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A method to assess wear rate in pig teeth from archaeological sites

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ABSTRACT

The recording of age at death is an important aspect of zooarchaeological analysis as it provides evidence about a variety of research questions, spanning from the origins of domestication to husbandry strategies.

Age estimation based on tooth eruption and wear is a commonly used method to establish the age at death of archaeological populations. However, this approach has its limitations. It relies on the principle that tooth wear rate is relatively constant in different populations but, since no method has ever been developed to quantify the rate of wear, such an assumption has never been fully verified. As a consequence, the extent to which variable speeds of wear in different populations may affect age estimations is still unknown. To clarify this bias and offer transparency into the issue, the development of a method to assess wear rate in archaeological teeth is of paramount importance. In this paper, we propose a simple system that allows such an assessment to be undertaken. The system has been developed for pig mandibular/lower teeth but can also be extended to other species.

The methodology is then tested on several English Late Medieval and Early Modern pig assemblages which represent ideal case studies as they cover a historical period when extensive changes in pig dietary regimes occurred.

The evidence reassuringly suggests that differences in wear rates between these periods were not substantial, which bodes well for the comparability of kill-off patterns. However, comparisons with several outgroups indicate that the potential range of wear rates is much greater than attested in our core case study. Wild boars and prehistoric pigs, in particular, appear to wear their molars more slowly. Caution is therefore needed and it is suggested that tooth wear rates (TWR) and average wear rates (AWR) should routinely be calculated when tooth-based age profiles are analysed.

1. Introduction

The recording of age at death is an important aspect of zooarchaeological analysis. By establishing the age at death of an archaeological animal population, zooarchaeologists can make inferences about hunting and husbandry strategies adopted at a site, as well as many other research questions, such as the use of animals, seasonality patterns, and the origins of domestication.

The methods commonly used to establish the age at death of domestic animals in an archaeological assemblage are based on the epiphyseal fusion of bones (Silver 1969) and tooth eruption and wear (e.g. for sheep and goat, cf. Payne, 1973, 1987; for cattle and pig cf. Grant, 1975, 1982). Both methodologies have been, and still are, commonly applied; however, it is generally accepted that age estimations based on dental data are more accurate (Albarella and Payne, 2005; Silver, 1969; Wright et al., 2014), though both approaches have their limitations.

Several methods have been developed to determine the age at death from tooth wear for different species (Benecke, 1988; Brown and Chapman, 1990; Bull and Payne, 1982; Grant, 1982; Müller, 1973; Payne, 1973) in parallel with several other studies providing detailed accounts of eruption ages (Boitani and Mattei, 1992; Matschke, 1967; Silver, 1969). All these contributions are based on some common principles, such as:

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1) Following eruption, each tooth comes into bite and gets worn down. During this process, as the enamel of the occlusal surface gradually wears down, showing the darker dentine underneath, patterns develop which can be used to determine the age at death of an animal (Grant, 1975, 1982);
2) The timings of tooth eruption are presumed to be largely genetically controlled and should therefore be relatively consistent for different individuals of the same species (Davis, 1987: 42).

The most commonly used recording system for pigs is the one developed by Grant (1982), which is based on a series of codes describing the different stages of eruption (following Ewbank et al., 1964) and wear to record dental attrition of the first (M_1), second (M_2), and third lower molars (M_3), as well as permanent (P_4) and deciduous (dP_4) fourth premolars. By assigning a score to each tooth, based on its particular stage of eruption or attrition, a mandible wear stage (MWS) can be calculated by simply adding all the scores for the cheek teeth in a mandible. This sum represents an evaluation of the overall wear of the molar dentition in the lower jaw; the higher the MWS, the older the animal (Grant, 1982).

