# Feeding the sick: an insight into dietary composition at a Medieval leper hospital using dental wear pattern analysis.

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## Abstract

In the Middle Ages, palliative dietary regimens were fundamental to the treatment of disease. It was believed that the foods eaten were central to bringing balance to the human body. Alleviating the symptoms of leprosy required the consumption of foods considered moist and mild, which included certain kinds of meat. Medieval lepers were housed and treated in leprosaria (leper hospitals), often located on the outskirts of towns and cities. The quality of the food consumed at each institution, however, varied considerably according to its financial situation. The extent to which the diet of lepers corresponded to that advised by Medieval physicians, therefore, remains largely uncertain. Here, a method of 3D dental wear pattern analysis, called Occlusal Fingerprint Analysis, is used to infer the dietary composition of individuals interred at the cemetery associated with the medieval leprosarium and later almshouse of St James and St Mary Magdalene, Chichester (n=24). It was found that the dental wear pattern of individuals with osseous changes consistent with lepromatous leprosy showed an enlargement of buccal phase I wear when compared to the rest of the cemetery and a comparative group interred at St Michael's Litten lay cemetery, Chichester (n=17). Differences in dental wear patterns suggest that the lepers at this cemetery had regular access to meat beyond the quantities consumed by the majority of the lower social strata of Medieval society and more consistent with the palliative care recommended by Medieval medical theory.

## Keywords

Leprosy, diet, dental wear, medieval, wear facets.

## 1. Introduction

Leprosy (Hansen's disease) is a chronic disease caused by *Mycobacterium leprae*, which typically involves the peripheral nervous system, the skin and mucosa of the upper respiratory tract (Dwivedi *et al.* 2019). The effects of the disease are closely related to an individual's immunological response mediated by genetic risk factors (Alter *et al.* 2011) and nutrition (Dwivedi *et al.* 2019). The incubation period can be between 3-5 years. The disease is classified clinically into several types. The two extremes of this spectrum are the tuberculoid form, involving small single skin lesions and solitary enlarged peripheral nerves, and the lepromatous form, which presents as numerous confluent skin lesions and symmetrical anaesthesia in the hands and feet (Lockwood 2005). Skeletal involvement is often associated with lepromatous leprosy and can be identified in archaeological material based on the presence of rhino-maxillary syndrome: resorption and loss of the central portion of the maxilla, destruction of the nasal aperture and modification of the nasal aperture (Andersen and Manchester 1992; Kasai *et al.* 2018; Møller-Christensen 1978; Manchester and Roberts 1989; Waldron 2008).

In Britain, historical and archaeological evidence indicates that leprosy had become a disease of marked prevalence and social importance from the 11th to 13th centuries CE but had begun to decline in prevalence by the 16th century (Manchester and Roberts 1989). Medieval physicians attributed various factors, ranging from poor diet to sexual misconduct to divine will, to the development and aggravation of leprosy. Prolonged contact with lepers was not universally deemed a risk factor (Rawcliffe 2006). Despite this, leprous individuals were housed in special hospitals called leprosaria, which were often located on the outskirts of towns and cities. Most of England's 300 documented leprosaria were founded prior to the 14th century. Many of these institutions may have served small rural communities. In the 15th century, the majority of leprosaria took on a more general use as accommodation for the ill, sick and poor (Roffey 2012).

Medieval medical authorities were informed by Greek humoral theory and were dominated by references to Galen (c. 200 CE) and Hippocrates (d.c. 370 CE) (Kibre 1945; Riddle 1974). The body was theorised to function effectively when the four humours, blood, phlegm, yellow bile and black bile, were in balance (Huggon 2018). The humours were believed to be generated by the digestion of food. The first principle of Medieval medicine, therefore, was diet and treatises circulated detailing the qualities and dangers of particular foodstuffs (Nicourd 2008). The classification of animals, plants and minerals, according to their heat, coldness, moisture and aridity, developed into a highly complex pharmacological science in the Middle Ages. Medical conditions were often treated based on individual symptoms and, therefore, required the prescription of multiple ingredients if humoral balance was to be restored (Riddle 1974). Excess accumulations of a humour could lead to illness, of which the build-up of yellow bile and black bile were particularly serious (Rawcliffe 2006). Galen attributed the origin of leprosy to the excess accumulation of black bile in the veins. This theory was later developed by Paul of Aegina, a 7th century Byzantine physician, to include two different types and origins of leprosy: a lesser type emerging from the build-up of black bile and a more severe type occurring when an excess of overheated yellow bile in the vessels of the body corrupted the black bile (Miller and Nesbitt 2014).

Consequently, careful attention was paid to the diet eaten at the leprosaria in order to restore a degree of humoral balance and strengthen the body's defences. The lepers were encouraged to eat mild and moist foodstuffs, such as poultry, freshly baked bread, eggs, veal, pork and fresh fish. These foods were regarded as easily digestible and capable of cooling their overheated digestive system. Hospitals with estates could draw upon their tenants for fresh produce. They also frequently had fishing rights and reared dairy cattle, pigs and hens to fulfil their dietary requirements (Brenner 2010; Radcliffe 2006). However, in the absence of this practice, Medieval hospitals and almshouses were noted for their tendency to economise on the quantity and quality of the food provided in some cases (Rawcliffe 1984).

More affluent institutions provided a palliative dietary regime more consistent with Medieval medical theory and the monastic template they emulated. At such institutions, meat was eaten regularly as shown by records of disobedience that demanded the forfeiting of an individual's customary ration. At the well-funded hospital of St Anthony in London the provisioning of meat was lavish, particularly on high days and holidays (Rawcliffe 1984). As income diminished the amount of meat available was likely reduced. In 1334 CE, the reduced budget of Hedon hospital led begrudgingly to the reduction of the otherwise generous daily ration of beef, pork, mutton or the herring eaten on fast days (Rawcliffe 2006).

Dental wear patterns have been previously used to infer diet in archaeological skeletal remains (Fiorenza *et al.* 2011; Fiorenza *et al.* 2018). Fundamental assumptions underpinning these methods are that human chewing patterns adapt to the mechanical and physical properties of the foods they consume (Woda *et al.* 2006) and that differences in chewing parameters will be reflected in the wear patterns that develop on the teeth (Kullmer *et al.* 2009; Kullmer *et al.* 2012). During each feeding sequence, puncture-crushing cycles, in which the molars come together in a vertically directed movement, pulp and reduce the ingested food whilst causing generalised abrasive wear across the occlusal surface of the tooth (Kay and Hiiemae 1974; Hiiemae *et al.* 1996*)*. As the food is reduced further, the opposing surfaces of the teeth come together more closely in a movement called the power stroke. The phase I movement, the slow part of jaw closing, involves the lower teeth moving from a lateral position into maximum intercuspation. Prominent shearing forces are exerted on the food during this phase I movement. A crushing action accompanies maximum intercuspation and is followed by phase II of the power stroke. The phase II movement, or slow stage of jaw opening, is mesially and downwardly directed and ends once the teeth are no longer in contact (Schultz and Martin 2014; Wall *et al.* 2006). The power stroke creates highly polished planar wear surfaces, called dental wear facets, at specific areas of the occlusal surface as the teeth move into and out of contact (Lewis and Dwyer-Joyce 2005). Dental wear facets represent the accumulation of tooth use over an individual's lifetime and reflect the prominent pathways of jaw movement during chewing (Fortelius and Solanis 2000; Kullmer *et al.* 2012; Fiorenza *et al.* 2018). Differences in dental wear facet patterns were identified between hunter-gatherers consuming different proportions of meat (Fiorenza *et al.* 2011). Dental wear facets are, therefore, effective indicators of diet (Janis 1990).

