Title: Geometric morphometric approach to dental health

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Abstract
This study evaluated correlations between poor dental health and craniomandibular morphology for the Radcliffe Infirmary population buried between 1770-1855. The Radcliffe Infirmary is situated in Oxford, 90 kilometers north-west of London, in what used to be a rural area. The original report for this population observed high prevalence rates of dental caries, antemortem tooth loss (AMTL), and periodontal disease. Industrial societies are acknowledged to have highly processed foods that are not only detrimental to dental health but require less mastication. This softening of diet is suggested to be the leading influence on the modern morphology of the skull. By using two-dimensional geometric morphometrics (GM) and linear measurements of the skull, the Radcliffe population was evaluated for the effects of poor dental health and decreased wear on the masticatory structures. High frequencies of AMTL, periodontal disease, and caries, and low amounts of dental wear were observed in this sample population. Caries and AMTL showed weak correlations with skull shape and craniomandibular dimensions according to the results of the morphometric analysis and Kendall's Tau. Dental wear correlated with a wide bizygomatic breadth and a long narrow skull shape for the males only. Periodontal disease was the only dental health variable not correlated with shape or size. This study confirmed the Radcliffe population ate a cariogenic diet and suggests dental wear and pathology weakly correlates with craniomandibular shape and size. This unpredicted finding may be due to the limitations of two-dimensional shape analysis, a small sample size, and the sampling strategy. Future research is highly encouraged to better understand the consequences of poor dental health for skull morphology.

Introduction

The increased prevalence of caries in the post-medieval period in Britain is acknowledged to be the consequence of imported mass-produced cane sugar (DeWitte & Bekvalac, 2010; Mant & Roberts, 2015; Roberts & Cox, 2003; Smith, 2019). Periodontal disease, another common modern dental condition, initiates as an inflammatory gum disease primarily caused by bacterial and calculus build-up before progressing to loss of the periodontal ligament and degradation of the alveolar processes which hold the teeth in place (Larsen, 2018). Both conditions lead to antemortem tooth loss (AMTL), which is frequently observed in post-medieval populations (e.g. Loe et al., 2022; Mant & Roberts, 2015; Smith, 2019). These conditions were exacerbated by the lack of education on dental hygiene prior to the establishment of medical dentistry in the 20th century (Welshman, 1998). These dental conditions are also suggested to decrease masticatory efficiency, part of a broader phenomenon known as "Wolff's Law", which states that bone remodels in the direction to best balance mechanical strain (Dechow et al., 2010; Ruff et al., 2006; Wolff, 2012). Geometric morphometrics (GM) has previously been used to investigate muscle function and masticatory efficiency (Corte-Real et al., 2020; Kato et al., 2018; Small et al., 2016; Ueda et al., 1998), and AMTL has been correlated with shape changes of the orbits, maxilla, nasal aperture, zygomatic processes, and changes in upper facial height (Small et al., 2016). This study will evaluate how dental pathologies affected facial bone shape in the Radcliffe Infirmary population from Oxford, England. This voluntary hospital population dates to 1770-1855 and represents a population of lower income patients, many showing evidence of dental pathology (Loe et al., 2022). Two-dimensional GM was used to capture the shape of the skull of 63 individuals to evaluate how Wolff's law operates in parallel to dental disease (Wolff, 2012). The results of this study will demonstrate how untreated dental disease correlates with skull shape variation.

Context

18th-19th Century Diet

Diet in late 18th and early 19th century England was highly dependent on geographic region and socioeconomic status, with the general pattern of poorer nutrition and health affecting populations in the north and of lower socioeconomic status (Durbach, 2013; Greaves, 2018; Hughes-Morey, 2012; Lewis, 2002; Lewis & Gowland, 2007; Newman et al., 2019; Watts, 2015). The working classes, whose impoverishment was being noted by contemporaries such as Friedrich Engels (1845), were only able to purchase small amounts of meat, other animal products, and fresh produce (Clayton & Rowbotham, 2009). Instead, many families relied on bread, cheap meat cuts, and seasonal fruits and vegetables (Mauriello, 2008). Consequently, many working class households in 19th century England experienced nutritional deficiency (Newman et al., 2019). With the increase of imported goods from the Americas, sugar product consumption in England grew exponentially. What started as a luxury for the upper classes in the 16th century quickly trickled down to the middle classes as a staple foodstuff in the following century (Abbott 2011: 47). By 1760, the annual volume of sugar processed by refineries in Bristol alone amounted to 377,200 kg and recipe books included many recipes incorporating sugar (Smith, 2015: 28 & 81). Pure white cane sugar remained a product for the upper class, but brown sugar and molasses were popular amongst the middle and working classes (Mauriello 2008). Sugar consumption per capita in England was estimated to be 3.6 kg in 1750, rising to 8.2-10.9 kg by 1800, and doubling again during the 19th century (Mant & Roberts, 2015; Smith, 2015: 80). Excluding rent, working class families spent their largest expenditure on bread, meat, and alcohol, with a third of their budget spent on "extras" including tea, spices, sugar, and vegetables (Mauriello, 2008: 72). The increased reliance on bread and sugar was part of a nationwide deterioration in health (Mant & Roberts, 2015; Roberts & Cox, 2003). Caries, tooth loss, and periodontal disease steadily increased in the modern era with a strong connection to other degenerative conditions closely linked to an unhealthy diet such as cardiovascular disease, diabetes, and cancer (Pihlstrom et al., 2005). High rates of caries remained until modern dental care became more available to the general population in the 20th century, with schoolchildren receiving dental health education and care (Richards, 1968, 1971; Welshman, 1998).

