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RESEARCH ARTICLE

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How old are you now? A new ageing method for nonadults based on dental wear

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Abstract

The main aim of this study is to present a novel method of nonadult (ca. 1–19 years) age-at-death estimation using the dental wear of deciduous, mixed deciduous-permanent, and permanent dentitions, including the incisors, canines, premolars, and first and second molars. The stage-based method is derived from degrees of dental wear in known-age (n = 39) and estimated-age (n = 11) nonadults containing 951 teeth from the predominately 19th century cemetery of Middenbeemster, The Netherlands. The need for such a method is warranted in cases where dental development and/or eruption cannot be assessed for age-at-death estimation. As well, by establishing a baseline for normal age-related nonadult tooth wear, users may better document wear that could be due to extramasticatory behaviours. The regression analysis reveals a strong quadratic correlation—$F(2, 47) = 555.1$, $p < .001$, $R^2 = .95$, standard error of the estimate = 1.14, residual sum of squares (RSS) = 68.89, predicted residual error sum of squares (PRESS) = 77.67—between age and wear and multivariate adaptive regression splines ($R^2 = .95$, generalised cross validation = 1.67, RSS = 67.68, PRESS = 89.34), which are used to develop an R-package that users may employ to estimate age-at-death from dental wear. The accuracy of this method (78–98%) is evaluated using leave-one-out cross-validation. Analyses of males versus females, deciduous versus permanent, upper versus lower, and anterior versus posterior teeth revealed no apparent reason to warrant separate methods for these groups of separated dentitions. This method fills a disciplinary gap in the understudied area of deciduous and nonadult dental wear and hopes to stimulate much future research. With the R-package, we also provide the foundation and framework for the development of additional reference populations across different spatiotemporal contexts, to make the method more widely applicable.

KEYWORDS

age-at-death estimation, dental wear, nonadults, The Netherlands

1 | INTRODUCTION

Dental wear is a general term encompassing three types of dental degradation: abrasion, which is the contact between teeth and exogenous substances (e.g., food); attrition, tooth-on-tooth contact; and erosion (or corrosion), caused by chemical deterioration (Burnett, 2016; Larsen, 2015). The analysis of dental wear is an important aspect of the study of human skeletal remains, both on an individual and population level. It provides information on a wide variety of topics, including spatiotemporal dietary shifts and variation, social status, gender-specific behaviours, and dental wear also serves as a method for estimating age at death (Dawson & Brown, 2013; Kieser et al., 2001; S. Molnar, 1971). The ability to estimate age from dental wear relies on a simple concept that the large mineral component of enamel (approximately 97%) is unable to remodel once development of the crown is complete, thus gradually being worn away with time as the dentition is used for mastication and extramasticatory activities (Fitzgerald & Rose, 2008; Hillson, 1996). In populations with somewhat homogeneous diets, both the deciduous (i.e., baby or milk) and permanent (i.e., adult) teeth are subject to a fairly constant rate of wear, providing the framework for various methods of age-at-death estimation for adults (Brothwell, 1972; Faillace, Bethard, & Marks, 2017; Kim, Kho, & Lee, 2000; Kvaal, Kolltveit, Thomsen, & Solheim, 1995; Lovejoy, 1985; Maat, 2001; Mays, 2002; Mays, de la Rua, & Molleson, 1995); however, this concept has yet to be applied to nonadults. Previous studies employing deciduous dental wear have noted a strong correlation between the observed wear and age but were mainly focused on dietary transitions related to weaning and potential dietary differences in social status (Dawson & Brown, 2013; Mahoney et al., 2016; Mays, 2016; Mays & Pett, 2014; Prowse et al., 2008).

The rate of wear in deciduous teeth is expected to be influenced by similar factors as in the permanent teeth, including external factors such as diet and tooth-on-tooth contact and internal factors, such as crown morphology and enamel microstructure (Hillson, 2005). Yet there are (at least) three factors potentially unique to deciduous dental wear. First, during breastfeeding, mastication is not required and thus does not cause dental wear. The duration of breastfeeding can vary greatly between different populations (for meta-analyses, see Howcroft, 2013; Tsutaya & Yoneda, 2013). Additionally, liquid and soft weaning foods would also cause little to no wear. Second, the time period in which infants and toddlers place nondietary objects in their mouth to taste, suck, and chew on may cause dental wear in specific regions of the dental arcade. Young children will do this to learn about their environment, ease teething pain, and for self-comfort (Ashley, 2001; Rochat, 1998). Third, their wear pattern will be influenced by masticatory action during the time period in which they lack isomeric teeth (i.e., the upper and lower first incisors) because the corresponding tooth has not yet erupted or was exfoliated in order for the permanent tooth to enter occlusion. These nondietary factors of oral activity could affect the wear patterns of deciduous teeth (and possibly also early erupting permanent teeth) and may be one reason methods for scoring deciduous wear are so rare compared with those for scoring permanent wear. Whether or not these factors affect the predictability of the rate of nonadult dental wear will be assessed in this study.