The assemblage excavated from the cemetery associated with the leprosarium of St James and St Mary Magdalene, Chichester, represents one of the largest groups of skeletons from an English Medieval hospital context (Figure 1). The hospital was likely founded some time before 1118 CE. It comprised 285 adult individuals of whom 84 showed osseous changes consistent with leprosy (Magilton *et al.* 2008). The leprosarium of St James and St Mary Magdalene was probably moderately funded (Rawcliffe 2006). During the 14th and 15th centuries, several historical records refer to the inhabitants of the institution as 'the poor' of St. James' suggesting a shift in function to an almshouse during this period. The final documentary reference to leper inmates is dated to 1418 CE (Magilton *et al.* 2008). The cemetery area is divided into two parts. In Area A, the south-western portion of the cemetery, burials comprised mostly males with changes compatible with leprosy in 61.5% of individuals. This likely represented the earliest phase of burials at the cemetery occurring from the 12-14th centuries when the site functioned as a leprosarium. Area B, the north eastern parts of the cemetery, contained fewer individuals with skeletal changes indicative of lepromatous leprosy (only 15%) alongside more female and non-adult burials. This area likely primarily represented the period in which the function of the institution shifted to that of an almshouse from the 15th century onwards (Magilton et al. 2008).

Here a method of three-dimensional dental wear pattern analysis, called Occlusal Fingerprint Analysis (OFA), was used to assess the hypothesis that individuals (n=12) with osseous changes consistent with lepromatous leprosy interred at the leprosarium of St James and St Mary Magdalene, Chichester, were provided with a palliative dietary regimen in accordance with Medieval medical theory. Comparative material comprised 12 individuals from the site who did not present osseous evidence for lepromatous leprosy and 17 non-leprous individuals drawn from the Medieval and early Post-Medieval portion of the lay cemetery of St Michael's Litten, Chichester (1100-1700 CE) (Figure 1).


*Figure 1: Left: Map showing the location of Chichester in the United Kingdom. Right: Map showing the areas of excavation of the cemetery associated with the leprosarium of St James and St Mary Magdalene (purple) and the cemetery of St Michael's Litten (orange) in Chichester. Contains OS data © Crown copyright and database right 2018.*

## 2. Materials and Methods

Skeletons were selected from the cemetery assemblage associated with the leprosarium of St James and St Mary Magdalene, Chichester, held at the University of Bradford (12 with skeletal evidence of rhino-maxillary syndrome, which is pathognomonic of lepromatous leprosy (see Waldron 2008, p.101 for operational definition used), and 12 without). Twelve individuals examined were from area A and 12 individuals were from area B. Skeletal material (n=17) dating to the Medieval and early Post-Medieval periods (AD1100-1700) from the lay cemetery of St Michael's Litten, Chichester, was used as a group against which the St James and St Mary Magdalene material could be compared (Figure 1; Table 1; Supplementary Table 1). Non-adults were not included in the sample. These were defined as individuals without fully erupted dentitions excluding the third molars. Sex was estimated using pelvic and cranial morphology (Buikstra and Ubelaker 1994; Phenice 1967) and age-at-death was estimated based on the degeneration of the auricular surface of the innominate bone (Buckberry and Chamberlain 2002). All the individuals examined were scored within Buckberry-Chamberlain auricular surface stages I-III (2002). The deceased at the cemetery of St Michael's Litten were likely drawn from a broad cross-section of the socioeconomic classes of the town of Chichester.

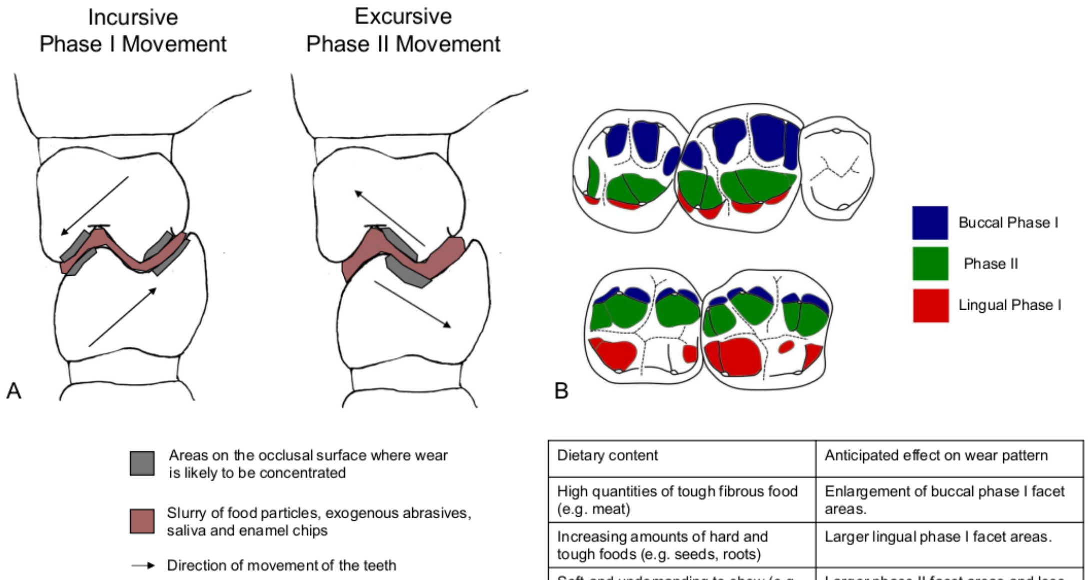
*Table 1: Table showing the demographic composition of the samples included in the current research.*

| Site | Lepromatous Leprosy | Present | | | Absent | | |
|---|---|---|---|---|---|---|---|
| | Sex | Female | Indeterminate | Male | Female | Indeterminate | Male |
| St James and St Mary Magdalene: Area A | | 3 | 2 | 4 | 2 | 1 | 0 |
| St James and St Mary Magdalene: Area B | | 1 | 0 | 2 | 7 | 0 | 2 |
| St Michael's Litten | | 0 | 0 | 0 | 6 | 2 | 9 |

Occlusal Fingerprint Analysis is described in detail in other publications (Kullmer *et al.* 2009; Fiorenza *et al.* 2011, Zanolli *et al.* 2019) so will be only briefly dealt with here. Individuals were selected with a lower second molar with a Smith (1984) wear score of 2 (moderate cusp removal with or without pin-point dentine exposure) as OFA can only be applied to relatively unworn teeth (Fiorenza *et al.* 2018). The second molar was selected as the target for OFA as it has been shown to provide an effective representation of masticatory behaviours in primates (Kay 1973; Knight-Sadler and Fiorenza 2017). Wear facet patterns can only be compared between a single tooth position due to functional differences between the molars from anterior to posterior, which relate to subtle differences in dental morphology and their position and inclination in relation to the temporomandibular joint (Spears and Macho 1998). The samples selected from the St James and St Mary Magdalene and St Michael's Litten material represented all of the suitable and available individuals within these assemblages. The remainder either lacked lower second molars or possessed molars that were too worn or inadequately worn.

A two-phase, two-step, putty-wash technique, utilising President® Putty Soft and President® Light Body polyvinylsiloxane impression materials (Coltène/Whaledent Inc), was used to take a dental impression of the lower second molar of each individual (Hung *et al.* 1992; Jamshidy *et al.* 2016; Varvara *et al.* 2015). A dental gypsum model was produced for each lower second molar using non-reflective dental die stone (Suprastone® Dental Die Stone Type IV; Kerr Corporation). This gypsum model was used to generate a 3D model of the tooth using a structured light scanning system (GOM ATOS 80 Scanner, GOM, Braunschweig, Germany).