The Radcliffe Infirmary

The Radcliffe Infirmary was a voluntary hospital that provided treatment to the working and middling classes. Hospital records indicate a high proportion of those admitted as inpatients were male laborers who suffered workplace accidents, often related to railway construction, agriculture and the printing industry, whilst females made up a higher proportion of outpatients (Loe et al., 2022). The primary health concerns for these patients were work-related trauma and infections which were exacerbated by poor sanitary conditions at the institution. Patients came to the hospital from both urban and rural areas, including Oxford itself, Oxfordshire and the surrounding counties, and further afield (e.g. Cheshire, Birmingham, Greater London, and Dublin; Loe et al., 2022). Unless it was an emergency, to be admitted, the prospective patient needed a letter of recommendation from a subscriber and a beneficiary to pay for expenses, including the deposit covering burial in case of death, if they were unable to cover the cost themselves (ibid. 2022). Those buried at the Radcliffe belonged to families who could not afford to have them transported home or were unclaimed by any friends or relations. Notably, hospital records indicate that those buried at the hospital had travelled on average longer distances (41km) to the overall averages for patients treated (17.2 km for surgical inpatients, 15.1 km for medical inpatients, and 9.2 km for outpatients; Loe et al., 2022). The original report noted high frequencies of periodontal disease, carious lesions, AMTL, dental enamel hypoplasia, activity-related wear, and teeth malalignment (ibid. 2022). It is believed this population accurately reflects the dental health crisis in England from the 18th to the 19th centuries.

Dental health

Cariogenic foods acidify the oral environment and demineralize teeth causing tooth decay, which first appears as a white opaque spot in the enamel or a brown band around the root before developing into a brittle black crater in the tooth (Hillson, 2023: 377-382). Caries typically occurs within small spaces which trap food debris, such as cusp fissures and contact points between the teeth, making the posterior teeth most susceptible (Hillson, 2023: 384-385; Larsen, 2015: 67). Without medical intervention caries expands and may spread to adjacent teeth. Caries therefore compromises dental integrity while also posing serious health risks (Hillson, 2023). Caries is strongly linked to the intake of extrinsic sugars, or sugar added during the food manufacturing process (Sheiham, 2001). Starchy foods and raw fruits are believed to contribute less towards the development of caries. Furthermore, dental caries has a stronger relationship with consumption frequency rather than overall amount of sugar (Hong et al., 2018; Sheiham, 2001). Untreated carious lesions expose the pulp cavity to harmful bacteria that may result in periapical lesions including cysts, granulomas, and abscesses occurring at the apex of the tooth (Karamifar et al., 2020). Chronically infected cysts may develop into granulomas or abscesses risking pus accumulation, alveolar bone resorption, tooth detachment from the jaw, and subsequent tooth loss (Herrera et al., 2014). However, these lesions are harder to detect without the help of a radiograph, which may explain why periapical lesions are not reported to increase with other dental diseases (Roberts & Cox, 2003).

Periodontal disease, like caries, is a modern health concern but with more serious impacts on systemic health (Hajishengallis & Chavakis, 2021). It involves inflammation of the gums progressing to degradation of the periodontal ligament and alveolus and can also lead to tooth loss (Gasner and Schure, 2023; Hillson, 2023: 396-400; Larsen, 2015: 78-79). The main contributor to periodontal disease is presence of dental plaque in close contact with the gingival tissues, combined with host risk factors including lack of dental hygiene, smoking, autoimmune diseases, consumption of cariogenic foods, increasing age and male sex (Hajishengallis & Chavakis, 2021; Hillson, 2023: 397). However, excessive mechanical loading has been identified as a potential contributing factor in pre-industrial populations consuming hard foods or using anterior teeth as tools (Larsen, 2015: 78-79). Deposits of calculus on the teeth, a hard substance consisting of mineralized dental plaque, encourages new plaque, and subsequently, micro-bacteria accumulation (Donos, 2018; Hillson, 2023: 373). Once bacteria reach the subgingival epithelial tissues, triggering an inflammatory response, a gingival pocket is formed.

Gingival pockets progress to periodontal pockets with detachment of the junctional epithelium and alveolar bone destruction (Bosshardt, 2000). They can also lead to the development of periodontal abscesses, where localized infection within the periodontal pocket leads to an accumulation of pus within its gingival wall (Herrera et al., 2017).

Periodontal disease and caries lead to tooth loss without treatment, and tooth loss prior to old age shares a close relationship with these conditions by increasing in frequency into the modern age (Pihlstrom et al., 2005; Roberts & Cox, 2003). Following this tooth loss, bone fills the empty socket and localized resorption of the alveolar bone occurs (Hong et al., 2018). This bone resorption is explainable by Wolff's law, due to a lack of mechanical strain (Wolff, 2012). This theory states that bone deposition occurs with increased strain whilst bone loss occurs with decreased strain, assuming there is an optimal window of equilibrium between strain and bone strength, which is defined by the bone's ability to resist structural collapse (Larsen, 2015: 214 -215). The major difficulty of Wolff's law research is distinguishing environmental from genetic factors. Within this paper, correlation analysis was used to focus on shape changes with relation to dental disease.

