**The relationship between dental wear and age at death in British archaeological human skeletal remains: a re-evaluation of the ‘Brothwell chart’**

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Abstract

The chart relating molar wear to age published by Brothwell in 1963 is widely used to estimate age at death in archaeological adult human skeletal remains, especially in Britain, but also more widely. The chart was based on examination of juvenile and adult dentitions from Neolithic to Medieval periods from Britain, but few further details of materials and methods were given. The aim of this work is to re-assess the value of molar wear for estimating age at death for adult human remains in Britain and, if necessary, to provide an updated replacement for the Brothwell chart. 870 dentitions (juveniles with at least one permanent molar erupted and adults) were examined dating from the Neolithic period onward. The aim was to use a Miles-like method to assess the relationship between molar wear and age – i.e. to calibrate wear rates using juvenile dentitions and then, by extrapolating from this baseline, estimating age from wear in individuals with successively more worn dentitions. We validate some key assumptions of the method. Molar wear bears a consistent relationship to dental age in juveniles and does not appear to vary greatly from Neolithic to Medieval times, nor in the post-Medieval rural group studied. First and second molars appear to wear at similar rates, as do third molars except in dentitions where wear is very advanced. The estimated rate of molar wear is somewhat slower than that estimated by Brothwell. The results allow a chart to be presented that replaces Brothwell’s (1963) chart, and permits age estimation from molar wear in British archaeological human remains dating from Neolithic to Medieval times and, tentatively, for rural post-Medieval remains. It is not applicable to post-Medieval remains from most urban contexts where dental wear is much reduced.

Keywords: molars; wear stage; tooth crown height; Miles method; age estimation

1. **Introduction**

Estimation of age at death from skeletal remains is fundamental in osteoarchaeology. The demographic structure of ancient populations is an area of enduring research interest. Age at death also provides an essential framework for interpretation for other osteoarchaeological data. For example, many pathological lesions accumulate with age and many skeletal diseases are age-progressive. Because of the potentially confounding effects of age, controlling for age at death is usually key for adequate comparative studies of disease prevalence or severity.

For adult remains, estimation of age at death is highly problematic. Most age estimation techniques involve an assumption that the rate of change of an age indicator in target individuals resembles that in the recent reference population of known age which has been used to generate the method. For archaeological populations, this cannot be assumed. Studies of modern known age individuals show that, for a given bony age indicator, the relationship with age differs in different populations (e.g. Schmitt et al., 2002; Macaluso & Lucena, 2012; Xanthopoulou et al., 2018). In archaeological studies, therefore, it is not clear whether the rate of change in an age indicator in a particular ancient population resembles that in any particular reference population. Furthermore, relationships between age indicators and age are generally weak, and much of the variation in the state of bony age indicators is due, not to age but to other factors, of which our knowledge is rather sketchy (Mays, 2015; Merritt, 2020). At a statistical level, the reference / target population model may be problematic, particularly when the relationship between age and age indicator is weak. In such circumstances, there is a tendency for age at death distributions, inferred for target populations, to be biased in the direction of the age structure of the reference sample used to develop the method (Buckberry, 2015). Statistical manipulations have been suggested to overcome this when estimating age at death, but none has proved very satisfactory (Jackes, 2011: 116-124; Mays, 2021: 81-82).

The above difficulties suggest that we might usefully direct attention toward development of adult ageing methods that eschew the reference – target population model. Current options in this respect comprise cementochronology and dental wear. The former relies on counting incremental layers in tooth cementum that apparently have an annual periodicity. Although the method holds promise, it is still being refined, is destructive of dental material, and is time-consuming (Naji et al., 2016; Bertrand et al., 2019). Age estimation using dental wear, recorded macroscopically, is reference population-free in the sense that the rate of wear can potentially be estimated in the population under study. Unlike cementochronology, it is non-destructive and rapidly applicable, making it ideally suited for the large-scale statistical studies that are the hallmark of modern, population-level applied research in osteoarchaeology.

Dental wear is the gradual wearing away of tooth substance that occurs as a result of natural mastication. Most of this wear occurs on the occlusal surface and, because it is irreversible, wear increases with age. The nature of the diet and the way in which foods are prepared are determinants of the rate of dental wear. The soft, processed foods consumed by modern industrialised populations mean that dental wear is minor, so it is not a good indicator of age, but prior to recent times, high rates of dental wear were universal with significant exposure of dentine by late adolescent or early adult life. This was because humans consumed tough, coarse diets that required vigorous mastication (Sengupta et al., 1999; Antón et al., 2011). Tough materials intrinsic to the diet, such as bone fragments ingested with meat, or fibrous content in plant foods, required high bite forces and prolonged mastication. This led to occlusal wear both by abrasion (tooth contact with food or other materials) and by attrition (tooth-on-tooth contact) during the chewing cycle. No food items are harder than dental enamel, whereas mineral grits inadvertently taken into the mouth adhering to food surfaces or within foods can be much harder, and hence may be particularly potent sources of dental wear (Lucas et al., 2013, 2014; Lucas & van Casteren, 2015).

Dental wear generally shows a higher correlation with age than is the case for adult bony age indicators. A recent meta-analysis (Mays, 2015) found that the median coefficient of determination (r2) for the relationship between bony age indicators and age was 0.38. For dental wear this was 0.52, rising to 0.90 once recent (19th and 20th century AD), low dental wear populations were excluded.