OFA was performed using GOM Inspect (Version 2018 Hotfix 6) based on the method of Kullmer *et al.* (2009). Wear facets on the occlusal surface of each lower second molar were identified, demarcated and labelled using the terminology of Maier and Schneck (1981; 1982). The area of each wear facet was measured and grouped according to the phase of the power stroke with which it was associated, either phase I (divided into buccal phase I and lingual phase I facets) or phase II (Figure 2). Levels of intra-observer error for this method have previously been demonstrated by the author to be within an acceptable range for repeated measures of metrics (Silvester and Hillson 2020). The area associated with each aspect of the power stroke was expressed as a proportion of the total area of the wear facets present across the occlusal surface. This data will reflect any major differences in dietary consistency between the groups examined. The inclination of wear facets provides evidence of the abrasive content of the foods eaten and through this an insight into food preparation techniques. Consequently, the inclination of each wear facet, called the wear facet dip angle, was measured by attaching a best-fit plane to the wear facet and measuring the angle between this plane and a best-fit plane fitted to a curve drawn around the cervix of the tooth. Tip crushing areas were not considered in the current analysis as previous studies have not attributed the formation of these wear areas to the power stroke (Janis 1990; Fiorenza *et al.* 2011; Fiorenza *et al.* 2018).




| Dietary content | Anticipated effect on wear pattern |
| --- | --- |
| High quantities of tough fibrous food (e.g. meat) | Enlargement of buccal phase I facet areas. |
| Increasing amounts of hard and tough foods (e.g. seeds, roots) | Larger lingual phase I facet areas. |
| Soft and undemanding to chew (e.g. modern industrialised diet). | Larger phase II facet areas and less well-developed phase I areas. |

*Figure 2: A) Illustration showing the two phases of the chewing power stroke in anatomically modern humans. The areas of the occlusal surface at which wear is concentrated during each phase of the power stroke is shown in grey. Figure created by author. B) Schematization of the wear facet pattern of the lower and upper molars in anatomically modern humans. The table below describes the anticipated effects differences in dietary composition may have on the dental wear facet pattern (Fiorenza* et al. *2011; Janis 1990). Redrawn from Journal of Human Evolution, Vol 8 (1), MaierW. & Schneck G., Functional morphology of hominoid dentitions, Pages 693-6, Copyright (1982), with permission from Elsevier.*

Ternary plots were used to visualise differences in wear facet area composition between individuals with and without skeletal changes consistent with lepromatous leprosy and between cemetery areas A and B. Cemetery areas A and B were compared because it has been argued that they may represent respectively earlier and later phases of burial at the site (Magilton *et al.* 2008). As most leprous individuals selected were drawn from cemetery area A, it was necessary to establish whether any temporal trends in dental wear pattern might be contributing to any differences observed between leprous and non-leprous individuals. A ternary plot is a diagram that displays three variables which sum to a constant (1 or 100%). Ternary diagrams were produced in R statistical software (v.3.6.1) using the package ‘ggtern’.

The statistical assessment of the relationship between the presence of leprosy, cemetery area and wear facet area composition were performed using the methods of Aitchison (1986) and Boogaart and Tolosana-Delgado (2013). The data was subject to an isometric-log ratio transformation prior to statistical analysis to overcome the issues with applying conventional statistical approaches to compositional data i.e. data in which each set of observations sum to 100% (Egozcue *et al.* 2003). Type II Permutational-multivariate analysis of variance (PERMANOVA) was then applied to the Euclidean distance matrix of the isometric-log ratio transformed data to assess differences in wear facet composition between the groups within the cemetery and with the St Michael's Litten material (Anderson 2001; Anderson 2017). A permutation value of 9999 was selected. The interaction effect between cemetery area and the presence of leprosy was also considered given that a significantly greater proportion of the individuals examined with osseous changes consistent with lepromatous leprosy were located in cemetery area A (chi-square value=4.17, df = 1, p-value = 0.04). The mean dip angle for each wear facet type (buccal phase I, lingual phase I and phase II) was calculated for each lower second molar examined. Type II PERMANOVA was also used to assess the relationship between leprosy, cemetery area and wear facet dip angle after transforming the data using a Bray-Curtis dissimilarity matrix. Statistical analysis was performed using the packages 'RVAideMemoire 0.9-66' and 'compositions' in R statistical software.

## 3. Results

Wear facet area proportions differed significantly between individuals with leprosy and those without rather than between the two cemetery areas (Figure 3 and 4; Table 2). Individuals with skeletal changes consistent with lepromatous leprosy had greater proportions of buccal phase I wear when compared to lingual phase I and phase II wear. There were no significant interaction effects between cemetery area and the presence of rhino-maxillary syndrome and differences in wear facet area composition. The wear facet composition of the Medieval and early Post-Medieval burials from St Michael's Litten also differed significantly from the leprous individuals inhumed at the leprosarium of St James (Figure 5; Type II PERMANOVA F-statistic=4.41, $R^2$=0.19, p-value= 0.003). They did not, however, differ significantly from individuals without leprosy buried at St James leprosarium (Table 3). There were no significant differences observed in wear facet pattern between males and females in the sample (Type II PERMANOVA F-statistic=0.88, $R^2$=0.47, p-value= 0.47).

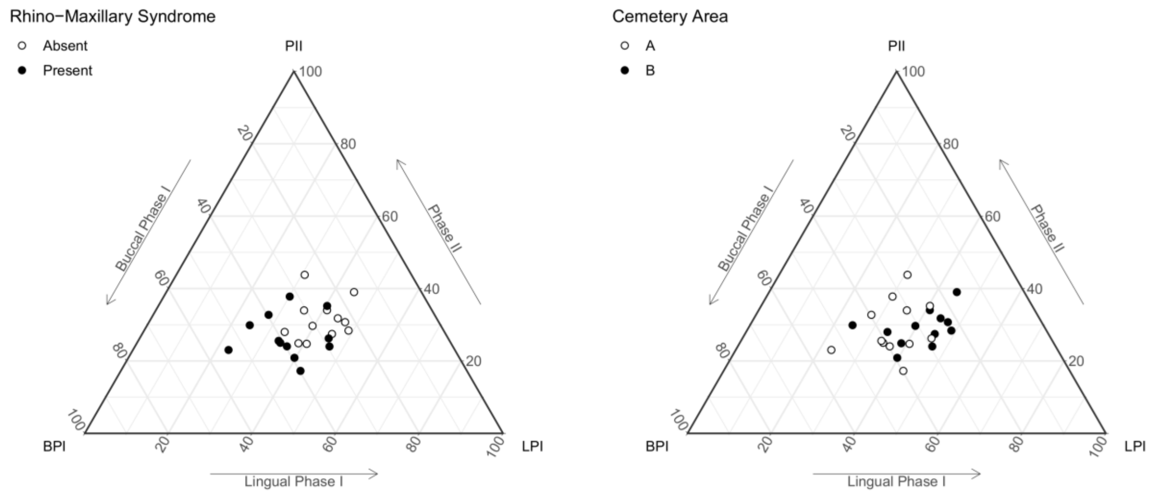



*Figure 3: Left: Ternary plot showing the differences in wear facet area proportions of the lower second molars of individuals with and without osseous changes characteristic of Rhino-maxillary syndrome from the cemetery of the leprosarium of St James and St Mary Magdalene, Chichester. Centre values for individuals with leprosy buccal phase I 37.92%, lingual phase I 35.27% and phase II 26.80%. Centre*

*values for individuals without leprosy buccal phase I 27.45%, lingual phase I 41.13% and phase II 31.14%. Each axis corresponded to one of the three variables that comprise the total wear facet area (Buccal phase I, Lingual Phase I and Phase II facet areas). Right: Distribution of relative wear facet areas according to cemetery area. Cemetery area A was the area reported to be the temporally earlier (approximately AD 1100-1400) and consisted of burials with a higher prevalence of skeletal changes consistent with lepromatous leprosy. Cemetery area B likely principally included burials dated to the period during which the cemetery was used by the later alms-house and included a greater number of non-adults and females (AD 1400-1600).*