In addition to Grant's work, several other studies have been published to improve the technique or establish similarly useful methods for reconstructing pig age profiles based on teeth (e.g. Anezaki, 2009; Bull and Payne, 1982; Hongo and Meadow, 1998; Lemoine et al., 2014; Magnell, 2002; Magnell and Carter, 2007; Rolett and Chiu, 1994; Wright et al., 2014). Besides, researchers have scrutinised Grant's approach and identified some inherent biases which need to be addressed (e.g. Ervynck, 1997; 2005; O'Connor, 2003). All these studies have contributed, to different extents and in different directions, to a better understanding of the potential and limitations of ageing analysis based on teeth.

However, an issue that remains largely unresolved is the extent to which variable speeds of wear in different pig populations may affect our age estimations. All approaches using tooth eruption and wear rely on the principle that tooth wear rate is relatively constant in different populations. Nevertheless, since no method has been developed to quantify the rate of wear, this commonly known and widely accepted bias (difficult to remove from data and interpretation) has never been fully addressed.

More work has been done in estimating the factors that may affect wear rate in animal teeth (e.g. Grant, 1978; Healy and Ludwig, 1965; Larsson et al., 2005; Magnell, 2002; McCance et al., 1961; Matschke, 1967), mainly focusing on dietary patterns (e.g. Frémondeau et al., 2017; Mainland, 1998; Mainland and Halstead, 2005; Merceron et al., 2016; Vanpoucke et al., 2009; Ward and Mainland, 1999; Wilkie et al., 2007; Yamada et al., 2018). Although these studies are very useful for our understanding of tooth wear rates, none go as far as providing a system for measuring them.

To tackle these problems, the development of a method to assess wear rate in pig teeth is therefore overdue. In this paper, we propose a system that allows such assessment and is specifically devised to be of simple and widespread application. Once devised, the approach is applied to several English Late Medieval and Early Modern pig assemblages. These assemblages cover a historical period when significant changes in pig husbandry techniques, which coincided with changes in dietary regimes, are most likely to have been introduced. These assemblages are therefore ideal as test-cases for our method. To place them in a broader perspective, the data from these sites are compared with a wide range of pig outgroups, which provide useful yardsticks for the interpretation of the evidence from the historical sites.

The work presented here will:

A) Assess the level of variability of tooth wear rates in different assemblages, therefore allowing us to make inferences about the degree of comparability of age profiles from different sites;
B) Provide an insight into the possible factors causing variation in the speed of wear in pig teeth.

2. Materials and methods

2.1. Materials

The method to measure tooth wear rate in pig assemblages was devised through the use of several English pig tooth assemblages with a chronology that covers the Late Medieval to Early Modern transition and deriving from sites that are located in different parts of the country (Table 1 and Fig. 1).

These assemblages were regarded as appropriate case studies because they cover an important period for which both documentary (Harvey, 1988: 130; Trow-Smith, 1957: 55; Wiseman, 2000: 39) and archaeological (Albarella and Davis, 1996; Albarella et al., 1997; Grant, 1988; Jones, 2002) sources attest to the introduction of pig husbandry changes in England. In the Middle Ages, pannage was the taxation system that regulated the predominant regime of pig husbandry for the period. This consisted of letting the pigs pasture in woodland areas where they could feed on roots, acorns, and beech mast in autumn and early winter[1] (Albarella, 2006; Holmes, 2017; Huntley and Stallibrass, 1995). Towards the end of the medieval period, however, this regime started to be progressively replaced by a sty-keeping system (Albarella, 2006; Wiseman, 2000). The increased tendency to enclose the animals allowed greater control of their life cycle, including their eating habits. Written records for the period attest that, when kept enclosed, pigs were fed on legumes, cereals, household waste, and by-products of the dairy and brewing industries (Campbell, 2000: 166; Overton, 1996: 25; Rixson, 2000:120; Wiseman, 2000: 41) - a significantly different diet compared to that available in the forest (Hamilton et al., 2009).

Since teeth are the means through which animals chew and initially process their food, major changes in the physical and chemical composition of the food could result in different tooth wear patterns. Considering this assumption, and the historical background of the chosen sites, our material is, therefore, ideal to verify whether variable husbandry regimes and diets may result in different degrees of tooth wear and to what extent this could compromise the comparison of age profiles.