Interest in dental wear as a method of age estimation for adults dates back at least 90 years (reviews in Brothwell, 1989; Rose & Ungar, 2001). It is a major technique used for age estimation in adult human skeletal remains from archaeological sites (Falys & Lewis, 2011; Clark et al., in press). Wear is most regular on the molar teeth, so it is these that are usually the focus of study. Various ordinal scales exist for recording wear. Given the rapidity of wear in most ancient populations, the most useful of these emphasise patterns of dentine exposure. The rate of wear on the molars in a particular population under study may be estimated by comparing wear on the different molar types using the difference in eruption times between the first, second and third molars as a means of calibration. This approach appears to have been originally suggested by Zuhrt (1956), but was more thoroughly described by Miles (1962, 1963). It is based upon the generation of a baseline in which wear is observed in juveniles for whom age can be reliably assessed from dental development. The first, second and third molars erupt at approximately 6, 12 and 18 years respectively (Gustafson & Koch, 1974; Smith, 1991; Al Qahtani et al., 2010; Liversidge, 2016). The age of the child, minus the eruption time of the tooth, gives the functional age of the tooth – the number of years that it has been in occlusion. The amount of wear observed can therefore be related to the number of years for which the molar has been in occlusion. For example, when the second molar erupts, the wear on the first molar represents about six years worth of wear; when the third molar erupts, the first molar shows ca. 12 years of wear and the second will have a functional age of about six years. Following study of this baseline cohort of immature individuals, the next step is to extend observations to successively older individuals in the adult part of a study population. Among these, if (using comparison with molars in the baseline group) a second molar on an individual shows a functional age of about 12 years, and a third molar about six years then that individual is probably about 24 years old; by looking at their first molars we can gauge the amount of wear that represents ca. 18 years of tooth function. Those with second molars with functional ages of about 18 years will be aged about 30 at death. By this process of successive extrapolation age can be estimated throughout the adult cohort, starting with the youngest and progressing to those with the most heavily worn dentitions (Miles, 1963, 2001).

Assumptions of the Miles method include that the variation in wear rates between individuals in the population or populations under study is not great, and that rate of wear on first, second and third molars is fairly similar (Mays et al., 1995; Millard & Gowland, 2002). The method does not require the assumption that wear rates remain constant throughout life because it involves updating wear in a step-wise manner to successively older individuals (Gilmore & Grote, 2012). There is a paucity of archaeological populations of documented age at death with heavy dental wear upon which to test the method, but it has been shown to be reliable in living heavy dental wear groups (Kieser et al., 1983).

The rate of dental wear can be calibrated as described above for the specific archaeological population under study provided there are sufficient juveniles (perhaps 20 or more – Nowell, 1978) with permanent molars in wear. However, many cemetery assemblages fail to provide enough juveniles. Brothwell (1963: Fig. 30) produced a chart showing a relationship between molar wear and age which he suggested was broadly applicable to British remains from the Neolithic to Medieval periods, intending its use for skeletal assemblages with too few juveniles to permit wear rate calibration. This chart has been reproduced in subsequent editions of Brothwell’s manual (Brothwell, 1972, 1981), as well as in other laboratory manuals (e.g. Bass, 1987) and in standard textbooks (e.g. Hillson, 1996). It is very widely used in Britain (O’Connell, 2004, 2017), and is also influential elsewhere (Falys & Lewis, 2011).

Brothwell (1963, 1989) indicated that he based his chart on the examination of wear in the dentitions of adults and children from British burials of different periods, and his finding that wear rates did not change much from Neolithic to Medieval times in Britain, and hence his assertion that his ageing chart could be applied across these periods was based on that work. His original work was contemporaneous with that of Miles (Miles’ seminal 1963 publication appeared in a volume edited by Brothwell, and was based on examination of remains access to which was facilitated by Brothwell). Brothwell referred to work of Zuhrt (1956), and it seems likely that Brothwell used a similar method to Zuhrt and Miles to produce his chart, but no further details are given. Nor is there any indication of the numbers of dentitions it is based upon, nor the particular burial grounds used. The only specific site referred to is “Maiden Castle Iron Age” (a fairly small assemblage, see Goodman & Morant, 1940) where it is also said that the age estimates from dental wear were cross-checked using age given by the pubic symphyseal face, a procedure of limited value given the problems associated with that ageing method (Mays, 2021: 75-80).

It would appear rather unsatisfactory to have such a widely used ageing chart based upon methods which are unpublished, and hence essentially unknown, and which therefore cannot be evaluated. The purpose of the current work was to re-assess Brothwell’s dental wear chart for age estimation in adult remains from British archaeological sites.