Currently available dental ageing methods for nonadults mainly utilise the timing of dental development (e.g., Demirjian, Goldstein, & Tanner, 1973; Harris & Buck, 2002; Moorrees, Fanning, & Hunt, 1963) and eruption (e.g. Buikstra & Ubelaker, 1994; Holman & Jones, 1998; Holman & Yamaguchi, 2005; Konigsberg & Holman, 1999). The first teeth to form, the deciduous central incisors (i1s), start developing around 14–16 weeks in utero, and the last of the deciduous teeth, the deciduous second molars (m2s), initiate around 18–19 weeks in utero (Hillson, 1996). Dental development is a continuous process that can be used to track the age of an individual until the end of development, concluding with the closure of the root of the permanent second molars (excluding third molars), at around 14–16 years (Harris & Buck, 2002; Hillson, 1996). Methods using dental development as an age-at-death indicator offer precise and reliable age ranges; however, they require preservation of specific tooth roots in order to document the stage of development following completion of the crown, which in adolescents can be contingent upon preservation and recovery of the second molars. Roots contain dentine and cementum, making them less resistant to diagenesis than the enamel-coated crowns (Hillson, 1996). The extent of root formation may also be obscured if a tooth is firmly anchored in the jaw, in the absence of forceable extraction or X-ray. The sequence of dental eruption is well documented and occurs within a fairly constricted range, typically varying by less than a year in the early stages of eruption, starting with a purely deciduous dentition (ca. 0–5 years), followed by a transitional mixed-dentition stage (ca. 6–10 years), and continuing to the fully erupted permanent second molar (ca. 11–15 years; again, disregarding third molar eruption; Holman & Jones, 1998; Holman & Yamaguchi, 2005; Konigsberg & Holman, 1999; Ubelaker, 1999). Yet age-at-death estimation from dental eruption requires a relatively intact maxilla/mandible in order to document the stage of eruption.

In this study, we present an age-at-death estimation method for nonadults incorporating both the deciduous and permanent dentition. This is done by documenting the average wear for all available teeth from known-age and estimated-age individuals and fitting the age and wear data in a regression analysis. The method has a wide age range of potential applicability, from the first signs of dental wear on the deciduous teeth, which usually occurs in the first year, up to 19 years of age. Additionally, we suggest further applications of regression analysis in the study of nonadult dental wear and highlight the versatility of R and the potential for its use in osteoarchaeology, which has also been shown in previous studies (Corron, Marchal, Condemi, Chaumoître, & Adalian, 2017; Kamnikar, Herrmann, & Plemons, 2018; Lynch, 2017; Lynch, 2018; Nikita, 2019; Santos, 2018; Sołtysiak, 2011). The proposed method would occupy a unique niche in dental ageing, as only the crowns are necessary for its utility, and it can be employed in cases where dental development and dental eruption are unobservable or inapplicable. We will demonstrate that, in relation to other factors, the dominant factor involved with nonadult dental wear is age, thereby presenting a strong argument for the reliable application of this method for age-at-death estimation, which can be calculated using the presented regression equations, or the R-package, BAMSAUR, which contains a user-friendly graphical user interface (GUI) to simplify this process (Data S1). The rate of dental wear is population specific, so the development of additional reference populations is necessary for a wider application of the method, which is also facilitated by the R-package.

2 | MATERIALS

All specimens in the sample originate from the site of Middenbeemster, a post-Medieval cemetery in the Dutch province of Noord-Holland (Figure 1). The cemetery is associated with the Keyserkerk church, where the inhabitants of the Middenbeemster village and the surrounding Beemsterpolder were buried between AD 1612 and 1866 (Lemmers, Schats, Hoogland, & Waters-Rist, 2013). Archival documents are available for specimens buried between AD 1829 and 1866, when the majority of burials occurred (Lemmers et al., 2013). The main occupation of the inhabitants was dairy farming, and their diet consisted mainly of wheat or rye bread, potatoes, eggs, and dairy products (milk, cheese, and butter; Falger, Beemsterboer-Köhne, & Kölker, 2012). Other crops included barley, oat, beans, peas, and mustard and caraway seeds (Aten et al., 2012). Stable carbon and nitrogen isotope data suggest the consumption of meat and fish was minimal (Waters-Rist & Hoogland, 2018).

The sample used in this study consists of 50 individuals between ages 1 and 19 years, and a total of 951 teeth (Data S1). Archival data were available for the majority of individuals in the sample (*n* = 39); however, due to limited archival data for older nonadults, 11 individuals aged 11–18 years old were added, whose ages were estimated using disciplinary standards, including dental development (Demirjian et al., 1973; Harris & Buck, 2002; Moorrees et al., 1963), dental eruption (Buikstra & Ubelaker, 1994), and skeletal development (Black & Scheuer, 1996; Buikstra & Ubelaker, 1994; Maresh, 1955). The inclusive sample represents all ages, whereas the sample with only documented-age individuals lacks 14- to 18-year-olds and contains a limited number of individuals aged 10 years and above (*n* = 8).

