TITLE PAGE

Title: Changes in mandibular dimensions during the medieval to post-medieval transition in London: A possible response to decreased masticatory load

Running title: Mandibular reduction in post-Medieval London

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ABSTRACT

(1) Objectives: Biomechanical forces, such as those produced during mastication, are considered a primary agent in stimulating craniofacial growth and development. There appears to be a strong connection between the strength of the masticatory muscles and the dimensions of the craniofacial complex, with changes in biomechanical force and muscular strength influencing and altering the underlying bony tissues. This is markedly apparent in the mandible and it is possible to infer that changes to mandibular form are due in part to dietary changes. This study aims to investigate this idea by using an archaeological sample from a period that experienced important dietary changes as a result of the Industrial Revolution. (2) Design: 279 skeletons from the Medieval and post-Medieval periods in London were selected for analysis, and a detailed metric examination of each mandible was carried out. (3) Results: Males and females were analysed separately and statistically significant reductions were observed in nearly all post-Medieval measurements. This effect was most pronounced in the areas of the mandible associated with masticatory muscles attachment, including the gonial angle, ramus height and width, bi-gonial breadth and bi-condylar breadth. (4) Conclusions: These recorded changes in mandibular morphology of Medieval and post-Medieval Londoners are most likely the result of a shift in diet (and associated decrease in masticatory function) observed in the period surrounding the Industrial Revolution.

TEXT

Introduction

The masticatory muscles are the strongest in the human skull and play the primary role in placing mechanical strain (compression, tension and shear) on the growing bones, with all growth zones (chondral, sutural and periosteal) responsive to biomechanical forces[1]. Changes in masticatory muscle activity can alter the strain applied to the bones of the skull, affecting the growth of the craniofacial complex[2]. According to Frost[3, p.5], during embryonic development, the 'biologic machinery that can adapt bones after birth to mechanical and other challenges' is created, and this machinery includes the thresholds that control bone resorption and formation. When the strain on a bone exceeds the upper thresholds, depositional mechanisms are switched-on which stimulate bone production and increase the overall strength of the bone; conversely, when strain falls below the lower thresholds, bone is resorbed, reducing bone strength[3]. Grunheid et al[4] note that bone mineral density is related to bone loading (strain), such that more heavily loaded bones tend to be less mineralized and stiff, while weakly loaded bones tend to be stiffer and more mineralised. The regions of bone most likely to be affected by changes to strain/loads are those directly involved in mechanical loading - such as muscle attachment sites - with membranous bones, including the mandible and the bones of the face, more susceptible to external factors[5].

The complex relationship between underlying masticatory muscle structure, bite force (strength), and craniofacial dimensions has been well established in the literature. Raadsheer et al[6] note four important connections when considering the dynamics between these variables: 1) bite force magnitude is related to jaw muscle cross-section; 2) bite force magnitude is related to craniofacial dimensions; 3) craniofacial dimensions and jaw muscle cross-sections are related;

and 4) a relationship between muscle size and craniofacial dimensions exists. Each of these will be briefly addressed considering both human and animal models.

Using human models, multiple studies have observed that changes in bite force strength are correlated with corresponding changes in craniofacial dimensions. Ingervall and Helkimo[7] observed that individuals with stronger bite force tended to have broader faces, a straighter cranial base, and a more uniform facial shape, while Ingervall and Minder[8] noted that larger bite force in children was correlated with smaller mandibular inclination, smaller gonial angles and larger posterior facial height. Tuxen et al[9] also noted that stronger molar bite force was associated with smaller gonial angles, as did Sondang et al[10]. In one of the few studies on this subject experimenting on human subjects, Ingervall and Bitsanis[11] initiated a muscle training program in children (between 7 and 13 years old) to observe the direct connection between increasing bite force and craniofacial measurements. Throughout the course of training, bite force in the children increased more than would be expected as a result of the normal aging process and the children with increased bite force experienced an increase in mandibular rotation and resorption along the gonial angle.

Jaw muscle thickness has been found to be connected to craniofacial dimensions, in that thicker muscles (more specifically, the masseter) tend to be negatively correlated with anterior facial height and mandibular length, but positively correlated with intergonial width and bizygomatic width[12]. Weijs and Hillen[1] observed a correlation between the cross-sectional size of the jaw muscles and craniofacial dimensions, suggesting that each of the different muscles of mastication plays a different role in the growth of the face; the cross sections of the masseter and temporalis are positively correlated with facial width, while the masseter and medial pterygoid are associated with mandibular length. Kubota et al[5] observed that the thickness of the masseter was significantly correlated with the mandibular plane angle and the thickness of the alveolar process, the mandibular symphysis, and the mandibular ramus.