Brothwell (1963) did not intend that his chart should be applied to estimate age in post-Medieval remains. In Britain, dental wear slows markedly in the post-Medieval period, at least for urban populations (e.g. Lavelle, 1970; Moore & Corbett, 1978; White, 2011: 115-6; Mays, 2017). Written sources indicate a change at that time in the treatment of flour for breadmaking in towns: it began to be passed through fine cloth sieves. This removed the tough bran material, rendering bread for urban consumers much softer than before. The introduction of this change also had the effect of removing much of the mineral grit contamination introduced by the milling process thereby making this dietary staple not only less tough but also less abrasive (Moore & Corbett, 1975, 1978). This played a key role in the marked reduction in dental wear in urban populations (Moore & Corbett, 1975). Limited observations on rural post-Medieval groups (e.g. Mays, 2007: 137) shows that heavy dental wear may be observed, but whether rates truly resemble those seen in earlier times is unclear. Therefore, in order to investigate this, the current study sample was extended to include rural post-Medieval remains.

1. **Materials**

An aim in selecting the study material was to obtain fairly balanced numbers of individuals from different archaeological periods from Neolithic to post-Medieval times (too few pre-Neolithic human remains are available in Britain for their study to be viable) that included both those aged ca. 6-18 years at death (henceforth ‘juveniles’) and adults. The burial record in Britain is dominated by remains from the historic period (Mays, 1999). In addition, for the Neolithic and Bronze Ages, individual burial sites contain few interments, so we had to combine remains from large numbers of burial sites to achieve satisfactory sample sizes. A major constraint in selecting all our study sites was obtaining sufficient well-preserved juvenile dental remains: mortality is characteristically low in the ca. 6-18yr age range (Waldron, 1994; Chamberlain, 2006), and burial practices during some periods (e.g. the Early Bronze Age - Healey, 2012) or at some types of sites (e.g. Medieval monastic houses - Mays, 2006) bias assemblages toward adult remains. In selecting our post-Medieval group, we were additionally constrained by the need for a non-urban assemblage, which, for that period are relatively few. In total, 870 individual skeletons from 106 archaeological sites from Great Britain were studied (Table 1). Further details of the study material are given in Supplementary Information.

Table 1. The study material

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Period | Approx. Date1 | No of sites | Juveniles | Adults | Total |
| Neolithic | 4000-2400BC | 40 | 40 | 115 | 155 |
| Bronze Age | 2400-800BC | 55 | 34 | 85 | 119 |
| Iron Age | 800BC-43AD | 6 | 41 | 87 | 128 |
| Romano-British | 3rd-4th cent AD | 4 | 44 | 94 | 138 |
| Anglo-Saxon | 5th-7th cent AD | 2 | 35 | 87 | 122 |
| Medieval | 950-1550AD | 2 | 32 | 74 | 106 |
| Post-Medieval | 1500-1850AD | 1 | 26 | 76 | 102 |
| Total |  | 106\* | 252 | 618 | 870 |

1Dates are for the general periods for the prehistoric ages; for the historic periods they are for the specific material studied. \*A few sites are multiperiod so the column total does not sum to this figure.

1. **Methods**

Age in juveniles was estimated using dental development (Al Qahtani et al., 2010). The boundary between adult and juvenile status was set for the present purposes at ca. 18 years as indicated by the eruption of the third molar and confirmed, where possible, by the state of epiphyseal union (Mays, 2021: Fig. 4.13). For the current research, no attempt was made to evaluate age at death using bony indicators in adults.

Molar wear was recorded on first, second and third molars of the maxillary and mandibular dentition. Left elements were recorded if present. If these were missing, the right was substituted. Wear was recorded using a 19 point ordinal scale (Fig. 1) This is based on the scales of Brothwell (1963) and Murphy (1959) with the addition of further stages for recording enamel wear based on those of Dawson & Robson-Brown (2013). The aim of using this more detailed scheme was to help facilitate use of a Miles-like approach under circumstances where physical seriation of dentitions, as described by Miles (1963), was impractical.

Ordinal wear scales are rapid and reliable in use and enable the application of Miles-like methods to calibrate molar wear. However, because they split the continuous process of loss of occlusal height into a series of categories, there is inevitably loss of information. We therefore used measures of crown height in order to provide more effective tests of hypotheses connected with rates of wear. The method for measuring crown height followed previous practice (Mays, 2002; Mays et al., 1995). In brief, measurements were made using digital callipers. Heights were recorded on the supporting cusps of each molar tooth – i.e. the buccal cusps of the mandibular and the lingual cusps of the maxillary molars. This method was chosen because it is more rapidly applicable than measurement of all four main cusps (e.g. Mehta & Evans, 1966; Walker et al., 1991), enabling study of larger numbers of individuals, and it has proven successful in previous work on dental wear ageing (Mays 2002; Mays et al., 1995). The supporting cusps were specifically selected for measurement as these wear more rapidly than the rest of the crown (Hillson, 1996: 237). Height was measured from the cemento-enamel junction to the perimeter of the wear facet on the mesial and distal corners of the tooth. In unworn teeth, the measurement was taken to the cusp tip. In teeth with significant dentine exposure, the level of the dentine sometimes lay a little below that of the surrounding enamel, a phenomenon often described in the literature as ‘cupping’ (e.g. Ganss et al., 2002) or ‘scooping’ (e.g. Kaidonis, 2008). However, this did not affect measurements which were always to enamel. If wear had advanced to the stage where the enamel rim had been obliterated at one or both sites of measurement (corresponding to stage 16 or higher, Figure 1), then crown height could not be recorded. The mean of mesial and distal measurements was used to express crown height in each molar.