3 | METHODS

3.1 | Dental wear scoring system

To score the degree of wear, a modified version of Smith's (1984) eight-stage method was created (Figure 2 and Table 1). All available deciduous teeth were scored, whereas third molars were excluded from the permanent dentitiondue to the variability of this tooth's

FIGURE 1 Map of The Netherlands showing the location of Middenbeemster [Colour figure can be viewed at wileyonlinelibrary.com]

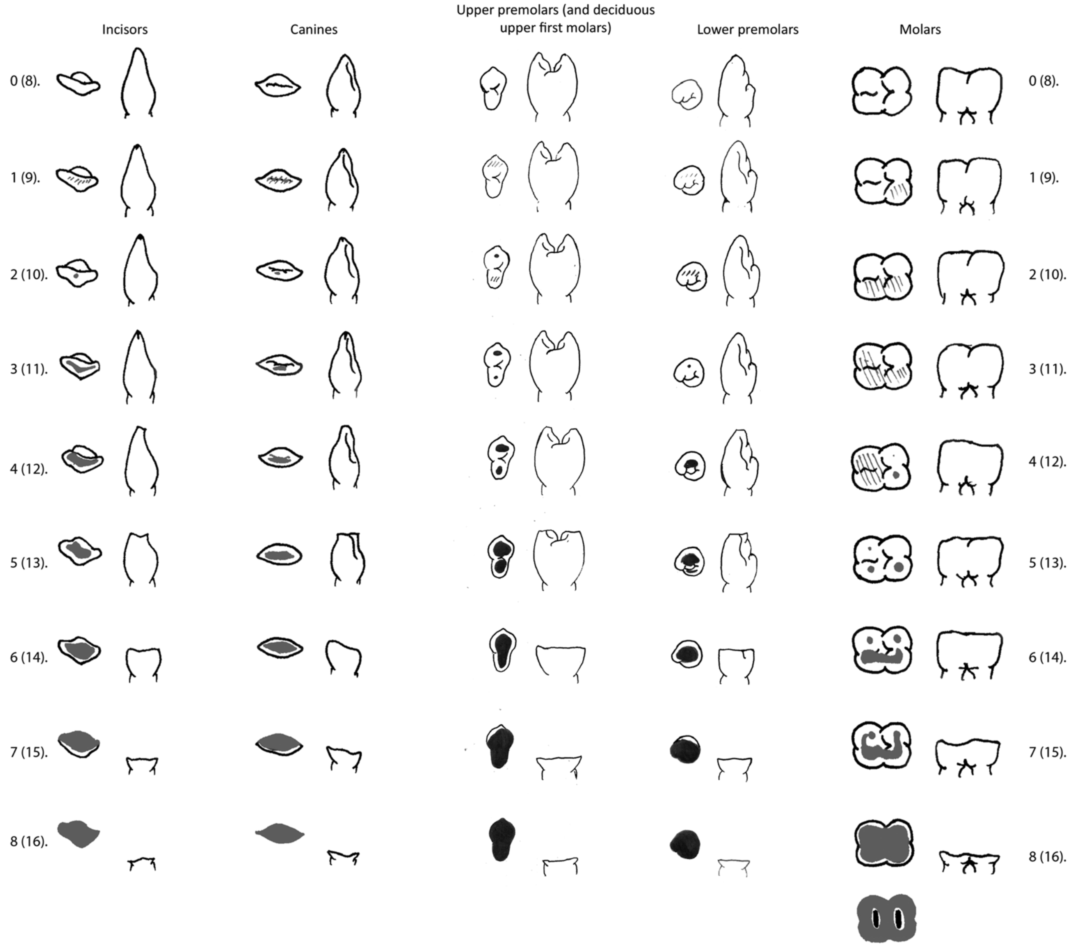

FIGURE 2 Illustrations of the wear stages. Numbers in parentheses are the scores applied to permanent dentition. Deciduous upper first molars (m^1) are scored as premolars

eruption age and presence within populations, and the fact that the timing of its eruption can extend beyond the range of interest (Mincer, Harris, & Berryman, 1993). The method contains nine stages that are the same for both deciduous and permanent dentitions, where deciduous teeth are scored from 0 to 8 and the permanent teeth are scored from 8 to 16.

The minimum requirements for scoring developing teeth was clear visibility of all cusps. Teeth containing cusps that were obliterated by caries or other processes, such as post-mortem damage, were not scored. Each tooth was scored individually, and the sum of the entire available dentition was divided by the number of teeth scored, providing an average wear score for each individual, which was subsequently analysed using linear and quadratic regression and multivariate adaptive regression splines (MARS).

3.2 | Accuracy of the method

The accuracy of the method was tested using leave-one-out cross-validation (LOOCV). Here, data from one individual were removed, the regression analysis was performed without the individual, and a predicted age at death was provided; this process was repeated for all the individuals in the sample. The age estimation was considered correct if the documented age at death fell within the predicted age range. Lower ranges were converted to integers to avoid underestimation of accuracy due to decimal points (a prediction with a lower range of 6.3 years should be calculated as correct if the actual age is 6 years).

3.3 | Intraobserver and interobserver error

Intraobserver error was conducted by the first author on the dentitions of four individuals (77 teeth), MB12, MB19, MB41, and MB46. Interobserver error was conducted on the same individuals by the first author and four researchers from the Laboratory for Human Osteoarchaeology, Faculty of Archaeology, Leiden University. Both intraobserver and interobserver error was evaluated using the intraclass correlation coefficient (ICC).

Statistical analyses were performed using Excel 2016, SPSS v. 23, and R v. 3.5.1 (R Core Team, 2018). MARS was performed using the "earth" package (Milborrow, 2019). Plots were developed using "ggplot2" (Wickham, 2016).