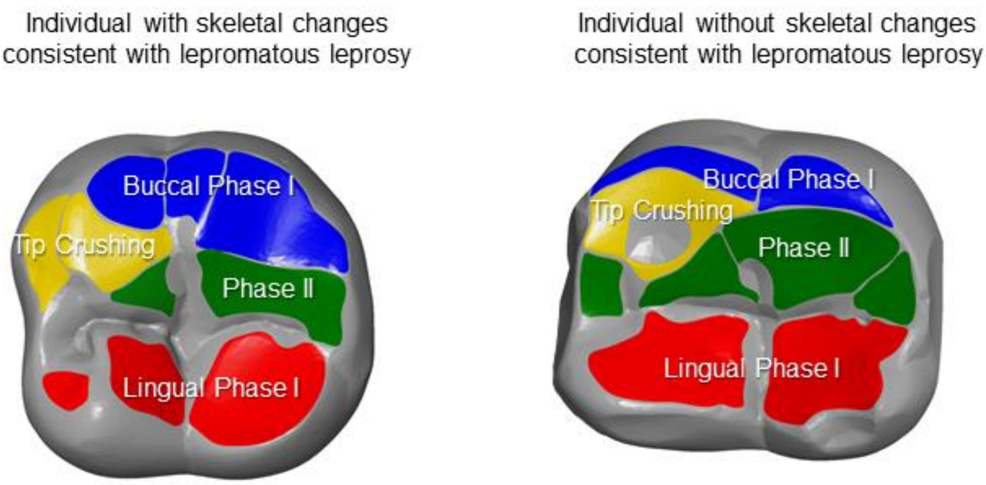



*Figure 4: Examples of lower second molars from the assemblages of St James and St Mary Magdalene, Chichester. The individual on the left (SK167) had osseous changes consistent with lepromatous leprosy and the individual on the right (SK315) did not. Note larger buccal phase I facets as a proportion of the total wear facet areas in the individual with skeletal changes consistent with lepromatous leprosy.*

*Table 2: Results of the type II permutational multivariate analysis of variance (PERMANOVA) assessment of the relationship between the presence of Rhino-maxillary changes, cemetery area and wear facet area composition within the St James and St Mary Magdalene assemblage. The significance of any interaction effects between the presence of leprous changes and cemetery area on wear facet area composition was also assessed.* ***Null hypothesis: significant differences in wear facet area composition in the St James and St Mary Magdalene assemblage were not associated with the presence of skeletal changes consistent with lepromatous leprosy and/or cemetery area.***

| ILR data | Df | Sum of Squares | Mean of Squares | F-model | p-value | Null Hypothesis |
|---|---|---|---|---|---|---|
| **Leprosy** | 0.61 | 0.61 | 1.00 | 4.54 | 0.02 | **Rejected** |
| **Area** | 0.11 | 0.11 | 1.00 | 0.79 | 0.44 | Not Rejected |
| **Leprosy: Area Interaction Effect** | 0.05 | 0.05 | 1.00 | 0.36 | 0.69 | Not Rejected |
| **Residuals** | 2.71 | 0.14 | 20.00 | | | |
| **Total** | 3.78 | | 23.00 | | | |

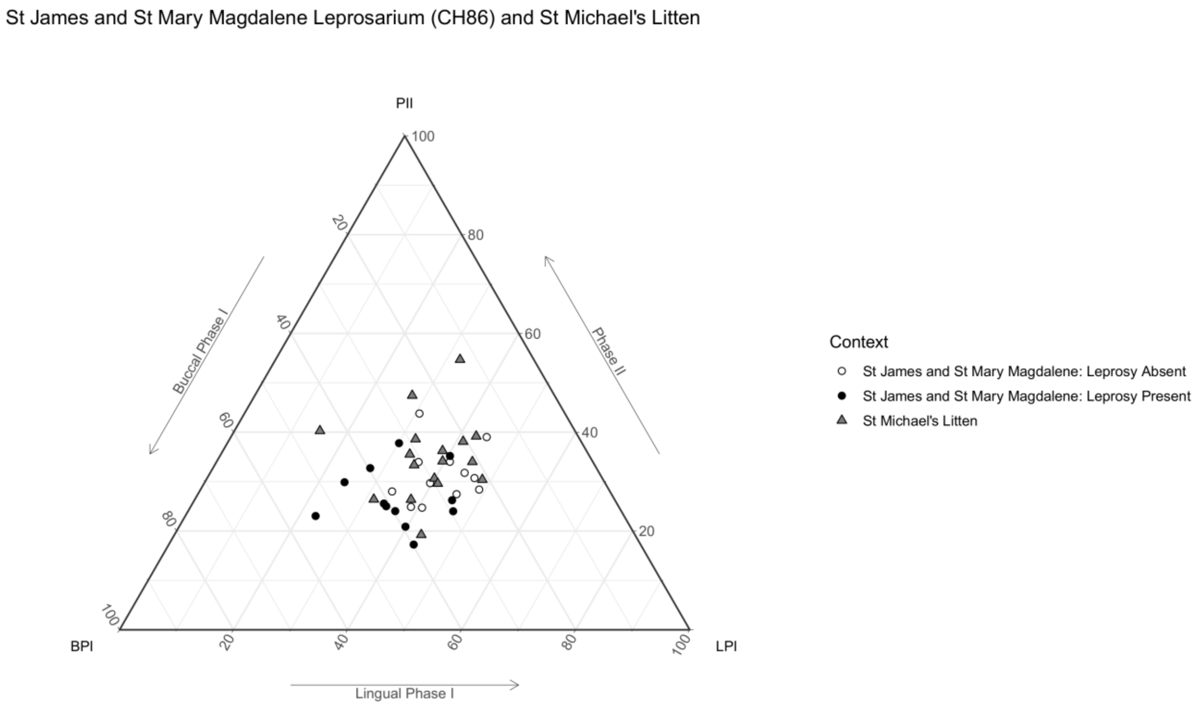
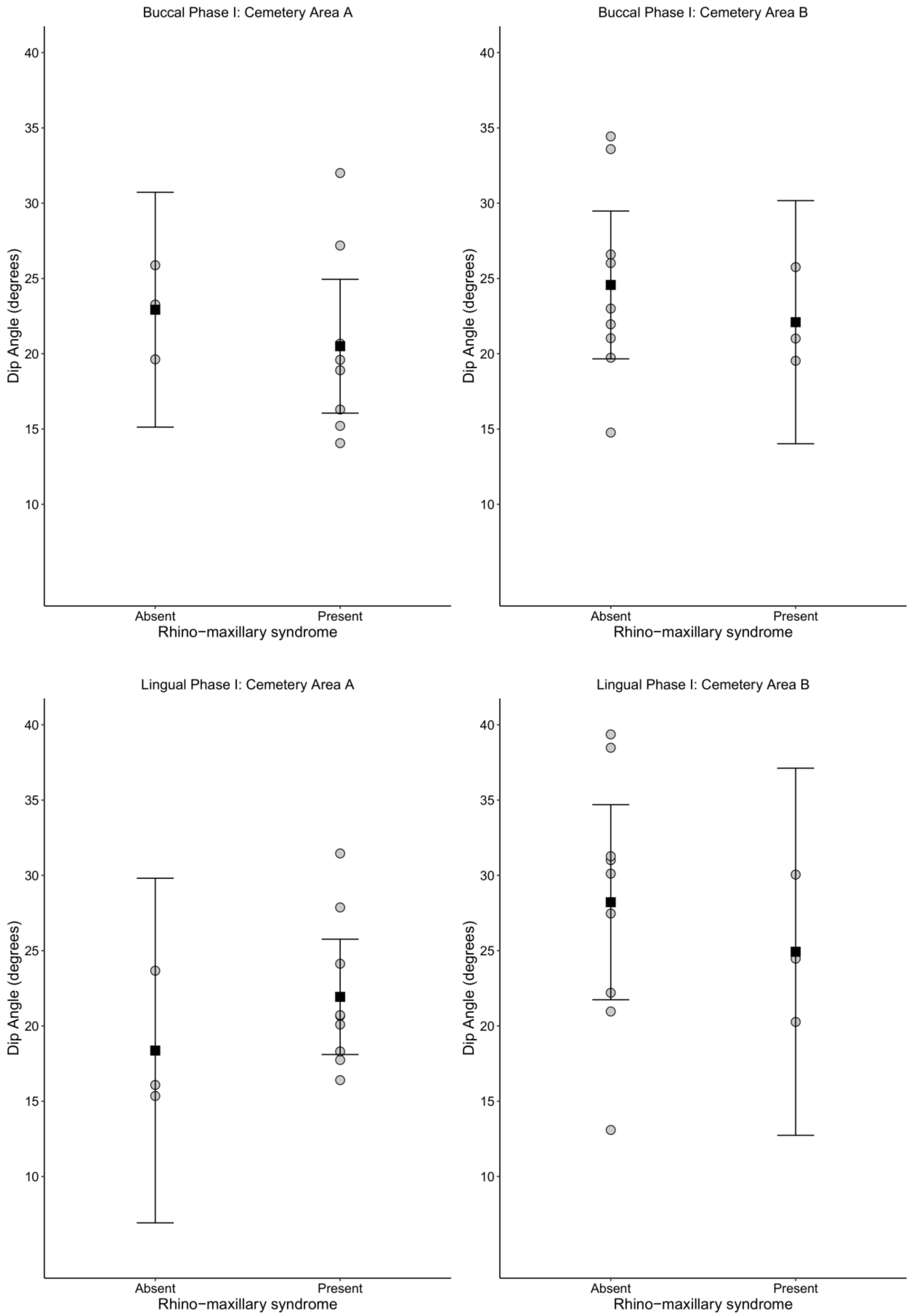