Materials and methods

All individuals in this study were patients who sought treatment, died, and were buried at the Radcliffe Infirmary, Oxford, between 1770-1855. The site was excavated by Oxford Archaeology between 2013-2014 as appointed by Oxford University. A total of 63 individuals (48 males, 14 females, and one of indeterminate sex) with an intact right mandibular ramus or face underwent macroscopic and morphometric analysis at Durham University. Only prime (26-35 years) and middle-aged adults (36-45 years) with no evidence for metabolic disease or any congenital condition affecting the skull were chosen for analysis. Sex and age estimations were based on the original skeletal reports by Oxford Archaeology (Loe et al., 2022). Individuals of indeterminate sex were re-evaluated for age and sex based on pelvic morphology and methods outlined by Brooks and Suchey (1990) and Lovejoy and colleagues (1985). To explore whether dental health and wear correlated with sex-related morphological traits of the skull, five features (the nuchal crest, mastoid process, glabella, mentum, and supra-orbital ridge) were scored based on methods by Buikstra and Ubelaker (1994) and included in the correlation analysis.

Each tooth and tooth position were recorded for the presence of caries and periapical lesions respectively based on definitions described by Brothwell (1981) and Ogden (2007). Periodontal disease was marked as either none, slight, medium, or severe based on methods by Ogden (2007). AMTL was recorded only if there were signs of healing such as infilling of the socket. Supernumerary and retained deciduous teeth were not recorded for AMTL or considered for the wear score but were considered for presence of dental lesions.

Dental wear was scored using methods by Scott (1979) for the molars, and Smith (1984) for the remaining teeth. The wear score was normalized for each individual based on the number of teeth present. The calculation takes the possible minimum ((number of molars * 4) + number of remaining teeth) and maximum ((number of molars * 40) + (number remaining teeth * 8)) wear score based on the number of scorable teeth present. The wear score is calculated with the following formula: (total score - minimum score) / (maximum score - minimum score + 1) * 100.

Skull size was evaluated by taking linear measurements defined by Buikstra and Ubelaker (1994); due to preservation limitations, not all measurements were taken for the entire sample. Sixty-one individuals were measured for the average minimum ramus breadth, maximum ramus height, and gonial angle while 33 individuals were measured for bicondylar breadth. Measurements taken were: maximum cranial breadth (n=48), maximum cranial length (n=46), basion-bregma height (n=46), bizygomatic breadth (n=39), and upper facial height (n=45). These measurements were used to calculate the cranial, breadth-height, and upper facial indices when possible. Those with missing measurements were not included in downstream statistical analysis.

An inter and intra-observer error test was completed by calculating standard error. The first author took the second set of measurements one month following the first. The remaining measurements were taken by three peers who were each given definitions of the measurements. The test revealed the cranial measurements (maximum breadth, length, and bizygomatic breadth) were the most subject to error (+/- 7.184mm) (see table S.1).

Evaluation of shape was achieved using two-dimensional GM. Two configurations, the lateral right mandibular ramus and anterior profile of the face, were chosen to capture predicted shape variation induced by dental pathology and wear. All photographs were taken using a Canon DSLR camera with an 18-55 mm lens. The camera was consistently positioned 67 cm from the ground and the grid in the viewfinder was used for accurate positioning of the subject. A timer was set to reduce any noise from movement. A total of 30 individuals (24 males and 6 females) were digitized for the facial configuration which included 17 landmarks and 30 semi-landmarks (see figure 1). A total of 57 individuals (45 males, 12 females, and one of indeterminate sex) were digitized for the mandibular ramus configuration which consisted of 9 landmarks and 20 semi-landmarks (see figure 2). Tables 1 and 2 display the definitions for each landmark (Buikstra & Ubelaker, 1994; Corte-Real et al., 2020; Hilgers et al., 2005). Landmarks were digitized twice for each unique element using tpsDIG v.2.32 (Rohlf, 2015). The sliding landmarks were created using tpsUTIL v.1.83 (Rohlf, 2015). TpsRelw v.1.75 was used to superimpose the configurations to factor out the non-shape variables of rotation, orientation, and size (Rohlf, 2015). A generalized Procrustes' alignment was used for the landmarks, and the sliding landmarks were aligned using the chord method. A full Procrustes fit was used on each digitization of the mandibular and facial configurations, then averaged to account for any inter-observer errors. To measure the shape variation in both configurations the program MorphoJ was used to complete principal component (PC) analysis, create wireframe graphs, and calculate fluctuating asymmetry (Klingenberg, 2011). All remaining statistical analyses were completed in SPSS 29.0 (IBM Corp, 2022).

Fluctuating asymmetry (FA) was explored for a closer evaluation of shape variation between the left and right sides of the face. It was predicted that an unequal distribution of dental lesions, AMTL, and periodontal disease would potentially alter skull morphology. Asymmetry was analyzed using MorphoJ's Procrustes ANOVA function (Klingenberg & McIntyre, 1998; Palmer & Strobeck, 1992). Individuals were then categorized based on left, right, or even spreads of caries and AMTL, as well as periodontal disease severity, for statistical analysis. Teeth with only their roots present were considered lost, for this analysis only, because of their lack of occlusion.

Correlations between shape components, size dimensions, FA, and dental health variables were completed using a Kendall's Tau correlation test. Variables statistically different between males and females were analyzed separately. Interpretations of the coefficients are based on methods described by Schober and colleagues (2018).