TABLE 1 Description of wear stages. Numbers in parentheses are the scores applied to permanent teeth. Deciduous upper first molars (m^1) are scored as premolars

Score	Anterior	Premolars (and m^1)	Molars
0 (8)	No wear	No wear	No wear
1 (9)	Polish/flattening of cusp	Upper: Polish/flattening of single cuspLower: Polish on cusp; cusp shape remains intact	Polish/flattening present on a single cusp
2 (10)	Pinprick dentine exposure	Upper: Flattening of both cusps; possible pinprick dentine exposure on a single cuspLower: Flattening of buccal cusp	Polish/flattening present on two cusps
3 (11)	Hairline dentine exposure or more than pinprick	Pinprick dentine exposure on all cusps	Polish/flattening present on three cusps
4 (12)	Dentine line of distinct thickness	Larger than pinprick dentine exposure on all cusps	Polish/flattening present on all cusps and possibly dentine exposure (no more than pinprick) on a single cusp
5 (13)	Moderate dentine exposure no longer resembling a line	Dentine exposure now covers >75% of cusps and the exposure on both cusps may be merging	Two or more dentine pinpricks present, or at least one area has expanded beyond pinprick size
6 (14)	Large dentine area with only an enamel rim remains, but rim remains complete	Cusps obliterated; only an enamel rim remains, but rim remains complete	Large areas of dentine present on cusps, with merging of no more than two areas of dentine
7 (15)	Enamel rim is lost on one or more sides of the crown	Enamel rim is lost on one or more sides of the crown	Dentine exposure covers >50% of the crown, and dentine areas have merged to form a single large patch of dentine exposure, with small "islands" of enamel still present on the occlusal surface
8 (16)	No enamel remains	No enamel remains	Little to no crown enamel remains and may be present as thin enamel rim.

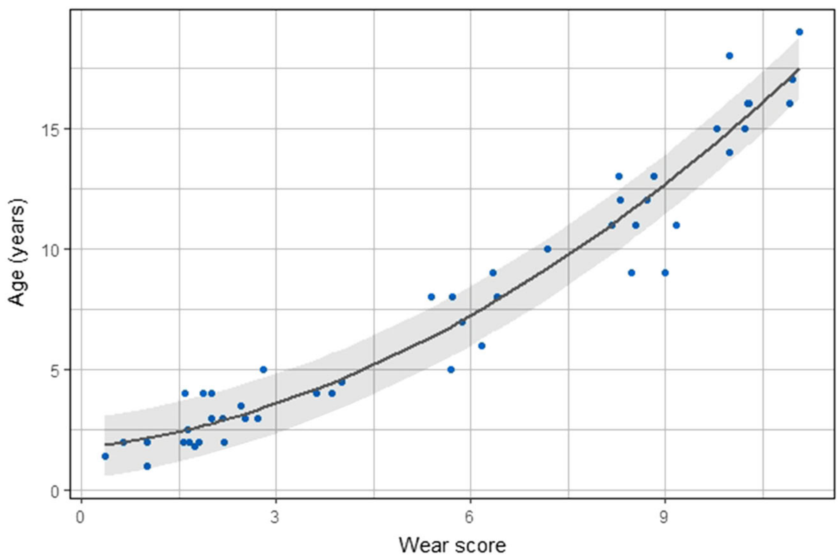

FIGURE 3 Plot and best-fit line from the quadratic regression analysis for the combined deciduous and permanent dentition, including the 68% prediction interval (shaded area) [Colour figure can be viewed at wileyonlinelibrary.com]

4 | RESULTS

4.1 | Relationship between dental wear and age

The results of the dental wear analysis can be found in Table S1. Figure 3 shows results of age regressed on dental wear scores (i.e. inverse calibration) of all the individuals in the sample and indicates that a strong linear—$F(1, 48) = 713.878$, $p < .001$, $R^2 = .93$, standard error of the estimate (SEE) = 1.40, residual sum of squares (RSS) = 102.18, predicted residual error sum of squares (PRESS) = 111.12—and quadratic—$F(2, 47) = 555.1$, $p < .001$, $R^2 = .95$, SEE = 1.14, RSS = 68.89, PRESS = 77.67—correlation exists between dental wear and age. The addition of individuals without documented archival age is justified by the increase of the coefficient of determination (R^2) compared with the sample that only includes individuals with documented age—$F(2, 35) = 219.52$,

TABLE 2 Summary of the leave-one-out cross-validation. The accuracy is based on the percentage of estimates whose age ranges contain the documented age at death

Regression model with equation for age estimation	R^2	Accuracy (%)	Estimates within 1 year (%)	Estimates within 2 years (%)
Linear*Age* = 1.46 × *wear* − 0.31	.93	84	72	94
Quadratic*Age* = (0.10 × *wear*^{2})+(0.32 × *wear*)+1.72	.95	82	80	98
Multivariate adaptive regression $\text{splines}Age = \begin{cases} -1.26 \times (wear - 9) + 11.65 \\ 3.17 \times (9 - wear) + 11.65 \end{cases}$	.95	78	84	92

$p < .001$, $R^2 = .94$—and the increased statistical robustness of adding 11 individuals to the sample, to ensure representation of all ages. The MARS analysis found the optimal formula to contain a single "knot" at wear = 9, resulting in two linear equations, after which adding more knots failed to improve the model R^2-value by more than .001; $R^2 = .95$, generalised cross validation = 1.67, RSS = 67.68, PRESS = 89.34. The regression equations and accuracies can be found in Table 2.