Individuals suffering from caries, *ante mortem* loss of some teeth, or other oral pathologies were not excluded from study. Pathologies of dental and periodontal tissues are commonplace in most assemblages and if any age estimation method is to be useful it must be applicable regardless of their presence.

We investigated a number of questions pertinent to the value of dental wear for estimating age, and in particular relating to the potential reliability of Brothwell’s (1963) age estimation chart. Firstly, we investigate whether dental wear shows a relationship with age at death in the material as a whole, and whether there is evidence that this differs between chronological periods. This allows us to test Brothwell’s (1963) assertion that permanent molar wear rates do not vary greatly from Neolithic to Medieval times in Britain, and hence that a single calibration of wear to age would be suitable for remains over these periods, and might potentially include non-urban post-Medieval remains.

Given that there are no assemblages of known age at death that cover the relevant time periods, we undertake the analyses described in the previous paragraph using the juvenile part of the assemblage where dental age is a reliable surrogate for age at death. Here we concentrate on first molars, because this enables study of wear during an approximately 12 year period between about 6 and 18 years of age. We also use this approach to investigate whether there is evidence of a difference in wear rate between maxillary and mandibular first molars during this period. We then build upon this by investigating whether maxillary or mandibular molars wear at different rates in the study group as a whole (i.e. including all ages), and whether differences in wear rates are evident between first, second and third molars within the maxilla or mandible. Given that age at death estimation in adult remains from conventional bony indicators is problematic, we do not attempt to compare dental wear age estimates with bony age estimates for this part of the work. Instead, we look at differences in wear between molar teeth and whether these alter as wear progresses. Given that crown height gives a more precise measure of dental hard tissue loss than dental wear stage, the above investigations use the former parameter.

Brothwell’s and Miles’ wear stage / age charts do not distinguish maxillary and mandibular molars. An assumption here would seem to be that a particular wear stage on a maxillary tooth is equivalent to that on its occlusal partner, but the point was little discussed by those authors. Some subsequent workers using Miles’ or analogous methods (Nowell, 1978; Kieser et al., 1983; Lovejoy, 1985) analysed maxillary and mandibular teeth separately for age estimation. As well as differing in external morphology, occlusal partners in upper and lower dentitions differ in aspects of internal structure, such as enamel thickness (Grine, 2005). We therefore analyse wear stage data on maxillary and mandibular molars separately.

We compare maxillary and mandibular molars, using data on wear rates and on the relationship between crown height and wear stage, in order to help us understand any patterned differences in wear stage between upper and lower molars. We conduct similar analyses to investigate differences in wear stages between different molar types within the upper or the lower dentitions. These analyses are carried out in order to help us to understand the expression of wear stages in our material and their relationship with loss of occlusal crown height. The overall purpose of the work on wear stages is to help provide a firmer underpinning for the construction of chart(s) showing the estimated relationships between molar wear stage and age. The ultimate aim of our study is, if the data show that it is justified, to construct a wear stage / age chart for the molar teeth, of similar format to that of Brothwell, that is broadly consistent with the totality of our wear data rather than one based on a narrow algorithmic approach derived from some particular aspect of it. The detailed methods used as our work progresses are contingent upon results generated in earlier stages. To aid clarity, we therefore describe these details of method in the relevant sections below rather than attempting to summarise everything here. The alpha level for inferential statistical tests was set at 0.05.

1. **Repeatability of observations**

In order to assess the replicability of the recording of the 19 wear stages, a total of 210 maxillary and mandibular molars were rescored by the same observer (SF). The results were analysed using the linearly weighted kappa statistic (Bland, 2015: 317-324). This gave a result of 0.94. A figure of zero would have indicated agreement between first and second observations to an extent no greater than expected by chance; 1.0 would indicate perfect agreement. The figure of 0.94 corresponds to ‘almost perfect’ agreement according to the interpretive scale of McHugh (2012).

Crown heights of 48 teeth of each type were remeasured, and results analysed using the method error statistic (Dahlberg, 1940; Knapp, 1992) (Table 2).

Table 2. Repeatability of crown height measurement

|  |  |  |  |
| --- | --- | --- | --- |
| Tooth | Sm | S | R |
| Mandibular M1 | 0.191 | 1.10 | 0.030 |
| Mandibular M2 | 0.204 | 1.39 | 0.022 |
| Mandibular M3 | 0.252 | 1.26 | 0.040 |
| Maxillary M1 | 0.239 | 1.27 | 0.035 |
| Maxillary M2 | 0.312 | 1.29 | 0.058 |
| Maxillary M3 | 0.301 | 1.05 | 0.082 |

Sm, standard deviation of the measurement (method error statistic) = √(Σd2/2n)

S, sample standard deviation

R, variance of measurement/sample variance, i.e. Sm2/S2

Table 2 indicates that about 2-8% of sample variance in crown height is likely made up of measurement error. This is in accord with previous reports of errors for this method (Mays et al, 1995; Mays, 2002).

