein (Nehlich, 2015). Alternatively, values greater than +14‰ can also be the result of sea-spray in coastal regions (Richards et al., 2001; Nehlich, 2015).

An isotopic dietary reconstruction of individuals with bone lesions of leprosy was also conducted by Roffey et al. (2017) for the medieval leprosarium of St. Mary Magdalen in Winchester (England) and by Bayliss et al. (2004) for a medieval cemetery in Norwich (England) that was probably also related to a leprosarium. The $\delta^{13}C$ and $\delta^{15}N$ results indicate a similar C3 diet at all sites with small contributions of marine protein. Individuals from the two Danish leprosy hospitals have higher $\delta^{15}N$ values (Table 5), which could indicate either a relatively larger consumption of aquatic or terrestrial protein for the Danish leprosy patients, and/or a $\delta^{15}N$ value increase in the Danish baseline that could be linked to different manuring and husbandry practices. Noteworthy, the diet of leprosy patients from all four leprosy sites show small contributions of protein from aquatic resources, which is also evident for the leprosy patients from medieval Barcelona, Spain (Montes et al., 2018).

The small contribution of marine protein in the diet of institutionalized leprosy patients is of interest. The establishment of major marine fisheries during this period in northern Europe (Enghoff, 1996; 2016; Barrett et al., 2008; 2011; Barrett, 2016), and the semi-monastic nature of medieval leprosy hospitals (Rawcliffe, 2006:264), which would have entailed the consumption of large amounts of fish as part of the fasting rules, would suggest that marine/freshwater protein should have constituted an important dietary component for leprosy patients. Although the medieval towns of Næstved and Odense were situated close to the sea, and thus access to marine resources should have been possible, there is no evidence for
a significant consumption of marine foods in the two leprosy hospitals. This observation is also in contrast with the information provided by the 15th century document describing the daily availability of fish to the leprosy patients from Næstved (Ehlers, 1898:79-80 in Richards, 1977:144).

With the aim to investigate whether the diet of the leprosy patients may reflect their hospitalization or the regional dietary habits, we explored isotopically medieval Danish diets of contemporary populations from the wider vicinity of the leprosy hospitals (Ringsted, Skælskør, Odense – St. Knud’s and St. Alban’s churches). Even though all sites, except for the cemetery of St. Alban’s church, are related to monasteries, they also served as burial grounds for the lay populations of the areas (Christensen, 2002; Koch & Lynnerup, 2003:118; Boldsen & Mollerup, 2006). The $\delta^{13}C$ and $\delta^{15}N$ results for the contemporary populations revealed a terrestrial C3-based diet with small amounts of marine protein, similar to the diet of the leprosy patients (Figure 4). This is also in agreement with the dietary reconstruction of other medieval Danish populations: Holbæk is located in Zealand, approximately 63 km north of Næstved (Jørkov, Heinemeier & Lynnerup, 2009), while Ribe (one of the largest towns in medieval Denmark), Viborg (an important administrative, ecclesiastical and mercantile town) and Øm Kloster (a rural Cistercian monastery) are located in Jutland (Yoder, 2006) (Figure 1).

Even though the aforementioned sites cover a large geographic area of Denmark, the isotopic analysis reveals a similar diet that was primarily based on terrestrial protein. While marine protein constituted a small dietary contribution at most sites, the carbon and nitrogen isotope data from the large town of Ribe suggest it made up a larger proportion of the diet. The $\delta^{13}C$ and $\delta^{15}N$ mean value differences between the sites are rather small, with the largest ones being between Næstved leprosarium and Ribe for both carbon (0.7‰) and nitrogen (1.0‰). The mean $\delta^{13}C$ values of the leprosaria are closer to the values of two monasteries with related monastic orders (Øm Kloster, a Cistercian monastery; St. Knud’s church, related to a Benedictine monastery). When compared with local populations, the population from the Odense leprosarium is statistically significantly different from the population of St. Alban’s church in $\delta^{13}C$ (p = 0.001, r = 0.30) and the population of St. Knud’s church in $\delta^{15}N$ values (p = 0.013, r = 0.39), while there is also a statistically significant difference between the leprosarium at Næstved and the sites of Skælskør ($\delta^{13}C$ and $\delta^{15}N$ values) and Ringsted ($\delta^{13}C$ values) (Table S11).