Results

All data for this sample population is provided in the supplementary information (table S.2). Table 3 displays the summary of dental health observations, illustrating the extent of poor dental health for this predominantly working-class population. Caries and AMTL were the most prevalent conditions while periapical lesions were less common, although it is possible radiographs would reveal a higher number of the latter. The poor dental health of the Radcliffe Infirmary population aligns with contemporary sites. Table 4 displays caries rates for post-medieval sites in England; the true prevalence rate for caries ranges from 14.1% to 26.5%, with the Radcliffe Infirmary having the highest crude prevalence rate of 87.7%. Carious lesions were most prevalent in the posterior maxillary and anterior mandibular teeth (see figure S.1), while periapical lesions most frequently affected the posterior right maxillary tooth sockets (see figure S.2). Coinciding with carious lesions, tooth loss typically affected the posterior maxillary and anterior mandibular teeth (see figure S.3). Nearly 70% of individuals presented some degree of periodontal disease, the majority of those with a medium degree of the disease. The average dental wear score was 22.87%. A regression analysis of dental wear against AMTL indicated AMTL had no relation to wear ($F(1, 61)=2.996$; $p=0.089$); there were also no convincing signs of bruxism. The results of this test suggest tooth loss reflects pathology rather than wear.

Table S.3 displays the results of the t-tests for the craniomandibular dimensions. Males had larger skull dimensions including maximum ramus height ($t=486.5$, p=0.007), bicondylar breadth ($t=2.553$, $p=0.016$), cranial breadth ($t = 4.490$, $p=<0.001$), cranial length ($t=3.842$, $p=<0.001$), upper facial height (t=220, $p=0.019$) and bizygomatic breadth ($t=5.390$, $p=<0.001$). Males also showed statistically higher dental wear scores than females ($t=515$, $p=0.003$). There were no differences between the two age categories of prime and middle adult.

The results of the facial morphometric analysis are displayed in figure 3. A scree plot revealed the first five PCs (approximately 75% variance) were significant in total variance observed (see figure S.4). A multivariate regression analysis of the centroid onto the Procrustes coordinates revealed size has significant influence on face shape ($p=0.011$), with size predicting 9.7% of the total variance. All downstream analyses for the facial configuration were subsequently fixed to exclude the influence of allometry. The same process was conducted for the mandibular configuration; results are displayed in figure 4. Similar to the face configuration, a scree plot revealed the first five PCs (approximately 75% variance) explained the most variance (see figure S.5). Size for the mandibular configuration did not have a significant influence on shape ($p=0.09$, 3.38%).

A Kendall's Tau correlation test was done to discover relationships between dental health variables and craniomandibular size and shape. Correlations with a significant p-value are displayed in table 5, the rest of the correlation results are displayed in table S.4. The third PC of the mandibular configuration had a strong correlation coefficient ($\tau_b=-0.595$) with female dental wear, but this sample size is very small (n=12), and the 95% confidence intervals suggest a range from a weak to strong relationship. This wide range questions whether this correlation is strong. Similarly, the second PC had a weak to moderate strength correlation ($\tau_b=-0.433$) with caries while the fourth PC had the same strength correlation with AMTL ($\tau_b=0.352$). This pattern of weak to moderate strength correlations continues between the craniomandibular measurements and dental health variables. There were also no correlations found between the shape PCs and masculine/feminine features of the skull.

It was predicted that an uneven distribution of lesions and AMTL would result in correlation with FA variation reflecting a preferred chewing side where there was a higher surface area of functional occlusal surfaces. Furthermore, it was predicted that more severe periodontal disease would result in asymmetry along the maxillary alveolar bone. Table 6 displays the results of this analysis. The results of the correlation test suggest periodontal disease (τ_b=0.029, p=0.827), AMTL (τ_b=0.143, p=0.327), and dental lesions (τ_b=-0.225, p=0.122) have no relationship with FA.

Discussion

The Radcliffe Infirmary population has a high frequency of carious lesions, aligning with contemporary sites. This trend of poor dental health is consistent with the increased importation of sugar. While white sugar was a luxury item well into the 19th century, processed sugar products such as treacle, jam, and chocolate became more attainable for the lower classes, and a significant amount of sugar was consumed in tea (Mant & Roberts, 2015; Mauriello, 2008). These sugar products, bread made with refined flour, and tea became staples for working class families in the 18th and 19th centuries (Mant & Roberts 2015).

Along with an increase in cariogenic foods, diet became increasingly processed and soft into the 18th and 19th centuries. Past studies have used advanced dental wear as a measure of hyperactive masticatory function to explain the structural adaptation of well-developed masticatory systems (e.g. Hirst, 2019; Rando et al., 2014; Varrela, 1992). Masticatory strength is suggested to relate to a short and wide face shape, smaller gonial angle, and overall, a robust mandible (Kiliaridis et al., 1995; Ueda et al., 1998). However, in this sample, higher degrees of dental wear were only weakly to moderately correlated with bizygomatic breadth and the cranial index (long narrow shaped cranium) in males (not females). This weaker correlation is inconsistent with other studies exploring cranial form and soft diets (Hirst, 2019; Rando et al., 2014; Ueda et al., 1998; Varrela, 1992). A correlation test revealed that overly masculine or feminine skull features had no relation to shape variation or dental health. This fact is important to note for bioarcheologists who utilize skull shape to aid skeletal sex estimation. However, more research is recommended of an equal male and female sample to determine the effect of dental health on morphology.