Since the Late Medieval-Early Modern archaeological samples have variable chronologies, in terms of both date and range, to maximise comparability, the data were organised into the following broad phases:

- Later Middle Ages (includes mainly data from the 12th to the 15th century, with only a few mandibles from the 9th and 11th centuries);
- 16th century (includes data ranging from the late 15th century to the end of the 16th-very beginning of the 17th centuries);
- Post 16th century (includes data from the late 16th century to the 18th-19th century).

Tooth wear stages of all the sites and outgroups considered in this paper were recorded following the method proposed by Grant (1982). Hereford and Winchester were recorded for the specific purpose of this study, while tooth wear data from the other assemblages were either publicly available (cf. references in Table 1) or made accessible by colleagues. Table 2 shows the sample size for each site and chronological period expressed as the number of molar pairs for each tooth combination included in the analysis. The number of jaws for each site and chronological period is provided in Supplementary Material 1.

To provide some comparative context to the English Medieval and Post Medieval sites, tooth wear datasets from different periods and geographic areas have also been used. These derive from:

[1] During the rest of the year, alternative food sources were used, which relied on the renowned adaptability of these animals (Dyer, 2003; Trow-Smith, 1957).

Table 1
List of sites included in this study with information about location, site-type, chronology, and references.

Site N.	Site	County and Region	Type	Chronology considered	References
1	Hereford (Aubrey Street, Bewell Street, Harrison Street and Berrington Street)	Herefordshire Central England	Urban	Late 12th century – 18th century	Noddle (1985); Foster and Carrott unpublished; Hamilton-Dyer unpublished; Baxter unpublished; Own data.
2	Winchester (Victoria Road, Chester Road, New Road, St John's Street, Sussex Street, Crowder Terrace)	Hampshire South England	Urban	Late 12th century – 17th century	Serjeantson and Rees (2009); Own data.
3	Launceston Castle	Cornwall South-West England	Castle	Mid 13th century – 19th century	Albarella and Davis (1996).
4	Norwich Castle	Norwich East England	Urban	Late 9th century – 18th century	Albarella et al. (2009).
5	Dudley Castle	Central England	Castle	Mid 13th century – Mid 18th century	Thomas (2005).
6	West Cotton	Northamptonshire Central England	Deserted village	10th century – 15th century	Albarella and Davis (1994); Albarella and Davis (2010).
7	Great Linford	Buckinghamshire South-East England	Deserted village	13th century – 18th century	Burnett (1992); Holmes (1992); Fraser unpublished.
8	Wharram Percy	North Yorkshire Northern England	Deserted village	13th century – 19th century	Richardson (2009); Pinter-Bellows (2000); Ryder (1974); Fraser unpublished.
9	Shapwick	Somerset South-West England	Rural	13th century – 18th century	Gidney (2007); Fraser unpublished.
10–11	The Shires, Leicester (St. Peter's Lane; Little Lane)	Leicestershire Central England	Urban	late 14th century – Mid 16th century	Gidney (1991a, b,c, 1992, 1993); Grau-Sologestoa and Albarella (2018).
12	Little Pickle	Surrey South-East England	Urban	Late 15th century – Mid 16th century (1490–1555)	Bourdillon (1998); Grau-Sologestoa and Albarella (2018).
13	Flaxengate, Lincoln	Lincolnshire East England	Urban	Late 14th -Mid 16th century	O'Connor (1982); Grau-Sologestoa and Albarella (2018).
14	Durrington Walls	Wiltshire South-West England	**outgroups**	Late Neolithic	Albarella and Davis (2010); Wright et al. (2014).
15	Elms Farm, Heybridge	Essex South-East England		Late Iron Age and Romano-British	Johnstone and Albarella (2015).
16	Crypta Balbi, Rome	Latium Central Italy		7th-10th century AD	Albarella et al. (2019).
17	Wild boars	Germany, Poland, Czech Republic		Modern specimens	own data (with data collection contribution by Keith Dobney)