### 4.2. “Leprosarium” and “Pre-leprosarium” diets

Ribs have a higher turnover rate than long bones, and thus their isotopic signature represents dietary patterns of the last few years of life (Cox & Sealy, 1997; Hedges, Clement, Thomas & O’Connell, 2007; Jørkov et al., 2009; Lamb, Evans, Buckley & Appleby, 2014). Although the period of residency in the leprosarium for the sampled individuals is unknown, the analysis of bones with different turnover rates likely provides us with information on diet both from the periods before and after the introduction to the leprosy community. Although new collagen was also synthesizing for the long bones during the last few years of life, their turnover rate was still much slower than the turnover rate of the ribs, and thus only a decadal (or longer) residency in the leprosarium could reflect the leprosarium’s dietary patterns also in the long bone samples. We, therefore, consider the rib isotope values as more representative of the “leprosarium” diet and the long bone isotope values as also indicative of “pre-leprosarium” diets.

Both rib and long bone mean ± SD $\delta^{13}C$ and $\delta^{15}N$ values indicate a C3 terrestrial diet with a small contribution of marine protein ($\delta^{13}C$ : ribs: -19.8 ± 0.5‰, long bones: -19.9 ± 0.6‰; $\delta^{15}N$: ribs: 11.9 ±
0.7%, long bones: 11.8 ± 0.8‰). The mean δ13C and δ15N value differences between long bone and rib samples are 0.1% and, thus, within analytical error, indicating that there was no significant dietary change between the last couple of decades and the last few years of life for these individuals. A similar diet between the two life periods is also indicated by rib and long bone δ34S results, with the majority of the individuals having δ34S offsets within the analytical error (i.e. lower than 1.2‰).

When considering the rib and long bone values of each individual separately, most offsets are too small (i.e. <0.6‰ for δ13C and <0.9‰ δ15N; Pestle et al. 2014) to indicate a meaningful change in the diet (Figure 7). We adopt the Minimum Meaningful Difference (MMD) reported by Pestle et al. (2014), which, however, was calculated to account for inter-laboratory differences and, thus, a smaller MMD may indeed be relevant here. In this study, collagen from all rib and long bone samples was extracted using the same procedure and analyzed by the same laboratory (Iso-Analytical). Although, 0.4‰ is four times above the analytical error and, thus, it accounts for “95% of the laboratory error” (Pestle et al. 2014:6), this value does not constitute a generalized threshold value, as larger values may be expected in mixed diets (cf. DeNiro and Schoeninger 1983 for monotonous diets). Further work, accounting for errors, such as intra-bone variability (Pestle et al. 2014), needs to be conducted to establish a more widely usable threshold value for meaningful intra-individual isotopic offsets.

Nonetheless, it is noteworthy that half of the individuals (25 out of 50) show an increase in the rib compared to the long bone samples in both δ13C and δ15N values. This pattern is perhaps indicative of an increase in marine protein consumption during the last few years of life. Based on a controlled feeding experiment, Webb et al. (2017) suggest that bulk isotope values should be cautiously interpreted when reconstructing paleodiet, since the contribution of marine protein may be either over, or underestimated, depending on the levels of protein consumption. Moreover, significant dietary changes between foods with similar isotopic value ranges may remain hidden and undetected by these analyses (problem of equifinality; Bogaard & Outram, 2013). We are currently conducting compound specific isotope analysis of individual amino acids to investigate further the contribution of different dietary sources in the diets represented by rib and long bone samples. Additionally, the fact that the majority of the δ13C rib/long bone offsets have the same (positive) direction may indicate a communal type of diet during the last few years of life, when the patients were most likely residing in the leprosy hospital.