*Figure 5: Ternary plot showing the differences between leprous individuals at St James' leprosarium, those without leprosy and between the Medieval and early Post-Medieval phases of burial at St. Michael's Litten, Chichester.*

*Table 3: Results of pairwise comparison after performing Type II PERMANOVA between leprous individuals at St James' leprosarium, those without leprosy and between the Medieval and early Post-Medieval phases of burial at St. Michael's Litten, Chichester*

| **Pairwise Comparison** | **St James' Leprosarium: Lepromatous Leprosy** | **St James' Leprosarium: No Leprosy** |
|---|---|---|
| **St James' Leprosarium: No Leprosy** | **0.005** | - |
| **St Michael's Litten, Chichester** | **0.005** | 0.40 |

There were no significant differences in wear facet dip angle between individuals with and without osseous changes consistent with lepromatous leprosy (Table 4). 95% confidence intervals around the mean were large and overlapping for the comparisons between lepers and individuals without leprosy and between cemetery areas (Figure 6). There was not a significant interaction effect between area and the presence of lepromatous leprosy and the inclination of wear facet dip angles (Table 4). There were no significant differences between the wear facet dip angles of the St James' assemblage when compared to the St Michael's Litten material (Type II PERMANOVA; F-statistic=1.82, $R^2$=0.09, p-value=0.12). There were not any significant differences in male and female wear facet dip angles (Type II PERMANOVA F-statistic=0.79, $R^2$=0.07, p-value= 0.58).


Buccal Phase I: Cemetery Area A
Buccal Phase I: Cemetery Area B
Lingual Phase I: Cemetery Area A
Lingual Phase I: Cemetery Area B
Dip Angle (degrees)
Rhino−maxillary syndrome
Absent
Present
10
15
20
25
30
35
40

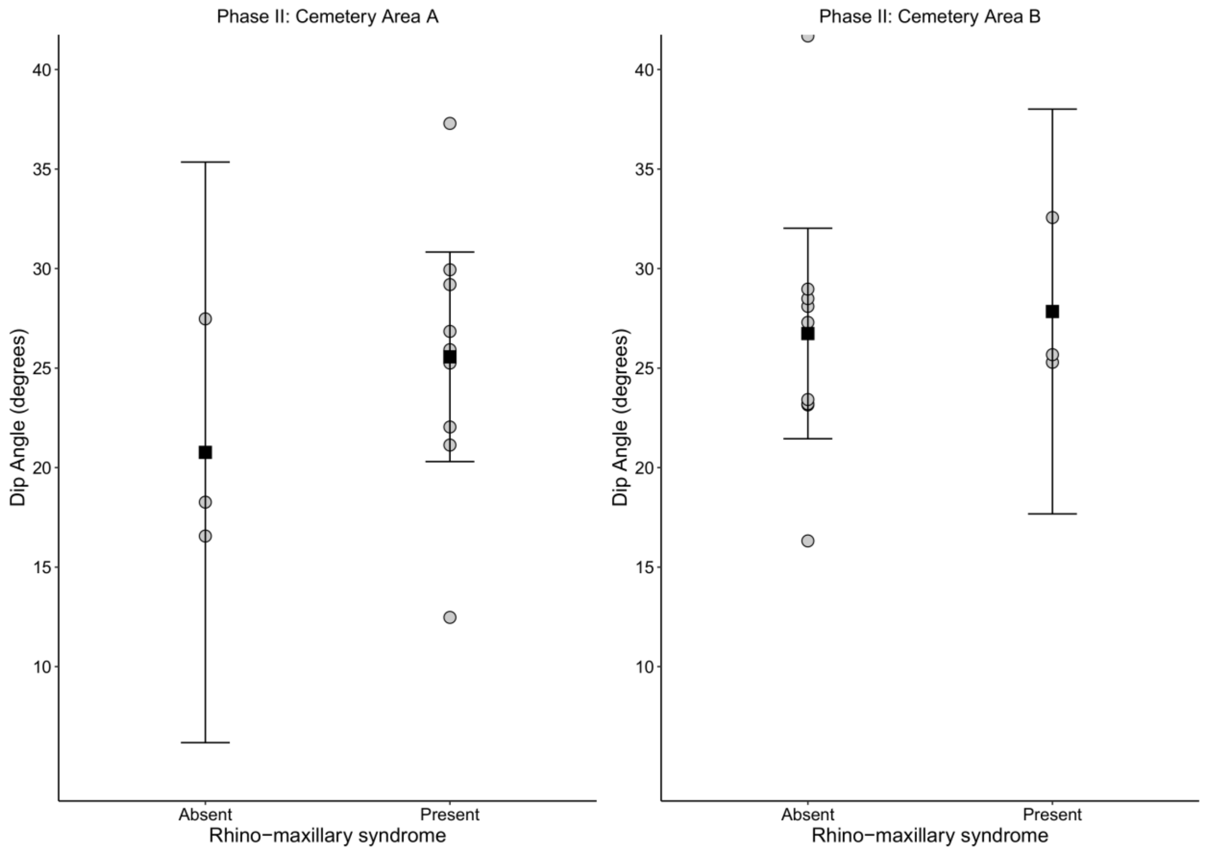



*Figure 6: Dot plots with mean values plotted with 95% confidence intervals comparing mean dip angles in the lower second molars between individuals with and without skeletal changes consistent with leprosy from cemetery areas A or B of the St James and St Mary Magdalene assemblage, Chichester (CH86).*

*Table 4: Results of PERMANOVA examining the influence of cemetery area and leprosy on wear facet dip angle. The Bray-Curtis dissimilarity matrix was used as the transformation for performing the test.* ***Null hypothesis: wear facet dip angles did not differ significantly between cemetery areas and/or individuals with and without skeletal changes consistent with lepromatous leprosy.***

| Standard data | Df | Sum of Squares | Mean of Squares | F-model | p-value | Null Hypothesis |
|---|---|---|---|---|---|---|
| **Area** | 0.03 | 0.03 | 1.00 | 2.42 | 0.08 | Not Rejected |
| **Leprosy** | 0.01 | 0.01 | 1.00 | 0.95 | 0.44 | Not Rejected |
| **Area: Leprosy Interaction Effect** | 0.01 | 0.01 | 1.00 | 0.63 | 0.61 | Not Rejected |
| **Residuals** | 0.25 | 0.01 | 20.00 | | | |
| **Total** | 0.30 | | 23.00 | | | |