Studies on animals have shown that reduced masticatory muscle function results in reduced size and altered proportions of the craniofacial complex, especially in the mandible[5]. This suggests that large masticatory muscles and strong chewing forces are needed to attain 'normal' facial growth. Research examining rats[13,14,15,16,17,18,19,20,21,22] and rock hyrax[23] has shown that animals fed a soft diet (compared against animals fed a hard diet) exhibit differences not only in facial dimensions, but also in the rate of bone growth. Hard diet fed animals tend to have larger dimensions overall, especially in the maxillary breadth[17,13] and posterior facial measurements[23], compared with the soft-diet groups. In their study, Maki et al[19] noted that it was rats fed a powdered diet, rather than those with just a soft diet, that experienced the most profound alterations to jaw bone morphology. The rate of bone growth appears lower in the soft-diet animals[15,16,17,18] , thought to be a result of reduced muscle function and reduced demands on the masticatory system. Alterations to bone density have also been observed in rabbits fed a soft diet, with heavily loaded bone being less mineralised or stiff and weakly loaded bone has a decreased rate of remodelling and is stiffer/ more mineralised[4]. Grunheid et al[4] further noted that this is most pronounced in areas of mechanical loading – such as those at muscle attachment sites.

Through examination of muscle thickness and the shape/size of the maxillofacial skeleton, multiple studies[5,24,25] have noted that changes in human diet have reduced the forces generated by the masticatory complex. This reduction has had an impact on craniofacial dimensions, furthering the idea that changes in masticatory function have been a predominating factor in the alteration of the human face since the emergence of agriculture and the adoption of less chewing intensive foods. Furthering this notion, clinical studies focused on dental attrition, bite force and cranial dimensions[26,27,28,29] have noted that patients with 'advanced' dental wear present with reductions in the height of the lower face, smaller gonial angles, increased bite force and somewhat more prognathic faces. It is worth noting here that the tooth wear observed in these cases may be considered pathological - the result of bruxing - and may not be useful when considering changes to dietary composition.

The post-industrialized human diet is notably softer and more refined than traditional agricultural diets, and as such contributes very little to tooth wear[30,31,32]. This is primarily the result of the advancement of food processing technologies which have effectively stripped food of any abrasive particles and fibrous content, and due to our 'reliance on [these] factory processed foods'[33, p. 861] as the main (and nearly only) means of food procurement. With the Industrial Revolution and increasing urbanisation, the majority of people no longer made or grew their own foods and had to rely solely on what was available for purchase. Naturally the most readily and convenient foods tended to be the most processed, softest, and sweetest ones, which caused a marked increase in oral pathology but created little in the way of tooth wear.

The evidence from the clinical literature supports the notion that bone responds to external mechanical stresses and that changes to diet, as observed in animal studies, can alter both the growth and form of the skull, particularly the jaws and the face. This study aims to investigate whether, in humans, important dietary shifts are associated with observable changes in the dimensions of the mandible. The Industrial Revolution, as a by-product of technological innovation and advancement, is a period when human dietary practices changed from a 'traditional' agricultural diet to one closer to the modern Western diet. The analysis of archaeological skeletal remains from this period should allow us to investigate if and how major changes in diet and masticatory function can alter of the human craniofacial complex.

Materials and Methods

Skeletal assemblages from the late Medieval period (1050 - 1550) and the post-Medieval period (1550 - 1850) in London were selected for the purposes of this study (n= 279). The archaeological material used here was obtained from the Museum of London Centre for Bioarchaeology. A list of the sites used can be found in Table 1. These sites were specifically selected as they were all in use either prior to or during/after the Industrial Revolution. Each specimen was required to be adult (18+), have both the pelvis and skull present for sex estimation, and have at least one quarter of the dentition present. Advanced tooth loss can cause specific changes in mandibular form, so no edentulous specimens were included.