1. **Results**
   1. ***Wear in juveniles***

***5.1.1. Wear versus dental age, chronological periods combined***

The crown heights of maxillary and mandibular first molars were summed to produce an overall measure of first molar crown height (M1CH). This could only be done for periods from the Bronze Age onward (N=162). The nature of Neolithic burial practices meant that most remains were disarticulated. Decline in M1CH with dental age in juveniles offers a means of monitoring the overall loss of hard tissue from the occlusal surfaces of the first molar teeth from about 6 to 18 years of age. The scatterplot (Fig. 2), is consistent with an approximately linear decline in M1CH with increasing dental age over this 12 year period. The correlation between M1CH and dental age is statistically significant (Table 3). The next step is to determine whether this relationship differs in different chronological periods.

***5.1.2 Variation in wear with respect to chronological period***

When the regression analyses of M1CH upon dental age are split by period, analysis of covariance indicates that the hypothesis of homogeneity of slopes cannot be rejected (F=0.71, P=0.40). The slope here is a measure of the rate of loss of hard tissue from the occlusal surfaces, insofar as rates can be inferred in cross-sectional samples. This analysis therefore provides no evidence for any difference in wear rates among juveniles from the Bronze Age through to the post-Medieval period. However, this leaves open the question of wear rates in the Neolithic. To explore this, and to investigate the wear rates in upper and lower first molars, the crown heights of maxillary and mandibular first molars (denoted MXM1CH and MNM1CH) are considered separately.

Table 3. Regression slopes and correlation coefficients from regression of first molar crown height versus dental age for juveniles aged 6-18 years.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | M1CH | | | MNM1CH | | | MXM1CH | | |
| Period | N | Slope | r | N | Slope | r | N | Slope | r |
| Neolithic | - | - | - | 27 | -0.139 | -0.493 | 19 | -0.192 | -0.729 |
| Bronze Age | 21 | -0.281 | -0.784 | 27 | -0.120 | -0.611 | 27 | -0.177 | -0.779 |
| Iron Age | 32 | -0.196 | -0.543 | 35 | -0.078 | -0.397 | 38 | -0.134 | -0.591 |
| Romano-British | 32 | -0.243 | -0.581 | 37 | -0.083 | -0.374 | 39 | -0.146 | -0.643 |
| Anglo-Saxon | 33 | -0.244 | -0.673 | 35 | -0.096 | -0.504 | 33 | -0.148 | -0.688 |
| Medieval | 26 | -0.240 | -0.662 | 32 | -0.152 | -0.722 | 26 | -0.114 | -0.599 |
| Post-Medieval | 18 | -0.179 | -0.591 | 22 | -0.110 | -0.668 | 21 | -0.035 | -0.180 |
| Periods combined | 162 | -0.232 | -0.631 | 215 | -0.107 | -0.510 | 203 | -0.137 | -0.617 |

M1CH, summed mandibular and maxillary first molar crown heights. MNM1CH, mandibular first molar crown height. MXM1CH, maxillary first molar crown height. r, correlation coefficient. All correlation coefficients are statistically significant at p<0.05 according to the t-test (except MXM1CH for post-Medieval burials).

As for M1CH, the scatterplots for MNM1CH and MXM1CH versus dental age (not shown) also suggest no great departures from a linear relationship. For MNM1CH, analysis of covariance provides no hint of any inhomogeneity of slopes across the seven different periods (F=0.70, p=0.45). For MXM1CH, the F value also failed to reach significance, albeit fairly narrowly (F=1.94, p=0.08). Table 3 indicates that the rate of wear for mandibular or maxillary Neolithic molars, indicated by the slopes of the regression lines, is little different from those from other periods.

The results support Brothwell’s (1963) contention that molar wear rates did not change appreciably from Neolithic to Medieval times in Britain. Overall loss of occlusal height, measured by the slope of M1CH upon dental age, was also similar in the post-Medieval sample studied. This would suggest that the diet in the post-Medieval population was no less conducive to dental wear than were those characteristic of the previous 5000-6000 years, although there was perhaps a hint that wear was differently distributed between maxillary and mandibular molars compared with earlier populations (Table 3). Because ANCOVA failed to establish evidence for differences between wear rates between periods, the dataset is, from this point forward, analysed as a whole.

For the juveniles as a whole, the slope of regression of crown height on dental age for the maxillary first molar is somewhat greater than that for the mandibular first molar (Table 3). To investigate the statistical validity of this difference, juveniles for which both maxillary and mandibular first molar crown heights were available were analysed. The regression slopes for these molars are 0.132 versus 0.097. This difference narrowly fails to reach statistical significance (t=1.86, p=0.066, N=169). Although the null hypothesis of equal wear rates cannot be rejected, the narrowness of the failure to do so meant that it seemed reasonable to investigate whether a differential wear rate between these teeth existed in the study group as a whole (i.e. including the adult remains), where it might be revealed by a greater sample size. We also investigated whether, in the study group as a whole, there was evidence for differential wear between mandibular versus maxillary teeth in the cases of second or third molars.