The results of this study suggest poor dental health is only weakly to moderately correlated with craniomandibular size and shape. This is surprising as current understanding of AMTL and periodontal disease indicates they have negative effects on the masticatory system. Weakened masticatory function is suggested to correlate with atrophy of the masseter and temporalis muscles, a reduction in number of occlusal surfaces, and general discomfort while chewing (Kiliaridis et al., 1995; Lamba et al., 2020; Small et al., 2016). Dental caries has been suggested to negatively affect masticatory efficiency based on studies measuring maximum biting force in schoolchildren (Kaya et al., 2017; Souto-Souza et al., 2020). A large gonial angle has been associated with a weak biting force potentially agreeing with findings of this research (Kiliaridis et al., 1995). Unfortunately, this weak correlation was the only evidence suggesting dental lesions influence skull morphology. However, the second facial PC's correlation with dental caries suggests a moderate correlation with facial shape variation.

A morphometric study by Small and colleagues (2016) found positive correlations between AMTL and orbit size, resorption of the maxillary alveolus, and bizygomatic breadth, while it was negatively correlated with total palatal arch length and upper facial height. The authors explain these patterns by masseter muscle atrophy following extensive tooth loss. For the Radcliffe individuals, AMTL correlated with bicondylar breadth weakly to moderately and the fourth facial PC weakly. It is possible muscle atrophy would have further progressed and influenced skull shape for this sample if these individuals lived longer.

Periodontal disease directly affects the underlying skeletal structure of the mouth and is believed to impair masticatory and para-masticatory function (Kato et al., 2018; Lamba et al., 2020). A clinical study revealed patients with periodontal disease had difficulty eating and speaking due to physical pain, and as a result, many required breaks during meals (Meusel et al., 2015). It was predicted periodontal disease would correlate with smaller skull dimensions and facial asymmetry. However, the only correlations found with periodontal disease in this study were AMTL and wear. These correlations can be explained by the nature of the disease as dental wear, in particular habitual teeth clenching and grinding (known as bruxism), is acknowledged to worsen gingival inflammation while tooth loss is the consequence of alveolar resorption and periodontal ligament detachment (Hillson, 2023: 400; Mostafa & Fatima, 2022).

Shape changes were not only predicted to correlate with poor dental health; degrees of facial asymmetry were also predicted to correlate with the distribution of dental lesions and periodontal disease. This was under the assumption that the preferred chewing location would be where fewer dental lesions and AMTL were situated, therefore adding more localized mechanical strain in the mouth. However, results show no relationship between FA and dental health. It is possible bone remodeling is not sensitive enough to reflect these differences. It is still uncertain what causes habitual unilateral chewing, but it is suggested to be unrelated to handedness (Martinez-Gomis et al., 2009). Chewing side preferences have many possible underlying etiologies such as occlusal differences, congenital conditions, facial trauma, facial tumors, and temporomandibular diseases

(Andrade et al., 2021). Therefore, based on the results of the present study, other etiological factors appear to have a stronger influence on facial asymmetry than unilateral chewing resulting from differences in the number of dental lesions and AMTL afflicting the left versus right sides of the mouth.

Limitations and future research

The limitations of this study primarily relate to the small sample size, as well as an over representation of males. Furthermore, an observer test revealed an inconsistency of cranial measurements (see supplementary S.1). There was a degree of inconsistency in landmark placement and element position during photography although each configuration was digitized twice and averaged to minimize error. Future research should aim for a larger sample and utilize three-dimensional GM to capture the full skull shape. Little attention was given to the influence of hereditary malocclusion during this study, which may have greater effect on the cranial form and masticatory efficiency. It may also be helpful to explore the difference in dental wear between males and females for other 18th and 19th century populations as this may influence skull sex estimation methods.

Conclusion

The purpose of this study was to analyze the effects of poor dental health for the working classes of 18th-19th century England using geometric morphometrics of the craniomandibular complex. Modern knowledge of poor dental health shows how dental caries and periodontal disease can decrease the quality of life and cause eating difficulties. Based on the extent of tooth loss and dental disease, it is evident the Radcliffe Infirmary population consumed a highly cariogenic diet. This pattern of poor dental health is consistent with other 18th-19th century populations prior to the establishment of, and equal access to, dental care. Due to a carbohydrate-based diet it was predicted that extensive periodontal disease and AMTL would cause muscle atrophy and bone resorption reflected in skull morphology. Weak to moderate correlations were found between dental disease (carious lesions, AMTL, and dental wear), and craniomandibular shape and size variables illustrating the potential of future research on this topic. Considering this sample only included 63 individuals more research on a larger sample with equal numbers of males and females is needed. It is also suggested that an older age range is considered to allow greater potential for morphological changes to develop as a result of dental disease. Additionally, three dimensional geometric morphometrics may better capture shape variation while reducing digitization error.

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Supplementary Information

Table S.1 Results of the inter and intra observer tests for the linear measurements of the skull. Results indicate the highest level of error for the cranial measurements.