[INSERT TABLE 1]

Mandibular metric analysis was performed on each specimen according to standard osteological methods (Buikstra and Ubelaker[34, p. 71-78], Table 2). Measurements of the mandibular condyle were based on Wedel *et al.*[35], redefined by the lead author in an earlier work (Rando 2007, unpublished master's dissertation). All measurements were taken to 0.01 mm and angle measurements to 0.5 degrees. Analysis was performed using the Independent Assemblages T-Test function in SPSS 14.0, using time period as the grouping variable. The sexes were analyzed separately as to eliminate the effects of sexual dimorphism on the results. Sex was established again using standard methods, which included visual examination of the pelvis (greater sciatic notch, ventral arc, ischio-pubic ramus ridge, and sub-pubic concavity) and of the skull (nuchal crest, glabella, mastoid process, supraorbital margin, and mental eminence) according to Buikstra and Ubelaker[34]. Age was not considered in these analyses. Results were considered significant at/below the level of $p<0.05$.

[INSERT TABLE 2]

Results

A similar pattern was observed for both the female and male specimens between the Medieval and post-Medieval periods (Tables 3 and 4). Statistically significant reductions were observed in all mandibular ramus dimensions (maximum breadth, minimum breadth and height) and in the overall width of the mandible (bicondylar breadth and bigonial width). These reductions were uniformly more marked in the male sample. A significant increase in the gonial angle was observed for both males and females, but only the female group showed a significant increase in overall mandibular length. No significant differences were observed in chin height or in the anterior posterior dimensions of the mandibular condyle in either males or females. However, the medio-lateral dimensions of the condyle were significantly reduced in both sexes. Figures 1 and 2 exhibit how these changes to size are reflected in the general shape of the mandible, showing a tendency for a reduced ramus, reduced overall width and increased angulation.

[INSERT FIG 1 AND 2]

Discussion

Between the Medieval and post-Medieval period marked changes were observed in nearly all mandibular dimensions studied here, with the most pronounced changes being an overall reduction in mandibular width, a reduction in mandibular ramus height, and an increase in the angulation of the gonial angle. The increase in the gonial angle produces more posterior rotation of the mandible, causing the lower face to increase in height creating the ‘long-face’ facial form often observed in individuals with relatively weak bite force.

The results observed here are in line with previous archaeological studies examining this transitional period. Generally, research comparing Medieval Europeans to Modern Europeans (ranging from the post Medieval period to the 20th century) have found medieval skulls to be somewhat larger overall, relative to modern ones, with generally larger mandibles, wider dental arches, more prominent faces, and greater posterior facial height. The modern skulls tend to have reduced facial and palatal width, accompanied by larger gonial angles than the medieval groups, more posterior rotation of the mandibular ramus relative to the corpus, and larger nasal and upper facial heights[36,37,38,39,40,41,42,43]. In all of these cases, the observed changes have been attributed to the overall soft diet of modern populations, which has become so processed that 'for all practical purposes, most chewing stress has been removed', although this is likely somewhat of an exaggeration[13]. Kaifu[44] commented that the temporal changes in mandibular size (between the Jomon and modern periods in Japan) were likely due to the ‘weak development and lack of rugosity of the attachment sites of (the main masticatory) muscles’ and that this may have created a situation where there is a ‘lack of sufficient stimulation for proper growth of the jaw bone’[44, p 237].

Diet in the Medieval period can be considered relatively coarse and rough, although the primary elements (such as bread and beer) comprising it are not so dissimilar to the modern one. The people of the Medieval period were, of course, agriculturalists, but with a component of wild foods (game and foraged foods) in the diet, especially in the lower/peasant classes. Bread was the primary food staple, eaten by all peoples, regardless of social class, although with varying degrees of quality. For the feudal lords, fine white breads made of wheat were commonly consumed, but for the lower classes, maslin, a mix of wheat and rye, was commonest, as were darker loaves made only of rye [45.42]. Bread flour was often mixed with various weed grains, as well as peas and beans for the cheapest of breads[46,45]. Another staple food was pottage, a stew-like dish, either runny or thick, comprised of grains, vegetables, cereals, pulses and occasionally meat, and, like bread, was eaten by the poor and rich alike[45,47].

Fish was an important component of the Medieval diet, as church doctrine demanded that fish (or at least no meat) be consumed nearly half the days of the year[45] and was usually eaten pickled or salted by most ordinary peoples. Isotopic analysis of the Medieval diet suggests that during these fasting periods, the upper classes consumed much more marine foods compared to the lower classes, who likely relied on dairy products and eggs at these times. Sugar was very rarely consumed, and then typically only by the feudal lords, as it was quite expensive and often kept under lock and key, like an exotic spice[(45)]. Use of sugar became more widely spread towards the latter parts of the Medieval period, but never to the levels of consumption seen in the post-Medieval period.