- The Neolithic site of Durrington Walls (Wiltshire, Southern England): chosen because of the unusually large pig tooth sample size but, also, as representative of the potential range of tooth wear variation in early domestic, unimproved, pig populations;
- The Late Iron Age and Romano-British site of Elms Farm, Heybridge (Essex, South-East England): chosen as representative of the potential range of tooth wear in Roman animals kept in a closely controlled husbandry regime (as confirmed by microwear analysis, see Wilkie et al., 2007);
- The 7th to 10th century BC site of Crypta Balbi, Rome (central Italy): selected as representative of the potential range of pig tooth wear variation in populations from Continental Europe but, also, due to the documented presence of two different pig management systems (Albarella et al., 2019) in the earlier period (7th and 8th century) and in the later period (9th and 10th century) which could potentially reveal different wear rates;
- Several Central European modern wild boar populations; selected to assess potential differences between domestic and wild forms.

The decision to include such outgroups was made to establish the extent to which data patterns seen in the Medieval and Early Modern English populations reflect the full potential range of tooth wear variation in pigs. This was essential for an accurate interpretation.

2.2. Methods

The method that we have developed allows us to establish the tooth wear rate for an individual jaw. On that basis, it is also possible to calculate the average for a whole archaeological assemblage. It was essential for us to devise a tool that is easy to use, relatively straightforward to interpret, and does not require the use of sophisticated equipment; a method which will add strength to the interpretation of mortality profiles and provide evidence in support (or not) of potential dietary changes affecting wear rates.

The proposed system relies on Grant's (1982) method to record tooth wear, as this is widely used. Most of the datasets we used were recorded according to Grant and, as such, to optimize comparability with published datasets, we decided to adopt the same methodology, though we were aware of potential alternatives (Lemoine et al., 2014; Rolett and Chiu, 1994; Wright et al., 2014). However, a similar system such as the one we propose in this paper can easily be developed based on other tooth wear recording methods. Our reliance on Grant (1982) also means that the method was only applied to mandibular teeth. The eruption stages used are those suggested by Ewbank et al. (1964), which are also adopted in Grant's seminal 1982 paper, as well as by many other researchers.

As we wanted to assess relative degrees of wear, we decided that it would be best to focus on the M_1/M_2 and M_2/M_3 pairs, as these are teeth

Fig. 1. Map of England with location of Medieval and Early Modern sites discussed in this paper (black dots) and comparative sites (outgroups) from different periods (red dots). In brackets is the reference number attributed to each site as showed in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Sample size for each tooth combination per chronological phase for each site considered in this study. Site numbers are as follows: 1 = Hereford, 2 = Winchester, 3 = Launceston Castle, 4 = Norwich Castle, 5 = Dudley Castle, 6 = West Cotton, 7 = Great Linford, 8 = Wharram Percy, 9 = Shapwick, 10 = St.Peter's Lane, 11 = Little Lane; 12 = Little Pickle; 13 = Flaxengate.