The age ranges were calculated using 68% prediction intervals (PI) of the quadratic regression, which is depicted by the shaded region of Figure 3. The accuracy (determined by the LOOCV method) for this sample is 82%, with an average age range of 1.25 years. Additionally, 80% of estimates fell within 1 year of the actual age and 98% fell within 2 years of the actual age (Table 2). There was a high concordance in accuracy between the MARS and quadratic regression analyses. A comparison of the linear, quadratic, and MARS results from the LOOCV can be seen in Table S1.

4.2 | Dental wear and sex

The archival data included the sex of 37 individuals in the sample and allowed comparison of the wear scores between the males ($M = 4.47$) and females ($M = 4.42$) using a Welch's two-sample t test, $t(35) = 0.04$, $p = .96$, 90% CI [−1.77, 1.86].

4.3 | Maxillary versus mandibular and anterior versus posterior teeth

Average wear scores from the mandibles ($M = 5.69$) and maxillae ($M = 5.67$) were separated and compared with each other using a Welch's two sample t test, $t(96) = -0.03$, $p = .98$, 90% CI [−1.21, 1.17], and similarly for the anterior ($M = 5.88$) and posterior ($M = 5.51$) teeth, $t(98) = 0.51$, $p = .61$, 90% CI [−0.83, 1.56].

4.4 | Separated deciduous and permanent dentition

Linear regression analysis was conducted with age (independent) and average wear (dependent) on separated deciduous— $F(1, 36) = 77.32$, $p < .001$, $R^2 = .68$, $b_1 = .36$—and permanent— $F(1, 29) = 62.81$, $p < .001$, $R^2 = .67$, $b_1 = .19$) dentitions, to get an indication of the rate of wear (illustrated by the slope, b_1) on the separated deciduous and permanent dentitions (Figure 4). The deciduous dentition has a steeper slope (as indicated by b_1) suggesting a faster rate of wear with age than the permanent dentition.

4.5 | Accuracy and the number of teeth scored

Using linear regression, no apparent association was found between the number of teeth (min. = 5; max. = 28) used for the analysis and the residuals from the quadratic regression, $F(1, 49) = 3.22$, $p = .08$, $R^2 = .06$.

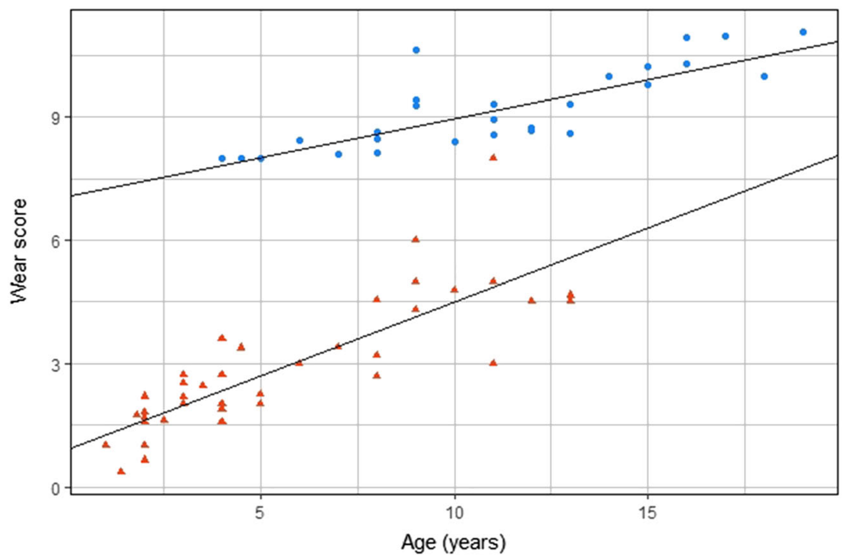

FIGURE 4 Plot and linear regression analysis for the separated deciduous (triangles) and permanent (circles) teeth [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Results of the interobserver and intraobserver error with the intraclass correlation coefficient (ICC) and 90% confidence intervals (CI)

Test	ICC Single measures	90% CI Lower	Upper	*F* test *F* ratio	p-value
Intraobserver	0.993	0.989	0.995	148.595	.000
Interobserver	0.969	0.959	0.977	159.067	.000

4.6 | Intraobserver and interobserver error

Both intraobserver and interobserver errors were determined to be within an acceptable range (Table 3).

5 | DISCUSSION

5.1 | Use of the method

There is no minimum requirement for the number of teeth to be used for the application of the method; however, a score based on a single tooth will be unreliable. There was no apparent correlation between the accuracy of the age-at-death estimate and the number of teeth scored; however, we suggest the individual should have at least five teeth to yield a reliable age-at-death estimate from the regression equation, as this was the lowest number of teeth used to score an individual in this study. Analyses of the separated anterior and posterior teeth, and the maxillary and mandibular teeth, showed no apparent need for separate age-at-death equations; and a single equation incorporating a larger number of applicable teeth is beneficial for archaeological specimens.