***5.2. Wear in the study material as a whole***

***5.2.1 Relative wear on maxillary versus mandibular molars***

If the rate of wear on the maxillary first molars generally exceeded that on the mandibular first molars then we would expect the difference in crown heights between those two elements, expressed as M1DIFF = MXM1CH - MNM1CH, to decrease as overall wear on these two elements, expressed as above by M1CH, increased. In the case of the null hypothesis, that there was no difference in rate of wear between the two, no correlation would be expected. Analogous approaches were taken to assess second and third molar pairs. For first, second and third molar pairs in the whole population, this exercise produced correlation coefficients of 0.37 (t=8.12, p<0.0001, N=418), 0.15 (t=2.84, p=0.004, N=369) and 0.15 (t=1.96, p=0.051, N=169) respectively. The positive correlation coefficients indicate that the MDIFF decreases as MCH decreases – in other words this is consistent with the maxillary element of a pair wearing at a faster rate in general in the study material. The correlation coefficients indicate that this effect is most clearly seen at the first molar. It is statistically significant for the second molar, although the effect size, as indicated by the correlation coefficient, is less. The correlation coefficient for the third molar, although resembling that for the second, is only marginally significant at p=0.05, but the sample size for third molars is smaller. In general, these results support the interpretation that, in the material as a whole, the maxillary element of a molar pair wears at a somewhat more rapid rate than the mandibular element. Given the value of ordinal wear stages for calibrating dental wear, the next steps are to investigate the extent to which wear stages relate to loss of crown height, and whether the differences in wear rates that we have identified between mandibular and maxillary teeth are reflected in differences in attained wear stages.

***5.2.2. Wear stages on maxillary and mandibular molars***

The relationship between crown height and wear stage is shown in Table 4. In a cross-sectional sample, we cannot know the starting height of molars that show wear, but this can be estimated using heights of unworn teeth. Subtracting the mean height of unworn teeth from the mean crown height for each wear stage provides an estimate of the relationship between wear stage and loss of crown height. These data are included in Table 4.

Table 4 suggests that the wear stages used here correspond in a general way to a progressive loss of crown height, but for each tooth, mean differences in crown height between neighbouring stages vary widely. In addition, although there is general pattern by which there is a tailing off in the number of individuals in the highest wear stages, which may be accounted for by a general tendency toward *ante mortem* loss of teeth before they reach the higher wear stages (see below), there is marked unevenness in numbers of individuals in some wear stages that is difficult to account for in terms of tooth loss or mortality at different ages. For example, there is a large number of individuals whose maxillary third molars fall into wear stage 3 compared with numbers in adjacent phases. Taken together, these aspects of the data in Table 4 indicate that, on a given tooth, different wear stages do not encompass equal increments of crown height, and that each wear stage is unlikely to be of equal time duration.

The relationship between wear stages on maxillary versus mandibular molars is shown in Tables 5-7. Comparing wear stages on a mandibular tooth with its partner in the maxilla seems, in general, to show that the former is in advance of the latter in the earlier wear stages, but when wear is more advanced, this pattern tends to become reversed. A number of factors may be at play here. For the first and third molars, the earlier wear stages tend to correspond to removal of lesser amounts of crown height in the mandibular tooth (Table 4): it may be that, despite the evidence we have for more rapid wear on the maxillary component of an occlusal pair, the ‘lead’ in terms of wear stage of the mandibular tooth due to the above factor is not overhauled until the later phases of wear. The disparity in the amount of crown height per wear stage does not seem to apply to the second maxillary versus mandibular molar (Table 4) so that explanation would not seem to play a significant role there. Disparities between the size, crown morphology, and structure of the maxillary and mandibular teeth may also be pertinent. For example with regard to the last, in humans, average enamel thickness appears generally greater in a permanent maxillary molar than in its corresponding mandibular partner (Smith et al., 2008). One might expect wear stages to be more advanced in thinner-enamelled teeth. Care is needed though, as detailed study of thicknesses at different locations on the occlusal surfaces gives a rather complex picture, but in the present context, the observation that the supporting cusps of the second molar show greater enamel thickness in the maxillary than in the mandibular tooth (Grine, 2005) is likely relevant.

***5.2.3. Relative wear on different molar types within the maxilla or mandible***

To assess questions pertaining to relative wear rates of first, second and third molars within a maxilla or mandible, analogous methodology to that employed above is used. If, say, mandibular first molars generally wear at a more rapid rate than mandibular second molars then the difference in crown height in individuals, expressed as MNM12DIFF = MNM2CH - MNM1CH, would be expected to increase as the overall wear on the mandibular molars increased. If this latter is expressed as MNCH = MNM1CH + MNM2CH + MNM3CH, then we would expect an inverse relationship between MNM12DIFF and MNCH if the first molar wore more rapidly than the second; if the null hypothesis of similar wear of M1 and M2 could not be rejected then we would expect no relationship between them. Analogous approaches are used to investigate relationships between first and third mandibular molar wear and for wear in molars in the maxillary dentition.

For first and second molars, the above procedure suggested no difference in wear rates between these teeth in either the maxillary or mandibular dentition. Comparing first and third molars, there was a significant inverse correlation between MNM13DIFF and MNCH and between MXM13DIFF and MXCH (mandible N=243, r=-0.13, t=2.05, p=0.04; maxilla N=197, r=-0.34, t=5.00, p<0.0001). This suggests slower wear in the third molar. The effect size, indicated by the r value seems greater for the maxilla, but the plots (Fig. 3a, b) appear to indicate that, in each instance, the r value is principally driven by a few points belonging to dentitions with very advanced overall wear (low overall crown heights, given by MNCH or MXCH); there seems little pattern in the main mass of data points.