Increased δ13C and δ15N values in ribs compared to long bones were also revealed for six medieval leprosy sufferers from England (Taylor et al., 2013) and Ireland (Taylor et al., 2018). However, the offsets were also small (most <0.6‰), and only one individual had both δ13C and δ15N offsets indicating a clear change in diet (0.8‰ and 3.2‰, respectively). In the Odense leprosy population one female (sk. 1147) and four male (sk. 65, 116, 616 and 936) patients have offsets that indicate a dietary change during their last few years of life. The female individual (sk. 1147) has negative δ13C and δ15N offsets between long bone and rib samples, respectively of 0.6‰ and 0.5‰, suggesting a decrease in marine protein consumption during the period that is represented by the rib sample (Figure 7). Sk. 936, too, has negative δ13C and δ15N offsets (0.7‰ and 0.2‰, respectively) between the two bone samples, as well as a negative δ34S offset of 1.5‰, suggesting either a decrease in the consumption of marine protein and/or an increase in the consumption of freshwater protein during the last few years of life. Likewise, the lower rib δ13C and δ15N values of sk. 65 (offsets: -0.1‰ and -1.0‰, respectively) indicate the consumption of terrestrial protein from a lower trophic level. In contrast, positive offsets are observed for the other two male patients (sk. 116 and 616). Sk. 116 has a δ13C offset of 0.8‰ and a δ15N offset of 0.7‰. The rib isotopic increase reflects either a larger dietary contribution of marine protein during the last few years of life, and/or an increase in the consumption of protein from terrestrial animals with higher isotopic values, such as possibly chickens.
This is also true for sk. 616, which shows an offset of 0.6‰ in δ^{13}C values and an offset of 0.3‰ in δ^{15}N values.

In the case of a hospital diet different from the diet of the pre-institutional period, we would expect the carbon and nitrogen isotope values of local populations to be closer to the values of long bone samples. However, when compared with the other two populations from Odense, both long bone and rib values of leprosy patients are statistically different from the values of St. Knud’s and St. Alban’s populations (Table S11). This could perhaps indicate that the analyzed individuals resided in the leprosy hospital for a period longer than 10 years, and thus their long bone values, too, represent the hospital diet. An alternative explanation could perhaps be the non-local origin of leprosy patients; an assumption, however, which is not supported by our strontium and sulphur isotope data (see further below). The cemetery of St. Knud’s church was in use until the early 19th century (Runge & Henriksen, 2018), and thus an isotopic mean value difference with the long bones of leprosy patients could be due to changing local diets through time. St. Alban’s church was demolished during the same period as the leprosarium (in 1542 CE, Boldsen & Mollerup, 2006) and, therefore, analyzed individuals from both sites fall more or less within the same timeframe. It is also likely that the leprosy population includes individuals from a wider region than the areas of origin of the people buried at St. Knud’s and St. Alban’s churchyards, with potentially different regional sources (and thus isotopic values; Hammers 2019:135) for grains and/or livestock. St. Knud’s church was related to a Benedictine monastery, and was the cathedral of the town (Christensen, 1988:97). Consequently, the churchyard would be used primarily by the monks of the monastery, but perhaps also by wealthy residents of the town (Christensen & Bjerregaard, 2017). Moreover, St. Alban’s church was one of the three parish churches of Odense, serving the central part of the town (Thrane, Nyberg, Grandt-Nielsen & Venge, 1982:212; Christensen, Bjerregaard & Runge, 2019).

4.3. Dietary variation in the leprosaria and possible interpretations

The main source of income for medieval Danish leprosaria was represented by the taxes that were paid to the hospitals by local communities, often in the form of foodstuffs (Richards, 1977:35). The dependence of Danish leprosaria on local communities, which may have experienced economic fluctuations through time, could perhaps explain the presence of different diets (i.e. fully terrestrial and mixed terrestrial-marine) in the leprosy hospitals by reflecting the changing ability of local communities to support them. Additionally, temporal changes in diet may have also occurred independently from the economic state of supporting communities. However, no dietary groupings based on chronological differences were revealed by the ^14C dating of a few individuals from the leprosy hospitals at Odense and Næstved. Yoder (2010) reports as well the absence of significant dietary changes through time in medieval Danish sites.