Sample Size for the combination M_1/M_2															
		Site Number													
	Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	TOT
M_1/M_2 all	Later Middle Ages	9	53	106	55	49	34	10	16	14	2	–	–	–	**348**
	16th c.	4	10	23	38	20	–	6	31	8	9	22	11	4	**186**
	Post 16th c.	14	–	12	–	–	–	7	33	11	–	3	–	–	**80**
	Outgroups														
	Durrington Walls	374													**374**
	Heybridge	54													**54**
	Crypta B. 7th-8th c.	72													**72**
	Crypta B. 9th-10th c.	53													**53**
	Wild boars	564													**564**
Total sample size															**1731**
	Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**TOT**
M_1/M_2 wear *versus* eruption	Later Middle Ages	2	14	2	12	9	3	4	3	10	1	–	–	–	**60**
	16th c.	2	6	4	11	2	–	–	7	1	4	13	1	–	**51**
	Post 16th c.	6	–	2	–	–	–	–	5	2	–	–	–	–	**15**
	Outgroups														
	Durrington Walls	135													**135**
	Heybridge	7													**7**
	Crypta B. 7th-8th c.	6													**6**
	Crypta B. 9th-10th c.	4													**4**
	Wild boars	176													**176**
Total sample size															**454**
Sample Size for the combination M_2/M_3															
		Site Number													
	Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**TOT**
M_2/M_3 all	Later Middle Ages	5	28	68	43	23	23	3	6	–	1	–	–	–	**200**
	16th c.	3	3	15	27	16	–	2	24	4	5	7	13	1	**120**
	Post 16th c.	9	–	9	–	–	–	4	9	3	–	1	–	–	**35**
	Outgroups														
	Durrington Walls	166													**166**
	Heybridge	42													**42**
	Crypta B. 7th-8th c.	92													**92**
	Crypta B. 9th-10th c.	56													**56**
	Wild boars	386													**386**
Total sample size															**1097**
	Phase	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**TOT**
M_2/M_3 wear *versus* eruption	Later Middle Ages	1	18	28	23	8	7	2	3	–	–	–	–	–	**90**
	16th c.	1	2	7	22	8	–	1	11	2	4	7	11	1	**77**
	Post 16th c.	4	–	4	–	–	–	2	5	1	–	1	–	–	**17**
	Outgroups														
	Durrington Walls	73													**73**
	Heybridge	15													**15**
	Crypta B. 7th-8th c.	39													**39**
	Crypta B. 9th-10th c.	27													**27**
	Wild boars	216													**216**
Total sample size															**554**

that erupt sequentially (i.e. M_1 then M_2, and, finally, M_3). Permanent premolars were excluded because the P_4 erupts a lot later than the contiguous M_1 and, therefore, is not directly comparable in terms of the rate of tooth wear. We could have used the dP_4/M_1 wear ratio because the M_1 is the first tooth to erupt after the dP_4, but the comparison between these two teeth wear stages would have been complicated by the influence of lactation on the diet and, consequently, the rate of tooth wear.

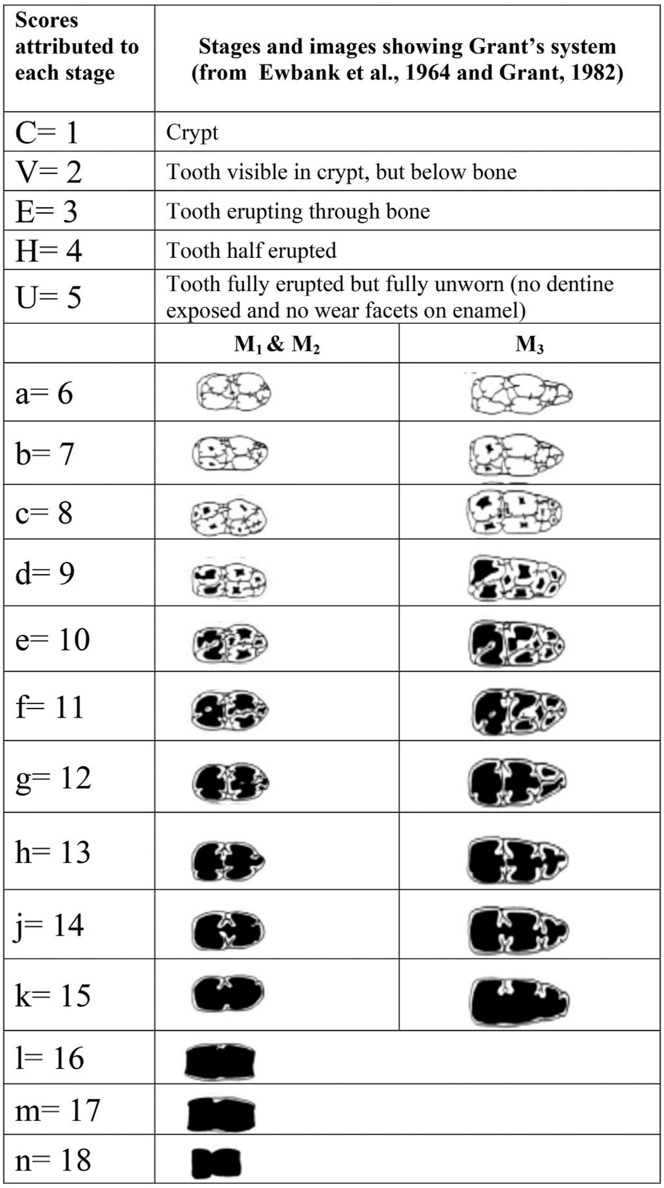
A progressive numeric value was attributed to each molar stage of eruption and wear (Fig. 2). This system allows us to quantify the difference in the wear scores between different teeth. For example, if an M_1 is at stage f, the M_2 at stage c and the M_3 at the eruption stage H, the **'tooth wear rate' (TWR)** would be 3 (f = 11; c = 8; 11–8 = 3) for M_1/M_2 and 4 (c = 8; H = 4; 8–4 = 4) for M_2/M_3.