This method uses inverse calibration, meaning future predictions are influenced by the structure of the reference sample (Aykroyd, Lucy, Pollard, & Solheim, 1997; Konigsberg, Hens, Meadows Jantz, & Jungers, 1998). Although the acquired age-at-death estimation formula can likely only be used on similar populations, that is, those from Medieval to post-Medieval Western Europe with similar diets, the format used for this method has the potential to be developed on other populations to cover larger spatiotemporal contexts. Additionally, this method uses inverse calibration, meaning future predictions are influenced by the structure of the reference sample (Aykroyd et al. 1997; Konigsberg et al. 1998). To facilitate testing of this method on other populations, the developed R package contains an age-at-death-estimation function and other functions to incorporate and test the accuracy of new reference samples using the LOOCV method described above (Data S2). In doing so, we hope to stimulate more data and research on nonadult dental wear.

This method provides a cohesive means to estimate the age-at-death of a large portion of a nonadult archaeological sample with considerable accuracy. The lower range of the method is determined by the age of the first signs of wear, which can occur at a relatively young age. These first signs of wear can be caused by weaning foods and implements used while the child is teething (Prowse et al., 2008). Elsewhere, signs of dental wear have been reported in individuals as young as 12–18 months (Mays, 2016; Prowse et al., 2008), and in this sample, dental wear was visible as early as 17 months. When using Middenbeemster as a reference sample, the recommended use is the quadratic equation with 68% PIs due to a higher calculated accuracy than for the linear and MARS models. However, users may also consider using a MARS model, as the calculated accuracy rates were very similar, and it may better account for the potential error from the added individuals with estimated age. MARS models have also seen successful applications in previous nonadult ageing studies (Corron et al., 2017; Stull, L'Abbé, & Ousley, 2014).

5.2 | Reinventing the wheel?

Displaying a close relationship between age and dental wear is by no means revolutionary. However, to our knowledge, this is the first ageing method for nonadults based on dental wear using both deciduous and permanent teeth to span the first signs of wear to the end of adolescence. Previous methods using dental wear have focused on adults and have generally relied on certain teeth being present in a specific region of the dental arcade and the separation of anterior and posterior teeth (e.g., Brothwell, 1972; Maat, 2001). This can cause issues due to antemortem tooth loss, caries, asymmetry, and diagenesis; all of which can skew the obtained dental wear score and have a detrimental effect on the accuracy. Expanding the number of applicable teeth increases the number of situations in which the method can be applied. Averaging the wear score across all scored teeth reduces the impact of variability within the dental arcade and inconsistencies in observer scoring, where something, supposedly, as simple as identifying dentine exposure in a tooth can be more complex in practice, especially in stages of initial dentine exposure (Ganss, Klimek, & Lussi, 2006). Additionally, the application of a single scoring method for both permanent and deciduous teeth, and anterior and posterior teeth, promotes simplicity of use.

As Mays (2002) observes, there is a loss of information when applying an ordinal scoring system to the continuous process of dental wear. Conversely, methods involving dental measurements are more tedious and can require access to radiographs and assumptions about the original height of a tooth's crown. Here, we apply an ordinal scale, but by calculating an average for the total dentition, we create continuous data––which could help limit the potential loss of information caused by categorical data collection––and maintain the “user friendliness” of an ordinal scoring system.

5.3 | Is nonadult dental wear a nonlinear process?

Some of the previous ageing methods using dental wear had success in applying linear regression (e.g., Faillace et al., 2017; Kim et al.,

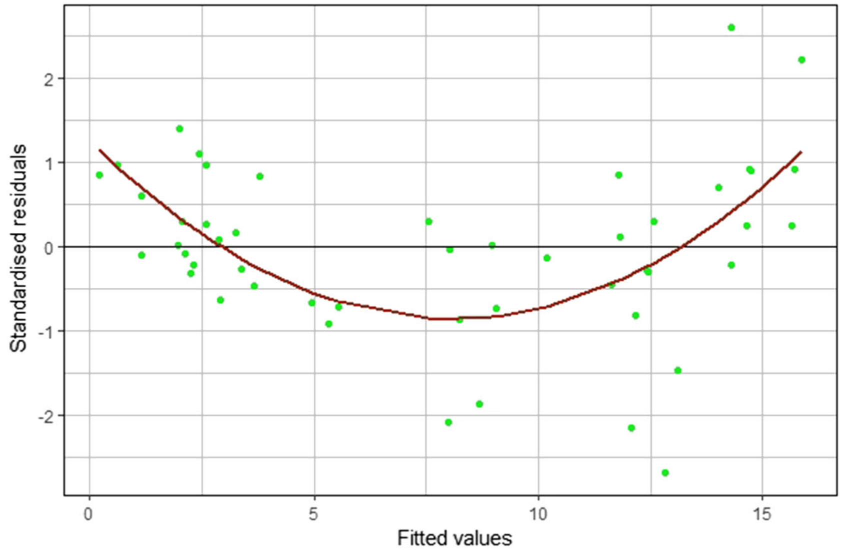

FIGURE 5 Plot of the standardised residuals and fitted values for the linear regression analysis with a best-fit line. The U-shaped best-fit line indicates a poor fit with a linear model [Colour figure can be viewed at wileyonlinelibrary.com]

2000; Maat, 2001; Yun, Lee, Chung, Kho, & Kim, 2007); however, in this study, the coefficient of determination (R^2) for both the quadratic regression and MARS models were higher than that of the linear model, and an examination of the residuals showed an irregular distribution for the linear regression, suggesting that the correlation between age and wear of nonadults may not be entirely linear (Figure 5). This deviation from a linear trend could be due to several methodological and/or physiological issues including, but not limited to, (a) dentine exposure, (b) differences between deciduous and permanent dentitions, (c) issues with the scoring methods, and (d) sample size and composition.