***5.2.4. Wear stages on different molar types***

Cross-tabulation of wear stages on first versus second molars (Tables 8-9) indicate that the former are consistently in advance of the latter in both maxilla and mandible, as one might expect given their similar wear rates. The same is true of first versus third molars (Tables 10-11), but, as expected, given the greater disparity in eruption times, the difference in wear stages between these elements is greater. Median difference in wear stages between first and second molars is 3 in both maxillary and mandibular teeth; for first and third molars it is 5.5 and 5 for mandibular and maxillary teeth respectively.

* 1. ***Summary of results***

The data confirm a linear relationship between wear, expressed as combined maxillary and mandibular first molar crown height, and dental age in juveniles. There was no evidence to support any great change in wear rates between Neolithic and Medieval times in Britain, supporting Brothwell’s (1963) contention. This conclusion can also be tentatively extended to the non-urban post-Medieval population examined.

In general, maxillary molars appear to wear a little more rapidly than their mandibular occlusal partners. There is no evidence for differences in wear rates between first and second molars. This is broadly true of third molars: although there is evidence of a tendency toward lesser wear in these teeth, it applies only to individuals with advanced dental wear.

As regards wear stage data, the disparities observed between stages attained in maxillary molars versus their mandibular counterparts is at least to some extent comprehensible in terms of differences in wear rates discussed above coupled with differences in tooth structure (although the latter was not directly investigated in the material under study). Wear stages of first molars were consistently in advance of second and third molars; as expected on the basis of eruption times, the disparity with the latter was greater than with the former.

The above observations support the use of dental wear ageing using a Miles-like method for early British material from the Neolithic to Medieval periods, and for at least some non-urban post-Medieval groups. In the following section we use our data to relate wear stage to age using a Miles-like approach.

***6.0.* Relating molar wear stage to age in our study group using a Miles-like approach**

For the process of extrapolation beyond the baseline of juveniles whose ages could be estimated from dental development, instead of an emphasis on matching similar appearances of wear stages between tooth types (as Miles did), emphasis was given to matching similar estimated quantities of crown height loss, more especially in the earlier phases of wear. This was thought justified given the lack of evidence, described above, for differences in wear rates between different molars within the maxillary or mandibular dentition. In addition, the correspondence between wear stages on different molar types, and between maxillary and mandibular teeth was also taken into account in an attempt to produce maxillary and mandibular Miles tables that were congruent with the dataset as a whole. Wear will likely become more variable with increasing age, therefore, for more worn dentitions, cross-matching of similar amounts of crown height loss was given less emphasis and more weight was attached to matches between wear stages on different molars (i.e. with reference to Tables 5-11)**.** The resulting Miles table, relating wear stage to age, is shown in Table 12. We then group these findings into the four age categories used by Brothwell (1963) to produce a chart, analogous in layout to his, for the maxillary and mandibular molars (Table 13).

Table 12. Wear chart produced from applying the Miles-type method for estimating the rate of dental wear in the current study material. Table entries are wear stages (see Fig. 1).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Estimated age (years) | | | | | | |
|  | 12 | 18 | 24 | 30 | 36 | 42 | 48 |
| Maxilla |  |  |  |  |  |  |  |
| M1 | 3 | 5 | 8 | 9 | 11 | 15 | 16+ |
| M2 | 0 | 3 | 5 | 7 | 10 | 12 | 13+ |
| M3 | - | 0 | 2 | 3 | 4 | 8 | 9+ |
| Mandible |  |  |  |  |  |  |  |
| M1 | 4 | 5 | 7 | 9 | 11 | 13 | 15+ |
| M2 | 0 | 3 | 4 | 5 | 8 | 10 | 13+ |
| M3 | - | 0 | 2 | 3 | 5 | 7 | 9+ |

Table 13. Correspondence of wear stages and age in the current study material, based on Table 12. Table entries are ranges of wear stages (Fig. 1) on the different molar teeth.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Age category (years) | | | |
|  | 18-25 | 25-35 | 35-45 | 45+ |
| Maxilla |  |  |  |  |
| M1 | 5-8 | 9-10 | 11-15 | 16+ |
| M2 | 3-5 | 6-9 | 10-12 | 13+ |
| M3 | 0-2 | 3 | 4-8 | 9+ |
| Mandible |  |  |  |  |
| M1 | 5-7 | 8-10 | 11-14 | 15+ |
| M2 | 3-4 | 5-7 | 8-12 | 13+ |
| M3 | 0-2 | 3-4 | 5-8 | 9+ |

Although we found evidence from the crown height data that the mandibular and maxillary molars wear at different rates, this is not strongly expressed in the wear stage data in Tables 12 and 13. This probably reflects the fairly irregular relationship between wear stage and crown height (Table 4). In fact, the estimated age / wear stage relationships in adults are fairly similar in the maxillary and mandibular molars. It therefore seems justified, for convenience’s sake, to combine the results for maxillary and mandibular molars into a single chart as Brothwell did. This chart (Fig. 4) shows the range of wear phases, both pictorially and in terms of the numbered wear stages, that might be expected to correspond to the different age groups in British archaeological populations.