The post-Medieval period in England was a time of rapid technological advancements that accompanied the Industrial Revolution; these included the invention of steam power, the intensification of agriculture (made possible via better fertilizers), crop rotation, and the introduction of fodder crops, allowing for the year-round availability of animal products[48,49]. For the first half of the post-Medieval period diet remained much the same as before, persisting throughout the Tudor period and into the 17th century. However, it is during the 17th century when changes to food composition, availability, and production occur, a result of "…rapid development[s] of scientific and technological discoveries affected nearly every area of life, including both the preparation of food and the quality of food itself'[50, p.219]. New imported goods, such as tea, coffee and chocolate[51] became available during this time, and there was a marked increase in the consumption of sugar and in the use of finely milled flour[52].

The changes observed in the 17th century continued on into the 18th and 19th, the diet of which was, for all intents and purposes, similar to the modern one. Sugar consumption increased significantly in the 19th century, from approximately 20 pounds per person per year, to almost 90 pounds by the start of the 20th century[53]. Bread was no longer made at home, but rather bought from bakeries and was soft and white. Fresh fruit and vegetables were consumed less frequently and the ‘staple diet’ of the lower classes was sweet tea, bread and jam[53]. As a result of these dietary changes, the post-Medieval diet was remarkably different from the Medieval one, substantially more processed, sweeter and softer - contributing little to tooth wear and potentially not as effective in promoting cranio-facial growth and development.

Simple measurements of linear dimensions and angles limit the aspects of morphology that can be captured but, in this study, it was found that they nonetheless showed clear and consistent differences. These results are supported by Geometric Morphometric analysis (not reported here, *forthcoming*), in which the quantifiable changes in shape were observed that correlate with the reduction in size. The results presented here give clear support to the idea that chewing is a stimulating agent in the development of the cranium and mandible, but other factors do need to be considered. The post-Medieval period involved a great deal of population movement, with individuals from rural communities moving to the cities to seek employment (and then leaving to return home). Such patterns may in part explain some differences in facial morphology by introducing a degree of genetic variation[54,55,56]. Sexual selection, however unlikely, may also have changed during the post-Medieval period, with certain facial features, such as smaller faces and jaws, being favoured[57]. However, the results obtained in this study are most probably the result of changes in subsistence. In the archaeological literature, dental wear is often used to represent the diet of a population or to interpret dietary shifts between time periods or groups[58,59,60,61]. Research examining the changing pattern of dental wear between the Medieval and post-Medieval Londoners (C Rando et al in prep) has observed a marked decrease in dental wear in the post-Medieval population. Not only has the degree of wear changed, but so too has the rate and the pattern, suggesting behavioural changes in the way teeth were used. Again, this is most likely to be the result of the dietary and food processing changes observed during this transitional period.

Conclusion

The past 1,000 years of human history have been full of rapid technological advancements, particularly those that occurred with the Industrial Revolution of the 18th and 19th centuries. During the Industrial Revolutions, technological achievements, such as the invention of steam power and the rotative engine, profoundly changed the way in which people lived and, somewhat indirectly, what they ate. Finer milling processes and agricultural intensification, along with increasing trade for sugar and other goods, led to dietary changes. No longer rough, fibrous or time consuming to chew, the modern industrial diet was smoother, softer, and required very little chewing.

There have been few studies of cranial morphology in Medieval and Post-Medieval Londoners. In addition, the human mandible is a relatively little studied part of the cranial complex (especially in assemblages from London) particularly because of the complications caused by the mechanical factors which form the focus of this study. The large collections at the Museum of London have provided an opportunity to concentate on the people of a single urban centre. For the first time, it has been shown that the dimensions of the mandible were considerably greater in Medieval Londoners than in later periods. Post-Medieval males and females had significantly smaller and posteriorly rotated mandibles. These changes were most noticeable in the areas of the mandible associated with masticatory muscles attachment, including the gonial angle, ramus height and width, bi-gonial breadth and bi-condylar breadth. These reductions can be linked to historical evidence for the decrease in the rough/tough texture of the diet that occurred with modernization, a by-product of the Industrial Revolution, where the diet is soft, sweet and processed, providing little in the way of biomechanical stimulation for facial growth and development. This further supports diet, and changes in masticatory function, as being a primary agent in craniofacial growth, development and morphology.