First, the exposure of dentine may cause accelerated wear, because dentine is less dense than enamel (Low, Duraman, & Mahmood, 2008). However, this is unlikely to be a major problem in this study because only low wear stages were present, meaning the dentine exposure was limited. Deciduous teeth rarely displayed late-stage wear as they were exfoliated before such extensive wear could occur, and given the upper limit of the method (19 years), only the early wear stages were represented in the permanent teeth. Additionally, dentine may be less prone to microfractures than enamel, and, due to the softer deciduous enamel, the disparity between the hardness of deciduous enamel and dentine is less significant than for the permanent teeth (Mays & Pett, 2014). Dentine also differs from enamel in its reparatory ability. When experiencing stimulus due to attrition, abrasion, or erosion, tertiary dentine is secreted as a protective measure against degenerative processes such as wear and caries (Klinge, 1999; Kuttler, 1959; Tang, Cabec, & Antoine, 2016) and may reduce any potential disparity between the rate of wear of enamel and dentine.

Second, the rates of wear are expected to differ between the deciduous and permanent dentitions (and mixed deciduous-permanent), whether due to changes in diet between the age groups, differences in the (micro)structure of the two types of teeth, and/or other idiosyncratic factors. This difference can be seen in the linear regression equations for the separated deciduous and permanent dentitions, where the coefficient for the slope for the permanent dentition (0.19) is lower than the deciduous dentition (0.36), meaning the rate of wear is lower in permanent dentition, and a linear equation may not be able to account for this difference as accurately as a nonlinear equation. Additionally, the "knot" identified by the MARS analysis at a wear score of nine is associated with an age of around 11–12, which is when most individuals will have a complete permanent dentition (excluding third molars); although, the second premolars and second molars may not be in complete occlusion (Ubelaker, 1999). This difference in wear-rates may be attributable to both the smaller size of deciduous teeth and the lower density of the enamel (Low et al., 2008; Mays & Pett, 2014). More research is needed to compare the effect of these factors on deciduous and permanent dentitions.

Third, the issue could lie in the scoring system. The aforementioned problem of categorising a continuous process into ordinal stages, where time between the stages may not be equidistant (Mays, 2002), could promote a false nonlinearity. Additionally, an inherant problem of using a stage-based scoring system is that we are not scoring exact wear but inserting observed wear into an appropriate category that represents a close approximation of the actual degree of wear.

Fourth, this study is limited by a modest sample size, being restricted by the availability of archival data, which could cause false trends in the analysis. Individuals whose ages at death were estimated osteologically were included to mitigate the potential issues of a small sample size in the 10+ age range. Although this may have added a level of imprecision due to their less precise age at death, their inclusion did have a positive effect on the strength of the regression equation.

5.4 | Other complicating factors

Many factors are involved in the aetiology of dental wear in both deciduous and permanent dentitions, influencing the rate of wear and causing intrapersonal and interpersonal variation. These include behavioural and biophysiological differences. Idiosyncratic behaviours (both active and passive) that can affect wear rates include differences in erosion and abrasion (dietary and nondietary), cultural modifications, and the habitual grinding of the teeth (bruxism). These can have a significant effect on "normal" wear patterning, causing asymmetries across the dental arcade and affecting the reliability of age-at-death estimation methods (Burnett, 2016; El Aidi, Bronkhorst, Huysmans, & Truin, 2011; Shetty, Pitti, Satish Babu, Surendra Kumar, & Deepthi, 2010; Stojanowski, Johnson, Paul, & Carver, 2016). Biophysiological factors include salivary flow rates, oral pH, oral malformations, disease, crown morphology, enamel density, and enamel thickness (Featherstone & Lussi, 2006; Hillson, 1996; Lavelle, 1970; Lussi & Jaeggi, 2006; Molnar, 2008; Murphy, 1959; Nelson & Ash, 2010); however, limited research has been conducted on the relationship between dental wear and enamel properties in archaeological remains.

5.5 | Sociocultural transitions and interpersonal variation

Another factor involved in the aetiology and rate of dental wear is the behavioural differences between age groups. With a method that spans early childhood to adolescence, there are likely to be a number of sociocultural transitions that can cause the rate of wear to fluctuate, such as the transition to mixed- and permanent dentitions and dietary transitions. No considerable outliers were identified in the regression analysis, suggesting that behavioural and dietary variation between individuals may have been minimal in this sample, and/or that the method succeeded in minimising the error caused by minor asymmetries and observer errors. Increasing variation in the degree of dental wear is expected as age increases, as seen in a plot of the standardised residuals (Figure 6); however, an unexpected region of variation in the data occurred around the time period of the appearance of the first permanent molars. Here, a large range of average wear scores for the 4- and 5-year-olds is observed (n = 8; average wear scores range from 1.58 to 5.69), and is a potential source of inaccuracy and imprecision. One possible explanation for this result is a change in dietary consistency, from a softer diet for younger children (<4–5 years) to a harder adult-like diet for older children. Although the transition from breastmilk to weaning foods has been well documented in contemporary and past populations (e.g., Howcroft, 2013; Scott & Halcrow, 2017; Tsutaya & Yoneda, 2013) and has been shown to occur at ≤3–4 months with limited to absent breastfeeding thereafter in the Middenbeemster population (Waters-Rist & Hoogland, 2018), transitions from a child diet to an adult diet are not as well documented, for example, whether this was a change in food type or just a change in quantity (or no change at all). Combining dental wear and nonlinear regression analysis may be able to provide information regarding the timing of such an event. Mahoney et al. (2016) performed microwear analysis on deciduous teeth of children aged 1–8 years and were able to show two possible shifts in dietary hardness at 4 years and 6 years of age, similar to the variable region observed in this study.