With the aim to investigate whether differences in diet could be linked to the disease, we compared the isotopic values between individuals with and without bone changes related to RMS, which could perhaps be linked to the practical difficulties caused by this set of facial bone changes in relation to food consumption. Nevertheless, with mean δ^{13}C and δ^{15}N value differences of 0.1‰ for Odense and 0.2‰ for Næstved, no dietary difference was evident between the two groups in either leprosarium (Table S11). Rawcliffe (2006:304) supports that the consumption of food in the form of pottage would have been popular in medieval leprosaria as a means to accommodate the needs of leprosy patients suffering from loss of teeth and wounds in the oral cavity. The consumption of similar foods in various forms by different
leprosy patients would remain hidden in the isotopic record, and could thus account for the similar \( \delta^{13}C \) and \( \delta^{15}N \) values of individuals with and without bone changes related to RMS.

Dahl (2001) claims that Danish leprosy patients derived from the entire social spectrum, and thus social status differences, reflected in the diet of the patients, may constitute an additional reason for the dietary variety in the two leprosaria. While diets rich in carbohydrates were common among the poor (Adamson, 2004:132; Yoder, 2012), wealthy individuals could more often afford the consumption of meat and fish, with game and freshwater fish often offered as high status presents (Kjersgaard, 1978:210; Dyer, 1988a; Adamson, 2004:36; Woolgar, 2006). The slow turnover rate of bone tissues, therefore, combined with different durations of residency in the leprosaria, signify that social status dietary variations of the pre-leprosarium period may be evident in the rib values of the analyzed leprosy patients. However, the intensification of the cattle production in Denmark from the mid-14th century onwards (Arcini, 1999:44), and the establishment of major marine fisheries of herring and cod in northern Europe (Barrett et al., 2011) would have lowered the cost of meat and fish, making them more affordable to the wider public and reshaping the aristocratic dietary trends (Müldner, 2016).

Nevertheless, a social inequality among residents of leprosaria, which had an impact on the diet, has been reported for the medieval leprosy hospital of Mont-aux-Malades at Rouen, France, where the leprous monks of the hospital enjoyed a diet similar to that of the canons (Brenner, 2012; 2016). A stratigraphic social entity was also seen between this leprosy hospital and other leprosy institutions, and, thus, Brenner (2012:248) supports that at least in the area of Rouen, “the pre-existing social and religious status of individual lepers […] played a crucial role in determining their fate”. A social stratification may also have been present within Danish leprosy communities (Ehlers, 1898:79-80 in Richards, 1977:144). Nonetheless, regarding the provision of goods, the surviving documents refer to the leprosy patients collectively (Ehlers, 1898:74-80 in Richards, 1977:142-144). It, thus, becomes evident that, at least in certain cases and regarding access to foods, a relative equality existed among the different groups of residents of medieval Danish leprosaria. This is perhaps reflected in the rib/long bone isotope values of the majority of the 50 leprosy patients from Odense that show a similar change for the last few years of life. The various diets present in the leprosarium may be linked to the different social backgrounds of the leprosy patients, while differences in the offsets between rib and long bone values could reflect differences in the residential periods.