By doing so for every mandible in the sample – with at least one of the two combinations M_1/M_2 and M_2/M_3 being present - we obtain one or two values which, when grouped by unit of analysis (e.g. chronological phase, area, site) can reveal whether a difference in the wear rate between groups occurred. We call this overall value by unit of analysis **'average wear rate' (AWR).**

The principle underpinning this new method is that the age when teeth erupt in pigs is genetically defined (Davis, 1987: 42). Having approximately stable eruption stages means that the eruption sequences can be used consistently and reliably as a baseline to investigate the rate of wear in a population. If a population is characterized by a high Mean value or 'average wear rate' (AWR) for the difference in the wear of M_1/M_2 and/or M_2/M_3, that would indicate a faster rate of wear compared to a population with a lower Mean value.

For the purpose of this study four databases containing the following datasets were created:

- The different values for all mandibles grouped by chronological period for the combination M_1/M_2;
- The different values for all mandibles grouped by chronological period for the combination M_2/M_3;
- The values for the combination M_1/M_2, originating from mandibles where the M_2 was in an eruption stage (i.e. Ewbank's stages C to U). These values were then grouped by chronological period;



Scores attributed to each stage	Stages and images showing Grant's system (from Ewbank et al., 1964 and Grant, 1982)	
C= 1	Crypt	
V= 2	Tooth visible in crypt, but below bone	
E= 3	Tooth erupting through bone	
H= 4	Tooth half erupted	
U= 5	Tooth fully erupted but fully unworn (no dentine exposed and no wear facets on enamel)	
	M_1 & M_2	M_3
a= 6		
b= 7		
c= 8		
d= 9		
e= 10		
f= 11		
g= 12		
h= 13		
j= 14		
k= 15		
l= 16		
m= 17		
n= 18		

Fig. 2. Numerical values attributed to each eruption stage proposed by Ewbank et al. (1964), and wear stage proposed by Grant (1982). Reproduced with permission of BAR Publishing, www.barpublishing.com.

- The values for the combination M_2/M_3, originating from mandibles where the M_3 was in an eruption stage (i.e. Ewbank's stages C to U). These values were then grouped by chronological period.

These two latter databases containing a selection of mandibles were created because we considered the comparison between a tooth in an eruption stage and another in a wear stage more reliable in providing an estimate of the rate of tooth wear. In these instances, the erupting tooth would not be influenced at all by the rate of wear, thus providing an independent yardstick with which to measure the speed of wear of the adjacent tooth. Conversely, when both teeth are in wear, they will both have been influenced by the phenomenon we are trying to measure (wear rate), making the interpretation more difficult. However, since one tooth will have been exposed to that phenomenon for longer, it is expected that the difference between the wear of the two teeth will still reflect, to some extent, the speed of wear. Though not affected by wear, eruption stages may vary according to other factors, such as genetics or environmental stimuli, therefore both combinations (eruption *versus* wear and wear *versus* wear) have potential limitations. However, the combination of eruption *versus* wear seemed the less problematic of the two to interpret, for the reasons explained above.