	Cranium					Mandible				
	Max. breadth	**Max. length**	**Bizygomatic breadth**	**Upper facial height**	**Basion bregma height**	**Min. ramus (L)**	**Min. ramus (R)**	**Bicondylar breadth**	**Gonial angle**	**Max. ramus height**
Peer 1	144	188	127	63.9	137	29.27	30.31	118.28	34	57
Peer 2	143	191	121	63.06	136	29.71	30.61	117.62	37	57
Peer 3	142	187	128	72.51	136	30.8	30.94	118.29	35	58
Author	145	189	126	72.97	136	30.19	30.86	118.39	36	59
Author	143	192	127	73.02	136	29.82	30.64	118.24	36	57
Average	143.4	189.4	125.8	69.092	136.2	29.958	30.672	118.164	35.6	57.6
Error (+/-)	7.184			2.297	0.2	0.177		0.138	0.51	0.4

Table S.2 All data from this sample of the Radcliffe Infirmary. Table includes age and sex estimations, dental health variables, craniomandibular measurements, and results from the geometric morphometrics.

Table in separate .xcel file.

Figure S.1 True prevalence rate of carious lesions per tooth position. Results show dental lesions typically affected the posterior maxillary and anterior mandibular teeth.

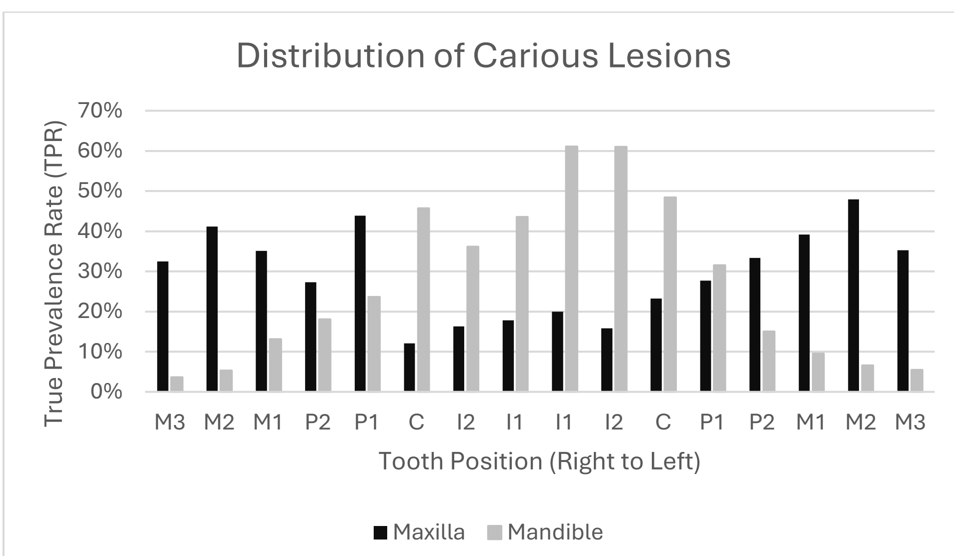

Figure S.2 True prevalence rate of periapical lesions per tooth position. For the sample population periapical lesions were more frequently observed at the posterior right maxillary tooth positions.

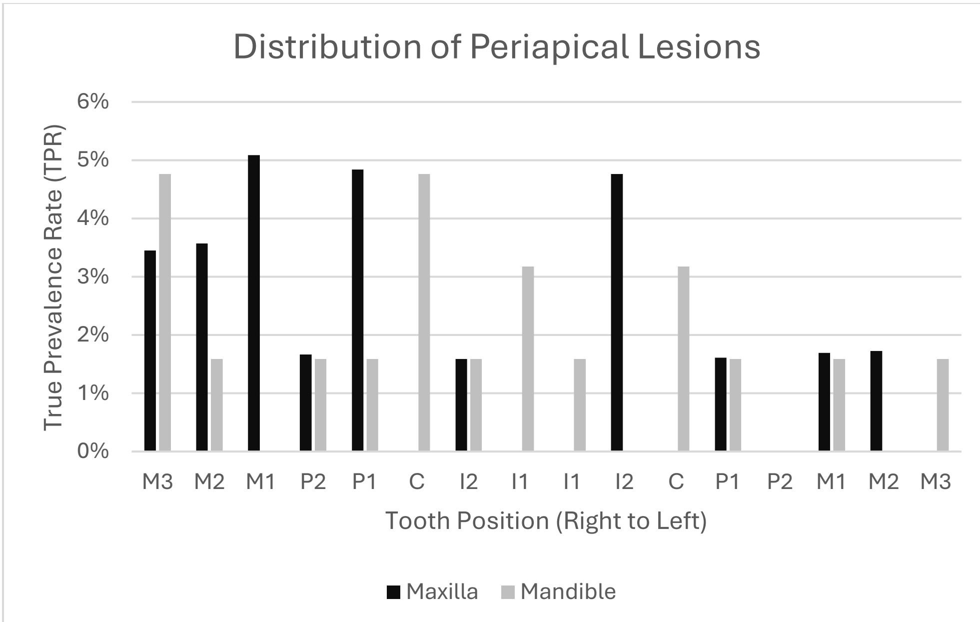

Figure S.3 True prevalence rate of recorded antemortem tooth loss (AMTL). Results indicate tooth loss typically affected the posterior maxillary and anterior mandibular teeth.