4.4. Mobility patterns of leprosy patients

The strontium isotope ratios of almost all analyzed leprosy patients are consistent with a childhood spent in Denmark. In Denmark, Late Cretaceous-Early Tertiary carbonate platforms and marine clastic sediments form a young and homogenous bedrock, which is covered by Quaternary glaciogenic sediments (Frei & Price, 2012). A mixture of deposits from the glaciogenic sediments and the geological backgrounds form the topsoils, which are enriched in strontium carbonates and have a narrow range of \( {^{87}Sr}/^{86}Sr \) (Frei and Price, 2012). The incorporation of geological derived strontium isotope ratios in human tissues may be influenced by factors such as agricultural fertilizers, precipitation, atmospheric dust, sea-sprays and the unequal weathering of different minerals in single soils (Böhlke & Horan, 2000; Price, Burton & Bentley, 2002; Evans, Montgomery, Wildman & Boulton, 2010). Frei and Price (2012) have established the bioavailable \( {^{87}Sr}/^{86}Sr \) within present-day Denmark (excluding Bornholm), and report ranges between
0.7078 – 0.7098 in the western part (Jutland) and between 0.7089 – 0.7108 in the eastern part (Funen, Zealand and the southern islands) of the country. This baseline, however, has recently been questioned and the range extended (Thomsen and Andreasen, 2019; Klassen, Price, Sjögren, Wincentz & Philippsen, 2020).

Because both leprosy hospitals are located in the eastern part of Denmark (Odense on Funen and Næstved on Zealand), strontium isotope values in tooth enamel between the range of 0.7089 – 0.7108 could potentially suggest a local origin for the analyzed leprosy patients. Almost all individuals (six from each leprosarium) have mean strontium isotope ratios that fall within the bioavailable range for eastern Denmark (Figure 8). The narrow ranges of mean $^{87}\text{Sr}/^{86}\text{Sr}$ (SD of mean = 0.0003) indicate that the individuals remained in an area with similar bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ during the whole maturation period of the enamel (i.e. from the first 4-5 months after birth until ~7 years of age; Schuurs 2013:431). One individual (sk. 896) from the Odense leprosy hospital has a maximum $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7124 (mean = 0.7114), and almost all data points collected from the enamel of this individual are higher than the maximum of the eastern Danish bioavailable range (0.7108). Slightly higher $^{87}\text{Sr}/^{86}\text{Sr}$ than 0.7108 (i.e. 0.711 – 0.714) have been reported for the area of Bohuslän in western Sweden (Sjögren, Price & Ahlström, 2009; albeit Klassen et al., 2020 report $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.710 – 0.711), which, up to the mid-17th century, was part of the Dano-Norwegian Realm. Nevertheless, in a recent study on $^{87}\text{Sr}/^{86}\text{Sr}$ from pristine waters in Jutland, Denmark, Thomsen and Andreasen (2019) reported higher ratios (reaching up to 0.715), and attributed the lower values of surface waters that have been reported by Frei and Frei (2011) in lime-affected samples, suggesting a wider bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ range for Denmark.

A possible local origin for these, and another five, leprosy patients from the Odense leprosarium is also evident by the small $\delta^{34}\text{S}$ offsets (maximum 1.5%) between rib and long bone samples (Figure 9). Plants (subsequently animals and humans) take up sulphur from the atmosphere and the soil (Nehlich 2015). The underlying bedrock and microbial activities influence the sulphur values of soils (Richards, Fuller, Sponheimer, Robinson & Ayliffe, 2003); albeit the bedrock exposure is minimal in Denmark (Klassen et al., 2020). Another contributing factor is oceanic sulphur, which is redeposited as rain and through sea sprays, rendering $\delta^{34}\text{S}$ values useful in distinguishing between an inland or coastal ($\delta^{34}\text{S}$ values intermediate between terrestrial and marine) influence on the analyzed tissue (Mizota & Sasaki, 1996). Consequently, provided that environmental $\delta^{34}\text{S}$ values differ between areas, significantly different $\delta^{34}\text{S}$ values can distinguish non-local from local individuals in a certain area (e.g. Vika, 2009; Moghaddam et al., 2018). The small rib versus long bone offsets, therefore, likely indicate that the analyzed individuals resided in an area with similar environmental $\delta^{34}\text{S}$ values during the last couple of decades and the last few years of their life.