## 4. Discussion

In the cemetery associated with the leprosy hospital of St James and St Mary Magdalene, Chichester, individuals with lepromatous leprosy were characterised by larger proportions of buccal phase I wear in the lower second molars relative to the non-leprous individuals interred at the cemetery and those buried at St Michael’s Litten. The lack of significant differences in wear pattern between cemetery area A and area B indicates that in the sample examined a temporal component did not markedly influence the differences in wear facet area composition observed between the burials diagnosed with leprosy and those without. Among modern hunter-gatherers, large buccal phase I shearing facets were found in groups habitually eating large amounts of meat when compared to those that followed a more mixed subsistence strategy (Fiorenza *et al.* 2011). Similarly, if lepers were eating larger quantities of tough and fibrous food items, such as meat, enlarged shearing facets would be anticipated relative to individuals without leprosy. A prominent shearing action is necessary to mechanically process meat with the teeth. The less affluent component of the comparative group buried at St Michael’s Litten likely consumed a diet dominated by wheat, barley and oats with limited meat content (Green 2011; Stone 2006). Access to meat was a key factor in the differentiation of social classes through eating during the Medieval period (Woolgar 2016). Significant differences between the wear facet area composition of individuals with lepromatous leprosy at St James’ and both the non-leprous component of St James’ and the St Michael’s Litten seems to support the consumption of a special diet by leprous individuals.

The provision of meat, sometimes in the form of substandard meat donated to the leprosarium, formed part of the dietary prescription to rectify the humoral imbalance believed to be part of the aetiology of leprosy in Medieval thought (Rawcliffe 2006). From AD 1158 to 1178, the Crown paid subscriptions of royal alms of food, clothing and land to the leprosarium. From the 13$^{th}$ century, Forest Law decreed that the meat of any animals found dead or wounded should be brought to the local leper house; this included the royal forest of the Broyle located just beyond the north gate of Chichester (Clay1909). Once the Broyle had been transformed into farmland, it was bequeathed to the leprosarium at the start of the 15th century suggesting that the institution likely had fairly extensive access to animal resources (Magilton *et al.* 2008). Greater access to poultry, pork, fish and other foods perceived to be mild and moist was in contrast to the dietary regimes of the majority of medieval individuals who were largely dependent on grains for the bulk of their dietary calories (Stone 2006; Walsh 2000).

Dental wear facets develop over an individual's lifetime and would require a prolonged period of consumption of a diet of contrasting composition to modify the wear facet pattern. This is because chewing behaviours would have to be consistently modified for a sustained period. The lack of skeletal changes consistent with leprosy in many of the individuals buried at the leprosarium of St James does not eliminate the possibility that they were still afflicted by the condition, exhibiting either the tuberculoid form or a less advanced form of lepromatous leprosy which may not yet have manifested osseous changes. It could be suggested that these individuals were residents at the leprosarium for a more limited period and therefore any contrasts between the dietary regime of the institution and that which they consumed previously would not yet have had a marked impact on their occlusal wear patterns. Isotopic data have similarly been utilised to argue that greater quantities of terrestrial and/or marine protein were available to lepers as part of their palliative care within leprosaria when compared to their diet prior to admission (Taylor *et al.* 2013; Taylor *et al.* 2018); rib collagen $\delta^{13}C$ and $\delta^{15}N$ isotopic values were enriched relative to collagen from the femurs reported by in a study of three individuals from the leprosarium of St. Mary Magdalen, Winchester (Taylor *et al.* 2013). This interpretation assumes that the isotopic composition of rib collagen changes more rapidly than that of the femurs, which would indicate a change in dietary composition in the final years of life (Lamb *et al.* 2014; Pollard *et al.* 2012). A recent study has challenged this assumption and indicates that the ribs may typically be enriched relative to the femur irrespective of diet, therefore, these isotopic data should be interpreted cautiously (Fahy *et al.* 2017).

Another factor to consider is that clinically, orofacial lesions are commonly reported among individuals with lepromatous leprosy (Manjunath Shenoy *et al.* 2007; Rodrigues *et al.* 2017). The loss of the central maxillary incisors is a frequent consequence of resorption of the alveolar process and associated involvement of the hard palate (Waldron 2008). Chronic gingivitis may also occur. The tongue is involved in up to 25% of cases. Ulceration and repair of the perioral tissues may result in microstomia, contracture of the mouth (Naik *et al.* 2011). More uncommonly, affecting 21% of a clinical group, the maxillary and mandibular branches of the trigeminal nerve and buccal and mandibular branches of the facial nerve may be involved resulting in a sensation of anaesthesia on the affected side, which may impact masticatory behaviours and speech (Dave and Bedi 2013). The symptoms of the disease may have altered chewing behaviours and, therefore, have also modified dental wear patterns in some individuals. Many of these symptoms will not leave evidence on the bone, however, so it was not possible to account for this during our analysis.

More shallowly inclined dental wear planes also characterise hunter-gatherers consuming more abrasive diets when compared to agriculturalists (Smith 1984; Fiorenza *et al.* 2018). More extensive flattening of the occlusal surface may also be anticipated when groups consume foods that require prolonged chewing sequences and the placement of greater loads on the teeth during mastication

(Borreo-Lopez *et al.* 2014). The lack of significant differences in wear facet dip angles between cemetery areas and individuals with and without leprosy likely reflects similarities in the quantities of abrasive particles within the foods consumed. Few major changes in dietary composition and food processing technologies occurred during the period of inhumations at the cemetery of St James and St Mary Magdalene. Grains were stone ground in watermills and windmills and the meal was shaken through a *teme*, a hand-held sieve made from either wool or linen. This resulted in the retention of many of the coarser particles within the flour produced and high amounts of dental abrasion (Drummond and Wilbraham 1957; Evensen and Øgaard 2007; Kaifu 1999). A substantial reduction in the abrasive content of the bread consumed did not occur until the introduction of the automatic boulter agitated by the mill machinery at the close of the 17th century (Petersen and Jenkins 1995).

Occlusal Fingerprint Analysis provides an insight into the physical properties of the foods eaten, such as those relating to food hardness and toughness (Fiorenza *et al.* 2011; Fiorenza *et al.* 2018). As such, the dietary differences most likely to be responsible for any variance in dental wear patterns observed between and within skeletal assemblages can be inferred using historical and archaeological evidence for the foodstuffs available and their associated physical properties. A key limitation of OFA, however, is that dental wear patterns are not specific to particular foods. In addition, any differences in the quantities of food items that comprise only a small portion of the total foods eaten are unlikely to be detectable using OFA as their impact on the masticatory power stroke, and therefore dental wear patterns, will not be substantial. Recent biomolecular approaches, such as metaproteomic techniques, may provide greater specificity in terms of the foods eaten (Hendy *et al.* 2018). Isotopic data could also be used to further assess the preliminary conclusions of the current research; the OFA data suggests that lepers buried at the cemetery may have consumed greater quantities of meat. Isotopic data, however, is not currently available for the St James and St Mary Magdalene material. OFA has recently been shown to provide useful additional data when attempting to reconstruct diet in the past using a multi-proxy approach, which included isotopic data and starch and micro-debris trapped in dental calculus (Oxilia *et al.* 2021). Future research utilising a multi-proxy approach may provide a more comprehensive reconstruction of diet at medieval leprosaria by drawing upon sources of evidence that highlight different aspects of the diet.