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TABLE 1. Summary of collections analysed.

Medieval			**Post-Medieval**		
Site	In use	n (%)	Site	In use	n (%)
MIN86 *East Smithfield Black Death*	*1348-1350*	27 (20%)	FAO90 *St Bride's Lower Churchyard, Farringdon*	*1770-1894*	72 (50%)
MIN86 *St Mary Graces*	*1350-1538*	15 (11.1%)	OCU00 *Old Church Street, Chelsea*	*1712-1842*	36 (25%)
MPY86 *Merton Priory*	*1117-1538*	16 (11.9%)	REW92 *Crossbones*	*1760-1853*	13 (9%)
NRT85/NRF88/SSP/ SSQ *Spital Square*	*1197-1320*	37 (27.4 %)	ONE94 *St Benet Sherehog – No 1 Poultry*	*1666-1853*	23 (16%)
GYE92 *Guildhall Yard*	*1050-1150*	15 (11.1%)			
BA85 *Bermondsey Abbey*	*1099-1538*	25 (18.5%)			
Total analyzed:		135 (100%)	Total analyzed:		144 (100%)

Table 2. Mandibular Measurements

Measurements	**Definition** (as described in Buikstra and Ubelaker 1994, 78)
Maximum Ramus Breadth (R/L)	'distance between the most anterior point on the mandibular ramus and a line connecting the most posterior point on the condyle and angle of the jaw'
Minimum Ramus Breadth (R/L)	'least breadth on the mandibular ramus measured perpendicular to the height of the ramus'
Ramus Height (R/L)	'direct distance from the highest point on the mandibular condyle to gonion (go)'
Body Length (Go – Me)	'distance of he anterior margin of the chin from a center point on the projected straight line placed along the posterior border of the two mandibular angles'
Gonial Angle (Co – Go – Me)	'angle formed by the inferior border of the corpus and the posterior border of the ramus'
Chin Height (Id – Gn)	'direct distance from infradentale (id) to gnathion (gn)'
Bicondylar Breadth (Co Lat – Co Lat)	'direct distance between the most lateral points on the two condyles'
Bigonial Width (Go – Go)	'direct distance between right and left gonion (go)'

Mandibular Condyles	**Definition** (as described in Wedel et al. 1978, 178)
Anterior – Posterior Width (R/L)	'the distance between the most prominent points on the anterior and posterior surfaces of the condyle, at right angles to the m-l axis'
Medio – Lateral Length (R/L)	'the distance between the most prominent medial and lateral points of the condyle, in relation to the m-l axis'

Table 3. Mandibular dimensions – Females only

Medieval and post-Medieval Females	**Time Period**	**N**	**Mean**	**Std. Deviation**	**P Value**
Max Ramus Breadth Right	Medieval	28	41.48	3.00	
	Post-Medieval	46	39.67	2.84	p<0.05
Max Ramus Breadth Left	Medieval	27	42.00	3.05	
	Post-Medieval	47	40.07	3.82	p<0.05
Minimum Ramus Breadth Right	Medieval	34	30.73	2.74	
	Post-Medieval	52	28.45	2.35	p<0.005
Minimum Ramus Breadth Left	Medieval	32	30.45	2.62	
	Post-Medieval	54	28.77	2.89	p<0.01
Ramus Height Right (Go - Co)	Medieval	35	66.36	4.11	
	Post-Medieval	52	62.79	4.63	p<0.005
Ramus Height Left (Go - Co)	Medieval	30	65.95	4.30	
	Post-Medieval	51	61.86	5.14	p<0.005
Body Length (Go - Me)	Medieval	20	73.77	11.16	
	Post-Medieval	45	79.03	5.29	p<0.05
Gonial Angle (Co - Go - Me)	Medieval	24	32.50	6.15	
	Post-Medieval	47	37.98	8.08	p<0.005
Chin Height (Inf - Gn)	Medieval	24	28.73	2.22	
	Post-Medieval	42	29.36	2.74	N/S
Bicondylar Breadth (Co Lat - Co Lat)	Medieval	13	117.05	3.88	
	Post-Medieval	38	111.64	6.71	p<0.01
Biogonial Width (Go - Go)	Medieval	20	95.49	6.75	
	Post-Medieval	44	91.29	6.22	p<0.05
Condyle Ant/Post Right	Medieval	37	8.19	0.83	
	Post-Medieval	56	8.17	1.36	N/S
Condyle Ant/Post Left	Medieval	38	8.11	0.98	
	Post-Medieval	56	7.89	1.05	N/S
Condyle Medio/Lat Right	Medieval	22	19.64	1.49	
	Post-Medieval	50	18.49	2.00	p<0.01
Condyle Medio/Lat Left	Medieval	26	19.60	1.22	
	Post-Medieval	49	18.27	2.55	p<0.01

Table 4. Mandibular dimensions – Males only.