A local origin for the leprosy patients could reflect admission rules to medieval Danish leprosaria. According to Ehlers (1898:10), admission to leprosy hospitals was only possible for residents of communities that were local to the leprosaria, and which paid taxes (often in the form of naturalia, Richards 1977:35) to these institutions. For instance, Arentoft (1999:225) mentions that the leprosy hospital in Svendborg received individuals from four districts, without specifying, however, the exact area that these covered. Moreover, residents of towns with no local leprosy hospitals could turn to the nearest leprosarium for admission (Ehlers, 1898:10). Nevertheless, a late 15th century royal decree mentions that admission to the leprosy hospital outside of Næstved was reserved only for sick individuals from the parish that paid taxes to the leprosarium (Ehlers, 1898:79-80 in Richards, 1977:144). A local origin as the main
factor for an individual to be accepted in a leprosy hospital has also been reported in other countries (e.g. England, Rawcliffe, 2006:293; France, Brenner, 2016; Spain, Jáuregui, 2018).

Despite the admission regulations for Danish leprosy hospitals, which entailed a local origin and/or residency for the leprosy patients, certain situations (such as the inability of a specific leprosarium to care for additional patients) may have obliged leprosy sufferers to seek a suitable place in a more distant leprosy hospital. However, about 46 leprosy hospitals were operating in Denmark some time from the 12th until the 16th century (Arentoft, 1999:195-206). The rather close proximity of the leprosy hospitals (cf. Arentoft, 1999:193) in connection to the relatively homogenous geology of Denmark that divides the area in only two $^{87}\text{Sr}/^{86}\text{Sr}$ groupings (Frei & Price, 2012), complicate the identification of such mobility patterns, since the “local” $^{87}\text{Sr}/^{86}\text{Sr}$ range for both leprosaria actually corresponds to the $^{87}\text{Sr}/^{86}\text{Sr}$ range of a much larger area (eastern Denmark), and, thus, mobility occurring within eastern Denmark cannot be detected.

5. Conclusions

Following a multi-isotopic approach, the present study has generated new knowledge on the dietary patterns and origin of leprosy sufferers from two medieval Danish leprosaria. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of rib samples reveal a terrestrial C$_3$-based diet with small contributions of marine and/or freshwater protein for some individuals. This dietary picture remains relatively the same through time, as well as between males and females, and patients with and without bone changes of RMS. A similar diet was also shown for individuals from other medieval Danish sites, although in certain areas marine foods played a greater dietary role. The small contribution of protein from aquatic resources in the diet of the leprosy patients is unexpected for institutions of a monastic character. It further contradicts the information provided by the late 15th century document regarding a daily availability of fish to patients from Næstved leprosarium (Ehlers, 1898:79-80 in Richards, 1977:144). Isotopic comparisons between bones with different turnover rates indicate that the isotopic change, even though small, is the same (i.e. higher $\delta^{13}\text{C}$ and/or $\delta^{15}\text{N}$ values) in the rib compared to the long bone sample for most individuals, pointing towards a communal type of diet and revealing organizational aspects of the institution. As an extension, differences in the rib/long bone offsets between different individuals possibly reflect differences in the duration of residency in the leprosarium before death occurred. Nonetheless, only five individuals show a definitive dietary shift (sk. 65, 116, 616, 936 and 1147; Pestle et al. 2014), and, thus, these interpretations are made with caution. Moreover, strontium isotope data in tooth enamel and bone collagen $\delta^{34}\text{S}$ values are consistent with a local origin for the analyzed leprosy patients, which is in line with historical evidence (Ehlers, 1898:10; Arentoft, 1999:225). Even though the sample size is small, our study is the first to generate strontium isotope data using the laser ablation technique for archaeological Danish samples.

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Data availability statement
The data that supports the findings of this study are available in the supplementary material of this article.

Conflict of interest
The authors have no conflicts of interest to report.

References


Danmarks Kirker, Thisted Amt, XII (1940-1942). Edited and published by the National Museum of Denmark (Nationalmuseet).