It is well-established that tooth loss is strongly age progressive (Mays, 2002, and refs therein). In British archaeological populations, the advanced molar wear stages, that Figure 4 suggests would be associated with ages over about 45 or 50 years, are rarely seen, although *ante mortem* molar loss is commonplace. Work on populations consuming premodern diets suggests that individuals showing loss of more than about 50% of their molar dentition are generally older than about 50 years of age (Mays, 2014, 2017; Wasterlain et al., 2011). In this light, it seems reasonable to suggest that those individuals from archaeological sites showing advanced *ante mortem* loss of their molar dentition are likely to be predominantly past middle age. Even if they lack molar teeth upon which to record wear, they cannot simply be omitted from analysis. To do so would falsely truncate demographic profiles. For this reason, in Figure 4 we advise classifying those individuals with severe molar wear and / or >50% molar loss into the 45+ age category.

**7. Discussion**

Our study supports Brothwell’s contention that dental wear rates varied little in Britain from Neolithic to Medieval times, but the wear rates in our material over this extended period are slower than those concluded by Brothwell. The result is that our wear / age chart will give somewhat higher ages for a given wear stage than will the one devised by Brothwell (1963). This is generally in accord with the results of Millard & Gowland (2002). They used Romano-British and Anglo-Saxon remains from 10 burial grounds in southern England to investigate the relationship between dental wear and age using a Miles approach. Although their methodology differed somewhat from ours, they too found a rate of wear that appears somewhat slower than is implied by Brothwell’s (1963) chart. Our age / wear findings for the first and second molars seem to resemble those of Millard & Gowland (2002). In our material there is a paucity of heavily worn third molars, and this is reflected in our ageing chart (Fig. 4). This seems consistent with our observation that third molar wear may slow down in the most heavily worn dentitions. In addition, because our study required comparison of wear on different molars, individuals with fairly complete molar dentitions were required. Although timing of molar loss cannot be directly investigated in our study material, it may be that third molars tended to be lost after other molars as they have been exposed to the risk factors for tooth loss for a shorter period due to their later eruption (Mays, 2014). If so, individuals with heavily worn third molars may often have lacked first and second molars and hence tended to have been excluded from our study.

When using molar wear to estimate age in skeletal remains, the preferred approach is normally to calibrate the rate of wear in the population under study using juvenile dentitions, provided there are sufficient juvenile dental remains to permit this. When this is not the case, the chart presented here (Figure 4) may be applied to British populations ranging from Neolithic to Medieval periods, and we would advocate that this be used in place of the chart of Brothwell (1963, 1972, 1981).

Our findings are not applicable to post-Medieval urban British populations as these generally show markedly reduced dental wear compared with earlier times. We do, however, tentatively apply them to post-Medieval non-urban groups, as, in our one post-Medieval assemblage (from a small riverside market settlement), there was no indication that diet was less abrasive than in earlier times. However study of juveniles in that group hinted that wear may have been differently distributed between upper and lower molars compared with earlier populations; this may point to some difference in the development of molar occlusion (Sayania et al., 2017; Yang et al., 2019). Further study of dental wear in post-Medieval populations from non-urban contexts (however ‘non-urban’ might be defined) is clearly merited.

Dental pathologies, in particular *ante mortem* loss of an occlusal partner, might be expected to impact upon dental wear, but the few studies of adult, documented age, earlier populations that have investigated this problem have not found substantial effects (Mays, 2002; Benazzi et al., 2008). For this reason, and for simplicity, we encompassed both individuals with and without dental pathologies in our study, and did we did not orientate selection of our study sample toward investigating this topic. However, future work specifically focussing on the effects of dental diseases upon wear would potentially be a useful refinement.

When molar loss becomes advanced, which is often the case once individuals are more than about 50 years of age, molar wear can no longer be readily applied as an ageing method. That it is not easily applicable in the second half of the potential human lifespan is something dental wear holds in common with other skeletal adult ageing methods (except perhaps cementochronology for those retaining at least one single rooted tooth). Following tooth loss, there is localised resorption of alveolar bone, which is normally irreversible and may be lifelong. Among those showing tooth loss, an inverse relationship between mandibular alveolar bone height and age has been reported in living and skeletal populations (refs in Mays, 2017). This potentially offers a means of estimating age in mandibles where adequate documentation of molar wear is precluded by *ante mortem* tooth loss, but there are difficulties in operationalising these observations into providing a practical age-estimation method (Mays, 2014, 2017). This reinforces our suggestion that, rather than attempt to age dentitions more precisely for individuals aged over about 45 to 50 years, either by analysing the advanced wear on whatever teeth do remain or by studying the morphology of the residual mandibular alveolar ridge, it may be preferable, as matters currently stand, simply to cast those showing more than 50% molar loss into a general ‘45+’ age group.

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Figure captions

Figure 1. Molar wear stages

Figure 2. Regression line and scatterplot of summed maxillary and mandibular first molar crown heights versus dental age.

Figure 3. Scatterplot of difference in crown height between third and first molars versus overall wear in the molar tooth row (expressed as the sum of first, second and third molar crown heights) for (a) mandibular and (b) maxillary dentitions.

Figure 4. Suggested age at death categories and associated molar wear patterning applicable for British remains from Neolithic to Medieval periods and (tentatively) for rural post-Medieval remains.

Additional online material.

Site list and location maps.

Original research data.