Medieval and Post-Medieval Males	**Time Period**	**N**	**Mean**	**Std. Deviation**	**P Value**
Max Ramus Breadth Right	Medieval	72	45.21	3.78	
	Post-Medieval	75	41.88	3.08	$p<0.005$
Max Ramus Breadth Left	Medieval	73	45.50	4.08	
	Post-Medieval	73	42.42	3.62	$p<0.005$
Minimum Ramus Breadth Right	Medieval	85	32.28	3.02	
	Post-Medieval	84	30.20	3.03	$p<0.005$
Minimum Ramus Breadth Left	Medieval	83	32.38	2.63	
	Post-Medieval	81	30.56	2.96	$p<0.005$
Ramus Height Right (Go - Co)	Medieval	81	72.48	5.00	
	Post-Medieval	82	68.39	4.85	$p<0.005$
Ramus Height Left (Go - Co)	Medieval	78	72.38	4.83	
	Post-Medieval	76	67.95	4.63	$p<0.005$
Body Length (Go - Me)	Medieval	68	83.41	5.86	
	Post-Medieval	64	85.05	7.28	N/S
Gonial Angle (Co - Go - Me)	Medieval	75	30.90	7.13	
	Post-Medieval	67	35.29	8.84	$p<0.005$
Chin Height (Inf - Gn)	Medieval	75	32.45	2.91	
	Post-Medieval	68	33.25	3.15	N/S
Bicondylar Breadth (Co Lat - Co Lat)	Medieval	41	123.39	6.82	
	Post-Medieval	60	115.30	7.39	$p<0.005$
Biogonial Width (Go - Go)	Medieval	62	103.87	7.08	
	Post-Medieval	64	98.69	7.12	$p<0.005$
Condyle Ant/Post Right	Medieval	92	8.40	1.17	
	Post-Medieval	85	8.17	0.95	N/S
Condyle Ant/Post Left	Medieval	92	8.22	0.94	
	Post-Medieval	87	8.19	1.25	N/S
Condyle Medio/Lat Right	Medieval	62	20.98	1.63	
	Post-Medieval	75	19.90	2.36	$p<0.005$
Condyle Medio/Lat Left	Medieval	65	22.39	1.44	
	Post-Medieval	79	19.76	1.81	$p<0.05$

FIGURE 1

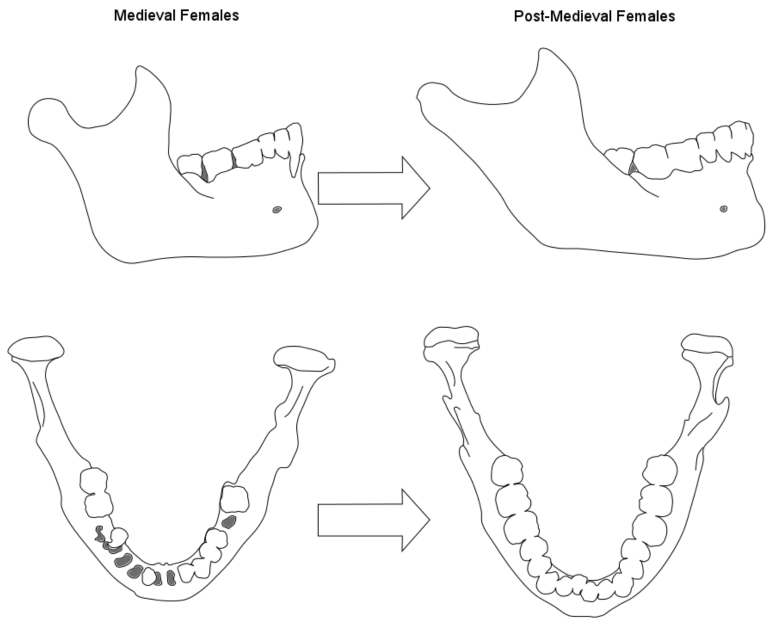

Figure 2