Although not the focus in this study, it should be mentioned that reversing the regression analysis by changing age at death (by methods other than dental wear) to the independent variable and average wear of the permanent dentition as the dependent variable could provide a means for identifying fluctuating rates of wear at the population level across the nonadult phase and can complement other methods of investigating behavioural changes at a population level. Behavioural changes can include differences between boys and girls and differences between age groups, such as the social transition into adulthood including dietary transitions and performing adult tasks. Modelling a large subsample of a population also allows for the recognition of outliers, that is, individuals who experienced a different rate of wear than individuals of similar age, due to a variety of the potential factors discussed earlier. Although the analysis of dental wear patterns alone cannot identify the multitude of causes of the rate of wear, it can certainly be beneficial for identifying overall trends, regions of variability and nonlinearity, and individual outliers, which may then warrant further investigation by other methods (e.g., microwear analysis, stable isotopes, and aDNA).

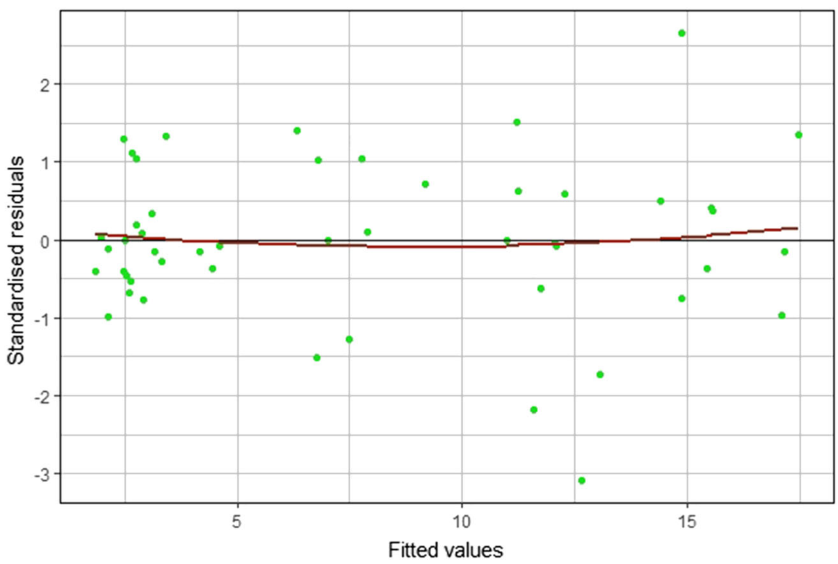

FIGURE 6 Plot of the standardised residuals and fitted values for the quadratic regression analysis with a best-fit line, which indicates a better fit than the linear model [Colour figure can be viewed at wileyonlinelibrary.com]

5.6 | Future directions

Further research on additional samples of individuals with documented age at death is needed to properly validate the method. Additionally, applying the method on other geographically proximate populations from similar time periods using the function created for Middenbeemster to see if these are applicable across multiple populations would be beneficial. Use of this method on additional populations, for which Middenbeemster would be a poor reference, is facilitated by the option to upload additional reference samples to the BAMSAUR age-at-death estimation function. The selection of different regression models is also possible, as we acknowledge that quadratic regression may not be appropriate in every situation, and, given its adaptive nature, future application may reveal MARS models to be more applicable. We hope to be able to expand the utility of this method by incorporating additional samples from multiple populations across wide spatiotemporal contexts into the BAMSAUR database. Future directions should also involve further development of the scoring system to see if it is possible to increase the age range of the method into adulthood.

6 | CONCLUSION

Many factors have the potential to influence the rate of dental wear in nonadults; however, wear seems to occur in a predictable pattern, with age consistently proving to be the dominant factor affecting the rate of wear. We presented strong evidence for the potential of quadratic regression to reliably predict the ages at death of individuals from 1 to 19 years old. Application of this method only requires preservation of the dental crowns and thus can complement other nonadult dental age-at-death estimation methods. Additionally, by employing an average wear score obtained from any available teeth, our method may be more widely applicable than other methods of dental ageing and minimises errors caused by minor asymmetries that may be present across the dental arcade. To facilitate the use of this method, an R-package (BAMSAUR) with a user-friendly graphical interface was developed with the option to use Middenbeemster as a reference population or to upload an alternative reference population. It also provides flexibility in the choice of regression model. Given the valuable information contained in dental wear data, as portrayed in this study and emphasised by previous studies, more systematic recording of dental wear in nonadults should be implemented. The proposed method promotes recording of nonadult dental wear and provides a reliable means for estimating age-at-death.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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