## 5. Conclusion

Medieval medical treatment relied heavily on palliative dietary regimens for the alleviation of many medical conditions. The management of leprosy required a diet rich in moist and mild foods many of which were meat products. It remains unclear from current historical and archaeological evidence to what extent these dietary recommendations were followed at Medieval leprosaria. This study of dental wear facet patterns, which provide an indication of the foods consumed by an individual over a substantial period of their lives, gives evidence to support the hypothesis that a special diet comprising greater quantities of meat was consumed at this Medieval leprosarium. Donations of food and access to farms and fishing grounds likely resulted in greater provisioning of meat at Medieval leprosaria than was available to the majority of the lower social strata of Medieval Britain. The study provides evidence to support the utility of using OFA to identify dietary differences within skeletal assemblages and may provide a complimentary source of data for reconstructing past diets alongside faunal, historical, isotopic and botanical evidence. The small sample size examined, however, renders these conclusions preliminary. Further insight into the diets at leprosaria may be gained by applying OFA to remains associated with other institutions within the UK, such as the leprosarium of St. Mary Magdalene, Winchester, and also those in Europe, such as the Danish medieval leprosy hospital at Næstved.

## Declaration of competing interest

The author declares that they have no conflict of interest.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## References


Aitchison, J.A., 1986. The statistical analysis of compositional data. Chapman and Hall, London.

Alter, A., Grant, A., Abel, L., Alcaïs, A., Schurr, E., 2011. Leprosy as a genetic disease. Mamm. 22(1-2), 19-31.

Andersen, J.G., Manchester, K., 1992. The rhinomaxillary syndrome in leprosy: A clinical, radiological and palaeopathological study. Int. J. Osteoarchaeol. 2(2),121-129.

Anderson, M.J., 2001. A new method for non-parametric multivariate analysis of variance. Austral Ecol. 26(1), 32–46.

Anderson, M.J., 2017. Permutational Multivariate Analysis of Variance (PERMANOVA), in: Balakrishnan, N., Colton, T., Everitt, B., Piegorsch, W., Ruggeri, F. and Teugels, J. L. (Eds.) StatsRef: Statistics Reference Online. Oxford, Wiley.

Boogaart, van den K.G., Tolosana-Delgado, R., 2013. Analyzing compositional data with R. Berlin, Springer.

Borrero-Lopez, O., Pajares, A., Constantino, P.J., Lawn, B.R., 2014. A model for predicting wear rates in tooth enamel. J. Mech. Behav. Biomed. Mater. 37, 226-234.

Brenner, E. 2010. Recent Perspectives on Leprosy in Medieval Western Europe. Hist. Compass 8(5), 388-406.

Buckberry, J., Chamberlain, A., 2002. Age estimation from the auricular surface of the ilium: A revised method. Am. J. Phys. Anthropol. 119(3), 231-239.

Buikstra, J.E., Ubelaker, D.H., 1994. Standards for data collection from human skeletal remains. Proceedings of a seminar at the field museum of natural history. Arkansas archaeological survey research series no. 44. Arkansas, Arkansas Archaeological Survey.

Clay, R.M., 1909. The Mediæval Hospitals of England, reprinted 1966. London: Frank Cass.

Dave, B., Bedi, R., 2013. Leprosy and its dental management guidelines. Int. Dent. J. 63, 65-71.

Drummond, J.C., Wilbraham, A., 1957. The Englishman's food: A history of five centuries of English diet. London, Jonathan Cape.

Dwivedi, V., Banerjee, A., Das, I., Saha, A., Dutta, M., Bhardwaj, B., Biswas, S., Chattopadhyay, D., 2019. Diet and nutrition: An important risk factor in leprosy. Microb. Pathog.137, 103714.

Evensen, J.P., Øgaard, B., 2007. Are malocclusions more prevalent and severe now? A comparative study of Medieval skulls from Norway. Am. J. Orthod. Dentofacial. Orthop. 131(6), 710-716.

Fahy, G.E, Deter, C., Pitfield, R., Miszkiewicz, J.J., Mahoney, P., 2017. Bone deep: Variation in stable isotope ratios and histomorphometric measurements of bone remodelling within adult humans. J. Archaeol. Sci. 87, 10-16.

Fiorenza, L., Benazzi, S., Tausch, J., Kullmer, O., Bromage, T., Schrenk, F., Rosenberg, K., 2011. Molar Macrowear Reveals Neanderthal Eco-Geographic Dietary Variation (Neanderthal Tooth Wear). PLoS ONE 6(3), E14769.

Fiorenza L., Benazzi, S., Oxilia, G., Kullmer, O., 2018. Functional relationship between dental macrowear and diet in Late Pleistocene and recent modern human populations Int. J. Osteoarchaeol. 28(2), 153-161.

Fortelius, M., Solounias, N., 2000 Functional Characterization of Ungulate Molars Using the Abrasion-Attrition Wear Gradient: A New Method for Reconstructing Paleodiets. Am. Mus. Novit. 3301, 1-36.

Green, A., 2011. Cattle, Corn & Crawfish: 900 years of Chichester's markets. Chichester, Phillimore & Co.

Hendy, J., Warinner, C., Bouwman, A., Collins, M.J., Fiddyment, S.; Fischer, R., Hagan, R., Hofman, C.A., Holst, M., Chaves, E., Klaus, L., Larson, G., Mackie, M., McGrath, K., Mundorff, A.Z., Radini, A., Rao, H., Trachsel, C., Velsko, I.R., Speller, C.F., 2018. Proteomic evidence of dietary sources in ancient dental calculus. Proc. Royal. Soc. B 285(1883), 20180977.

Hiiemae, K., Heath, M.R., Heath, G., Kazazoglu, E., Murray, J., Sapper, D., Hamblett, K., 1996. Natural bites, food consistency and feeding behaviour in man. Arch. Oral Biol. 41(2), 175-189.

Huggon, M., 2018. Medieval Medicine, Public Health, and the Medieval Hospital, in: Gerrard, C.M., and Gutiérrez, A. (Eds.). The Oxford handbook of later Medieval archaeology in Britain. Oxford, Oxford University Press.

Hung, S.H., Purk, J.H., Tira, D.E., Eick, J.D., 1992. Accuracy of one-step versus two-step putty wash addition silicone impression technique. J. Prosthet. Dent. 67, 583-9.

Jamshidy, L., Mozaffari, H. R., Faraji, P., Sharifi, R., 2016. Accuracy of the One-Stage and Two-Stage Impression Techniques: A Comparative Analysis. Int. J. Dent. 7256496.

Janis, C.M., 1990. The correlation between diet and dental wear in herbivorous mammals, and its relationship to the determination of diets of extinct species, in: Boucot, A.J. (Ed.) Evolutionary Paleobiology of Behavior and Coevolution. Elsevier Science, Amsterdam.

Kaifu, Y., 1999. Changes in the pattern of tooth wear from prehistoric to recent periods in Japan. Am. J. Phys. Anthropol. 109(4), 485-499.

Kay, R.F., 1973. Mastication, Molar Tooth Structure and Diet in Primates. Doctoral dissertation, Yale University.

Kay, R. F., Hiiemae, K. M., 1974. Jaw movement and tooth use in recent and fossil primates. Am. J. Phys. Anthropol. 40, 227-256.

Keene, D., 1998. Feeding Medieval European Cities, 600-1500. E-seminars in History, Institute of Historical Research, London.

Kibre, P., 1945. Hippocratic writings in the middle ages. Bull. Hist. Med. 18(4), 371-412.

Knight-Sadler, J., Fiorenza, L., 2017. Tooth Wear Inclination in Great Ape Molars. Folia Primatol. 88, 223-236.

Kullmer, O., Benazzi, S., Fiorenza, L., Schulz, D., Bacso, S., Winzen, O., 2009. Technical note: Occlusal fingerprint analysis: Quantification of tooth wear pattern. Am. J. Phys. Anthropol. 139(4), 600-605.

Kullmer, O., Schulz, D., Benazzi, S., 2012. An Experimental Approach to Evaluate the Correspondence Between Wear Facet Position and Occlusal Movements. Anat. Rec. 295(5), 846-852.