Figure 1. Map of Denmark showing the different sites discussed. The site of Odense (2) refers to the populations from St. Knud’s and St. Alban’s churches, as well as to the Odense leprosarium (CC0 1.0 Universal; edited).

Figure 2. Stable carbon and nitrogen isotope data of animal samples from the site of Vilhelm Werners Plads in Odense and of the humans from the two leprosy hospitals.

Figure 3. Calibrated age probability distributions of $^{14}$C dated individuals (Table S12) from the Odense and Næstved cemeteries. The burial arm positions A, B, C/D are marked with green, blue and orange, respectively. Uncertain arm positions are marked with grey. Also shown are the expected arm position age intervals (see Boldsen, 2009). Onset and termination age of the two cemeteries (marked with black) are estimated using Bayesian phase model to 1142 AD – 1242 AD and 1473 AD – 1617 AD, respectively (95.4% confidence interval).

Figure 4. Mean $\delta^{13}$C and $\delta^{15}$N values of medieval Danish populations from Jutland (Øm Kloster, Viborg and Ribe: Yoder, 2006), Fyn (Odense leprosarium, St. Knud’s and St. Alban’s: present study) and Zealand (Holbæk: Jørkov et al., 2009; Næstved leprosarium: Brozou et al., 2019 and present study; Ringsted and Skælskør: present study).

Figure 5. Human and animal $\delta^{34}$S and $\delta^{13}$C results from medieval Odense, Denmark.

Figure 6. Human and animal $\delta^{34}$S and $\delta^{15}$N results from medieval Odense, Denmark.

Figure 7. Rib/long bong carbon and nitrogen isotope offsets for each male and female leprosy patient individually (Odense leprosarium).

Figure 8. Mean $^{87}$Sr/$^{86}$Sr ratios of twelve individuals from Næstved (N) and Odense (O) leprosy hospitals. All individuals have ratios within the suggested bioavailable $^{87}$Sr/$^{86}$Sr range for Denmark (0.7089 – 0.7108; Frei and Price, 2012, and 0.7150 as the maximum extent of the $^{87}$Sr/$^{86}$Sr range; Thomsen and Andreassen, 2019).

Figure 9. $\delta^{34}$S offsets between rib and long bone samples of eleven individuals from Odense leprosarium.
## Table 1. Number of samples and analyses conducted for each site.

<table>
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<th>Site</th>
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<th>Elem.</th>
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<th>Mean</th>
<th>SD</th>
<th>Min.</th>
<th>Max.</th>
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<td>0.4</td>
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<td>0.8</td>
<td>9.9</td>
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<td>0.3</td>
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<td>54</td>
<td>-19.7</td>
<td>0.3</td>
<td>-20.3</td>
<td>-19.2</td>
<td></td>
</tr>
</tbody>
</table>

## Table 2. Descriptive statistics of male and female individuals from the leprosy hospitals at Odense and Næstved.

<table>
<thead>
<tr>
<th>Site</th>
<th>Sex</th>
<th>Elem.</th>
<th>δ¹³C/δ¹⁵N</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odense leprosarium</td>
<td>males</td>
<td>ribs</td>
<td>δ¹³C</td>
<td>51</td>
<td>-19.5</td>
<td>0.5</td>
<td>-20.5</td>
<td>-18.6</td>
</tr>
<tr>
<td></td>
<td>males</td>
<td>δ¹⁵N</td>
<td>12.1</td>
<td>0.7</td>
<td>10.8</td>
<td>14.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Odense leprosarium</td>
<td>females</td>
<td>ribs</td>
<td>δ¹³C</td>
<td>49</td>
<td>-19.8</td>
<td>0.4</td>
<td>-20.5</td>
<td>-18.6</td>
</tr>
<tr>
<td></td>
<td>females</td>
<td>δ¹⁵N</td>
<td>12.0</td>
<td>0.6</td>
<td>10.2</td>
<td>13.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Næstved leprosarium</td>
<td>males</td>
<td>ribs</td>
<td>δ¹³C</td>
<td>16</td>
<td>-19.7</td>
<td>0.3</td>
<td>-20.3</td>
<td>-19.2</td>
</tr>
<tr>
<td></td>
<td>males</td>
<td>δ¹⁵N</td>
<td>12.0</td>
<td>0.4</td>
<td>11.3</td>
<td>12.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Næstved leprosarium</td>
<td>females</td>
<td>ribs</td>
<td>δ¹³C</td>
<td>15</td>
<td>-20.1</td>
<td>0.4</td>
<td>-20.8</td>
<td>-19.2</td>
</tr>
<tr>
<td></td>
<td>females</td>
<td>δ¹⁵N</td>
<td>11.7</td>
<td>0.8</td>
<td>9.9</td>
<td>12.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Descriptive statistics of individuals from the leprosy hospitals at Odense and Næstved with and without bone changes linked to RMS.