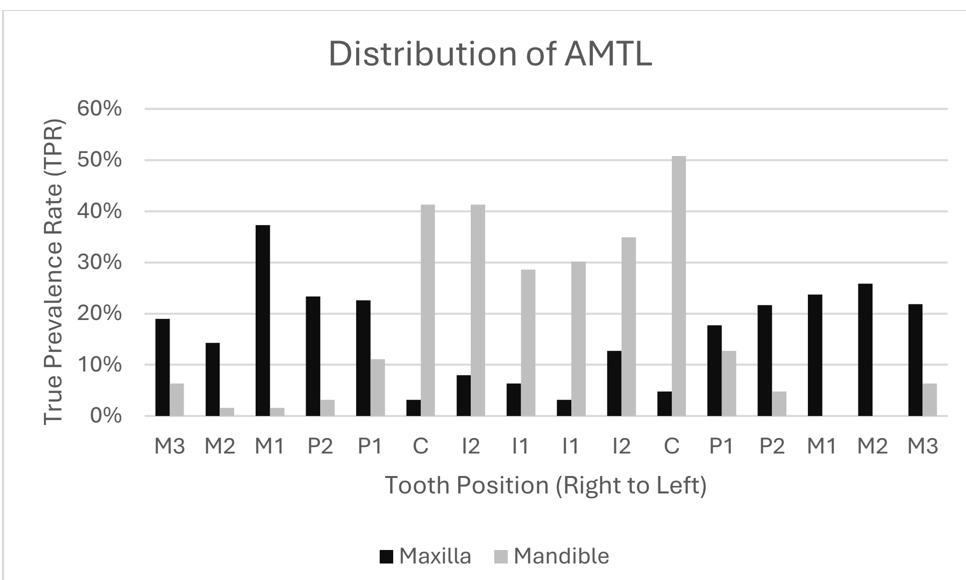

Table S.3 Results of the T-tests comparing the means between males and females. The significant correlations are highlighted in orange.

Table in separate .xcel file.

Figure S.4 Scree plot for the facial configuration. Results indicate the first five components (75% variance) explain most of the shape variation.

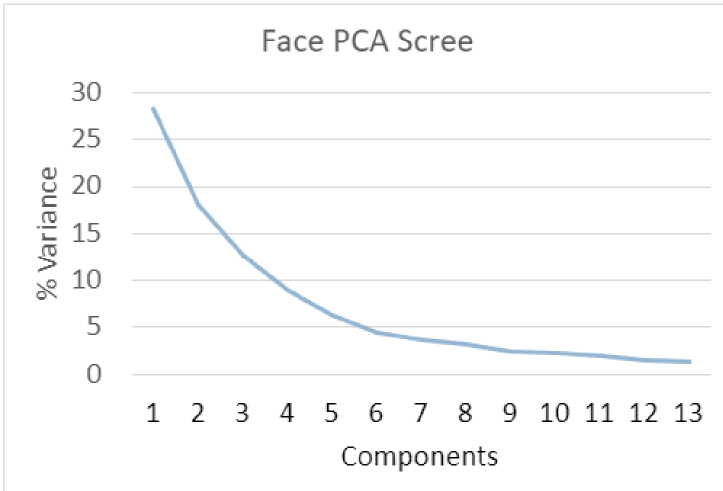

Figure S.5 Scree plot for the mandibular configuration. Results indicate the first five components (75% variance) explain most of the shape variation.

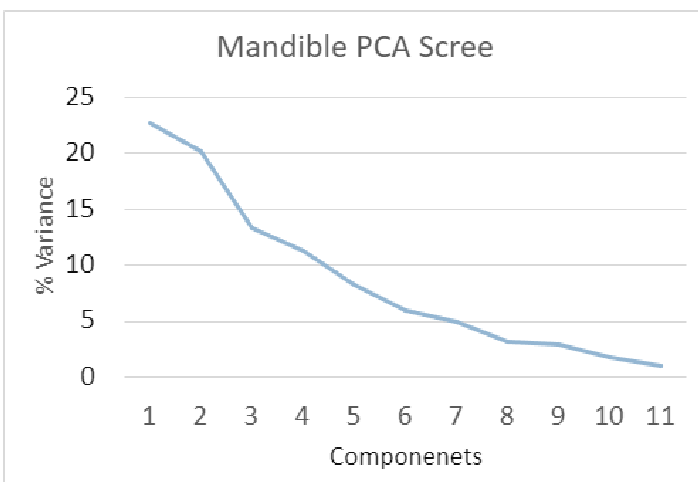

Table S.4 Results, including insignificant correlations, of the Kendall's Tau test. The significant correlations are highlighted in orange.

Table in separate .xcel file.

Tables

Table 1. Definitions of the landmarks chosen for the facial configuration.

Craniofacial Landmarks		
Landmark	**Definition**	**Source**
Nasion	Midpoint at the intersection of the frontonasal suture with the internasal suture joining the nasal bones	Buikstra and Ubelaker 1994
Frontomalare orbitale (paired)	The medial point on the orbit where the zygomaticofrontal suture is located.	
Frontomalare temporale (paired)	the most lateral positioned point on the fronto-malare (fronto-zygomatic) suture, most lateral inferior point on suture	Buikstra and Ubelaker 1994
Jugale (paired)	Where temporal and frontal processes of the zygomatic bone meet, lateral from orbitale. Advised to use a flat edge to find this point, occaisionally marked by the "V" shape of the zygomatic bone.	
Zygion (paired)	Most lateral point on the zygomatic arch.	Buikstra and Ubelaker 1994
Orbitale (2)	Most inferior point on the inferior orbital rim, usually falls along the lateral half of the orbital margin, on the inner rim	Buikstra and Ubelaker 1994
Superior zygomaxillare (paired)	Most superior medial point on the zygomaxillary suture along orbital rim.	
Inferior zygomaxillare	Most inferior point on the zygomaxillary suture.	
Ectomolare (paired)	Most lateral point on the lateral surface of the alveolar crest, found along the 2nd molar on the maxilla	Buikstra and Ubelaker 1994
Alveolar part of the maxilla (paired)	15 semi-landmarks on the line originating on the ridge starting at the premolar location, and stops at the most inferior point near the inferior of the zygomaxillary suture.	