Lamb, A.L., Evans, J.E., Buckley, R., Appleby, Jo., 2014. Multi-isotope analysis demonstrates significant lifestyle changes in King Richard III. J. Archaeol. Sci. 50, 559-565.

Lewis, R., Dwyer-Joyce, R., 2005. Wear of human teeth: A tribological perspective. Proc. Inst. Mech. Eng., Part J J. eng. tribol. 219 (1), 1-18.

Lockwood, D.N.J., 2005. Leprosy. Medicine 33(7), 26-29.

Magilton, J.R., Lee, F., Boylston, A., 2008. Lepers outside the gate: excavations at the cemetery of the Hospital of St James and St Mary Magdalene, Chichester, 1986-87 and 1993. York, Council for British Archaeology.

Maier, W., Schneck, G., 1981. Konstruktionsmorphologische Untersuchungen am Gebiß der hominoiden Primaten. Z. Morphol. Anthropol. 72(2), 127-169.

Maier, W., and Scheck, G., 1982. Functional Morphology of Hominoid Dentitions. J. Hum. Evol. 11(8), 693-696.

Manchester, K., Roberts, C., 1989. The Palaeopathology of Leprosy in Britain: A Review. World Archaeol. 21(2), 265-272.

Manjunath Shenoy, M., Suchitra, U., Girisha, B.S., Pinto J., 2007. Oro - Facial Lesions in Leprosy- A Review. J. Indian Acad. Oral Med. Radiol. 19(4), 467-472.

Miller, T., Nesbitt, J., 2014. Walking corpses: Leprosy in Byzantium and the Medieval West. Ithaca, Cornell University Press.

Møller-Christensen, V., 1978. Leprosy changes of the skull. Odense, Odense University Press.

Morgan, R.R., 1992. Chichester: A documentary history. Chichester, Phillimore & Co, Ltd.

Naik, V., Kini, R., Singla, S., Shetty, A., 2011. Leprosy Specific Orofacial Aspects. J. Indian Acad. Oral Med. Radiol. 23(3), 216-220.

Nicoud, M., 2008. Food consumption, a health risk? Norms and medical practice in the Middle Ages. Appetite, 51(1), 7-9.

Oxilia, G., Bortolini, E., Badino, F., Bernardini, F., Gazzoni, V., Lugli, F., Romandini, M., Radini, A., Terlato, G., Marciani, G., Silvestrini, S., Menghi S., Jessica C., Thun H.U., Fiorenza, L., Kullmer O., Tuniz, C., Moggi C., Jacopo, T.S., Fontana, F., Peresani M., Benazzi, S.,Cristiani, E., 2021. Exploring late Paleolithic and Mesolithic diet in the Eastern Alpine region of Italy through multiple proxies. Am. J. Phys. Anthropol. 174(2), 232-253.

Petersen, C., Jenkins, A., 1995. Bread and the British economy, c1770-1870. Aldershot, Hants, Brookfield, Vt., USA, Scholar Press; Ashgate Pub.

Phenice, T.W., 1969. A newly developed visual method of sexing the os pubis. Am. J. Phys. Anthropol. 30(2), 297-301.

Pollard, A.M., Ditchfield, P., Piva, E., Wallis, S., Falys, C., Ford, S., 2012. 'Sprouting like cockle amongst the wheat': the St Brice's Day massacre and the isotopic analysis of human bones from Sr Johns College, Oxford. Oxf. J. Archaeol. 31, 83e102.

Rawcliffe, C., 1984. The hospitals of later Medieval London. Med. Hist. 28(1), 1-21.

Rawcliffe, C., 2006. Leprosy in Medieval England. Woodbridge, The Boydell Press.

Rawcliffe, C., 2013. Urban Bodies: Communal Heath in Late Medieval English Towns and Cities. The Boydell Press, Woodbridge.

Riddle, J., 1974. Theory and practice in Medieval medicine. Viator 5, 157-84.

Rodrigues, G.A., Qualio, N.P., de Macedo, L.D., Innocentini, L.M.A.R., Ribeiro-Silva, A., Foss N.T., Frade, M.A.C, Motta, A.C.F., 2017. The oral cavity in leprosy: what clinicians need to know. Oral Dis. 23, 749-756.

Roffey, S., 2012. Medieval Leper Hospitals in England: An Archaeological Perspective. Mediev. Archaeol. 56(1), 203-233.

Roffey, S., Tucker, K., Filipek-Ogden, K., Montgomery, J., Cameron, J., O'Connell, T., Evans, J., Marter, P., Taylor, G., 2017. Investigation of a Medieval Pilgrim Burial Excavated from the Leprosarium of St Mary Magdalen Winchester, UK. PLoS Negl. Trop. Dis. 11(1), E0005186.

Schultz, J. A., Martin, T., 2014. Function of pretribosphenic and tribosphenic mammalian molars inferred from 3D animation. Sci. Nat. 101, 771–781.

Silvester, C.M., Hillson, S., 2020. A critical assessment of the potential for Structure-from-Motion photogrammetry to produce high fidelity 3D dental models. Am. J. Phys. Anthropol. 173(2), 381-392.

Smith, B.H., 1984. Patterns of molar wear in hunter-gatherers and agriculturists. Am. J. Phys. Anthropol. 63 (1), 39–56.

Spears, I.R., Macho, G.A., 1998. Biomechanical behaviour of modern human molars: Implications for interpreting the fossil record. Am. J. Phys. Anthropol. 106(4), 467-482.

Stone, D.J., 2006. The consumption of field crops in Late Medieval England, in: Woolgar, C.M., Serjeantson, D., Waldron, T. (Eds.) Food in Medieval England: Diet and nutrition. Oxford, Oxford University Press.

Taylor, G.M., Tucker, K., Butler, R., Pike, A.W.G., Lewis, J., Roffey, S., Marter, P., Lee, O. Y-C, Wu H.H.T., Minnikin, D.E., Besra, G.S., Singh, P., Cole, S.T., Stewart G.R. 2013. Detection and strain typing of ancient Mycobacterium leprae from a Medieval leprosy hospital. PloS One, 8(4), E62406.

Taylor, G.M., Murphy, E.M., Mendum, T.A., Pike, A.W.G., Linscott, B., Wu, H., O’Grady, J., Richardson, H., O’Donovan, E., Troy, C., Stewart, G.R. 2018. Leprosy at the edge of Europe-Biomolecular, isotopic and osteoarchaeological findings from medieval Ireland. PloS One 13(12), E0209495.

Varvara, G., Murmura, G., Sinjari, B., Cardelli, P., Caputi, S. 2015. Evaluation of defects in surface detail for monophase, 2-phase, and 3-phase impression techniques: An in vitro study. J. Prosthet. Dent. 1132, 108-113.

Waldron, T., 2008. Palaeopathology. Cambridge, Cambridge University Press.

Wall, C.E., Vinyard, C.J., Johnson, K.R., Williams, S.H., Hylander, W.L., 2006. Phase II jaw movements and masseter muscle activity during chewing in Papio anubis. Am. J. Phys. Anthropol. 129(2), 215–224.

Woda, A., Foster, K., Mishellany, A., Peyron, M.A., 2006. Adaptation of healthy mastication to factors pertaining to the individual or to the food. Physiol. Behav. 89, 28-35.

Woolgar, C.M., 2016. The culture of food in England, 1200-1500. New Haven, Yale University Press.

Zanolli, C., Kullmer, O., Kelley, J., Bacon, A.-M., Demeter, F., Dumoncel, J., Fiorenza, L., Grine, F.E., Hublin, J.-J., Tuan, N.A., Huong, N.T.M., Pan, L., Schillinger, B., Schrenk, F., Skinner, M.M., Ji, X., Macchiarelli, R., 2019. Evidence for increased hominid diversity in the Early-Middle Pleistocene of Indonesia. Nat. Ecol. Evol. 3, 755-764.