<table>
<thead>
<tr>
<th>Site</th>
<th>RMS</th>
<th>Elem.</th>
<th>$\delta^{13}C/\delta^{15}N$</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odense leprosarium</td>
<td>with ribs</td>
<td>$\delta^{13}C$</td>
<td>55</td>
<td>-19.7</td>
<td>0.5</td>
<td>-20.4</td>
<td>-18.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta^{15}N$</td>
<td></td>
<td>12.1</td>
<td>0.6</td>
<td>10.2</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td>Odense leprosarium</td>
<td>without ribs</td>
<td>$\delta^{15}N$</td>
<td>26</td>
<td>-19.6</td>
<td>0.5</td>
<td>-20.5</td>
<td>-18.6</td>
<td></td>
</tr>
<tr>
<td>Næstved leprosarium</td>
<td>with ribs</td>
<td>$\delta^{13}C$</td>
<td>24</td>
<td>-19.8</td>
<td>0.5</td>
<td>-20.8</td>
<td>-19.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta^{15}N$</td>
<td></td>
<td>11.8</td>
<td>0.6</td>
<td>9.9</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>Næstved leprosarium</td>
<td>without ribs</td>
<td>$\delta^{13}C$</td>
<td>4</td>
<td>-20.0</td>
<td>0.4</td>
<td>-20.4</td>
<td>-19.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta^{15}N$</td>
<td></td>
<td>12.0</td>
<td>0.7</td>
<td>11.3</td>
<td>12.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Descriptive statistics of $\delta^{13}C$ and $\delta^{15}N$ values from more than 500 human samples coming from medieval sites in Denmark.
<table>
<thead>
<tr>
<th>Site</th>
<th>n</th>
<th>δ¹³C Mean</th>
<th>δ¹³C Min.</th>
<th>δ¹³C Max.</th>
<th>δ¹⁵N Mean</th>
<th>δ¹⁵N Min.</th>
<th>δ¹⁵N Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odense leprosarium</td>
<td>100</td>
<td>-19.7</td>
<td>-20.5</td>
<td>-18.6</td>
<td>12.0</td>
<td>10.2</td>
<td>14.0</td>
</tr>
<tr>
<td>Næstved leprosarium</td>
<td>31</td>
<td>-19.9</td>
<td>-20.8</td>
<td>-19.2</td>
<td>11.8</td>
<td>9.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Winchester leprosarium</td>
<td>43</td>
<td>-19.3</td>
<td>-20.5</td>
<td>-18.2</td>
<td>10.5</td>
<td>8.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Norwich</td>
<td>8</td>
<td>-19.0</td>
<td>-20.6</td>
<td>-17.0</td>
<td>11.3</td>
<td>10.0</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table 5. δ¹³C and δ¹⁵N mean, minimum and maximum values for individuals from the medieval Danish leprosy hospitals of Odense and Næstved, as well as from one contemporary English leprosarium (Winchester, Roffey *et al.*, 2017) and a site in Norwich probably also related to a leprosy hospital (Bayliss *et al.*, 2004).