Table 2. Definitions of landmarks chosen for the mandibular configuration.

Mandibular Landmarks		
Landmark	**Definition**	**Source**
Gonion	Most inferior, lateral, and posterior point of the gonial angle.	Buikstra and Ubelaker 1994

Posterior ramus point	Most concave point at posterior border of the mandibular ramus.	Corte-Real *et al.* 2020
Posterior mandibular condyle	Most posterior extent of mandibular condyle (located approximately 4mm inferior to the apex of the superior condylar surface).	Hilgers *et al.* 2005
Condylion	Most superior and posterior point on mandibular condyle.	Corte-Real *et al.* 2020
Superior mandible condyle	Most superior point on the mandibular condyle.	Corte-Real *et al.* 2020
Anterior mandibular condyle	Most anterior extent of mandibular condyle (located approximately 4mm inferior to the apex of the superior condylar surface).	Hilgers *et al.* 2005
Inferior sigmoid notch	Deepest point of the mandibular notch.	Corte-Real *et al.* 2020
Coronoid	Most superior point of the coronoid process.	
Anterior ramus point	Most concave point at the anterior border of the mandibular ramus.	Corte-Real *et al.* 2020
Posterior coronoid sliding	10 semi-landmarks from the inferior sigmoid notch to the coronoid landmarks.	
Anterior coronoid sliding	10 semi-landmarks from the coronoid to the anterior ramus point landmarks.	

Table 3. Summary of dental health observations for this sample of the Radcliffe Infirmary.

Summary of dental health				
Dental Variable	**Crude prevalence rate**		**True prevalence rate**	
AMTL	57/63	90.48%	324/1975	16.41%
Caries	63/63	100%	389/1515	25.68%
Periapical Lesions	23/63	36.51%	35/1975	1.77%
Periodontal disease (slight)	13/63	20.63%	-	-
Periodontal disease (medium)	18/63	28.57%	-	-
Periodontal disease (severe)	13/63	20.63%	-	-

Table 4. Comparison of caries prevalence between the Radcliffe Infirmary and other populations in post-medieval England. Both crude (CPR) and true (TPR) prevalence rates are included in column two.

Comparison of caries across post-medieval England			
Site	**Rate of carious lesions**	**Context**	**Citation**
Original report for Radcliffe Infirmary	CPR = 87.7% TPR = 19.2%	1770-1855, Oxford	Loe *et al.* 2022
New Churchyard	TPR = 18.9%	1569-1739, East London	Smith 2019
St. Bride’s Lower Churchyard	CPR = 78.9% TPR = 26.5%	1770-1849, London	Mant and Roberts 2015
Chelsea Old Church	CPR = 79.5% TPR = 21.5%	1712-1842, London	Mant and Roberts 2015

Cross Bones	CPR = 79.5%	1800-1853, South London	Brickley *et al.* 1999
St. Nicholas' Church	TPR = 14.1%	1700-1840, Kent (England)	Boyle and Keevil 1998
Christ Church, Spitalfields	CPR = 87.0% TPR = 17.9%	1729-1852, East London	Whittaker 1993

Table 5. Results of the Kendall's Tau correlation test between craniomandibular shape, size, dental pathology, and dental wear.

Size/Shape Variable	Dental Variable	Coefficient (τb)	Lower 95% CI	Upper 95% CI	Sig. (2 tail)	n	Strength
Gonial Angle	Caries	0.233	0.03	0.425	0.011	62	Weak
Bicondylar Breadth	AMTL	0.276	-0.062	0.407	0.043	29	Moderate
Bizygomatic Breadth (Males)	Wear (Males)	0.294	0.027	0.552	0.025	30	Moderate
Cranial Index (Males)	Wear (Males)	-0.241	-0.431	-0.053	0.036	37	Weak
Facial PC2	Caries	-0.433	-0.689	-0.158	0.001	30	Moderate
Facial PC4	AMTL	0.352	0.102	0.588	0.009	30	Weak
Mandibular PC3	Wear (Females)	-0.595	-0.902	-0.24	0.007	12	Strong

Table 6. Results of the Procrustes' ANOVA test run in MorphoJ, analyzing facial asymmetry.

Procrustes' ANOVA: Facial Asymmetry					
Effect	**Sum of Squares**	**Mean Square**	**df**	**F Ratio**	**P value**
Individual	0.1257	0.0001	1305	6.95	<.0001
Side	0.0023	0.00005	45	3.75	<.0001
Ind*Side	0.0181	0.00001	1305	5.90	<.0001
Error 1	0.0063	0.000002	2700	-	-

Figures

Figure 1. Photograph demonstrating the craniofacial configuration chosen for this study (male estimated at 36-45 years of age). The red points indicate landmarks while the arrows pointing to the black lines indicate sliding landmarks.

Figure 2. Photograph demonstrating the mandibular configuration chosen for this study (female estimated at 26-35 years of age). The red points indicate landmarks while the arrows pointing to the black lines indicate sliding landmarks.

Figure 3. Results of the principal component analysis for the facial morphometrics.

Figure 4. Results of the principal component analysis for the mandibular morphometrics.