Concerning the outgroups, wear data were treated following the same procedure, but no chronological grouping was applied (except for the site of Crypta Balbi); as such, outgroups always appear in the analysis as individual datasets rather than chronologically grouped units.

All TWRs were tested using a Kruskal–Wallis test (1952) to see if statistically significant differences (i.e. not due to chance) could be identified between the compared groups. The Kruskal-Wallis test was chosen for the following reasons:

- It does not assume normality in the data and is much less sensitive to outliers (Field, 2009: 559) than the ANOVA and Student T-test;
- It allows comparisons between the Mean ranks of three or more different groups (as opposed to the Mann-Whitney, where only two groups can be compared).

Table 3
Results of Kruskal-Wallis test for M_1/M_2 (all) when run on the Late Medieval-Early Modern samples (three phases). *P* values equal or below 0.05 are highlighted in grey.

Null Hypothesis Testing: The distribution of scores is different between periods

Sites	Sig.	Decision
Hereford	.565	Reject the null hypothesis.
Winchester	.801	Reject the null hypothesis.
Launceston Castle	.286	Reject the null hypothesis.
Norwich Castle	.791	Reject the null hypothesis.
Dudley Castle	.454	Reject the null hypothesis.
Great Linford	**.032**	Retain the null hypothesis.
Wharram Percy	**.012**	Retain the null hypothesis.
Shapwick	**.048**	Retain the null hypothesis.
The Shires (St. Peter's Lane + Little Lane)	.524	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is 0.050.

Table 4
P values for the combination M_1/M_2 (all) when pairwise comparisons were carried out on Great Linford, Wharram Percy, and Shapwick. The probability level is determined as follows: *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), n.s. = not significant.

Pairwise Comparisons for Great Linford
Significance values have been adjusted by the SPSS Bonferroni correction for multiple tests.

Sample	Sig.	SPSS Bonferroni Adj. Sig.	Probability Level
Later Middle Ages-16th century	.016	**.048**	*
Later Middle Ages-Post 16th century	.056	.167	n.s.
16th century-Post 16th century	.589	1	n.s.
Pairwise Comparisons for Wharram Percy			
Later Middle Ages-16th century	.003	**.009**	**
Later Middle Ages-Post 16th century	.093	.278	n.s.
16th century-Post 16th century	.111	.334	n.s.
Pairwise Comparisons for Shapwick			
Later Middle Ages-16th century	.024	.071	n.s.
Later Middle Ages-Post 16th century	.071	.214	n.s.
16th century-Post 16th century	.552	1	n.s.

Each row tests the null hypothesis that Sample 1 and Sample 2 distributions are not the same.Asymptotic significances (2-sided tests) are displayed. The significance level is 0.05.

Table 5
Results of Kruskal-Wallis test for M_2/M_3 (all) when run on the Late Medieval-Early Modern samples (three phases).

Null Hypothesis Testing: The distribution of scores is different between periods		
Sites	Sig.	Decision
Hereford	.244	Reject the null hypothesis.
Winchester	.945	Reject the null hypothesis.
Launceston Castle	.850	Reject the null hypothesis.
Norwich Castle	.960	Reject the null hypothesis.
Dudley Castle	.848	Reject the null hypothesis.
Great Linford	.717	Reject the null hypothesis.
Wharram Percy	.117	Reject the null hypothesis.
Shapwick	.279	Reject the null hypothesis.
The Shires (St. Peter's Lane + Little Lane)	.673	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is 0.050.

For this paper, the Kruskal-Wallis test was first applied to test if significant differences were present between Medieval and Early Modern English phases. Subsequently, the same test was run to check whether significant differences could be identified between the Medieval and the Early Modern groups and the outgroups.

In both analyses, running many consecutive paired tests can lead to a Type I Error, namely the finding of an inflated number of significant differences; therefore, an SPSS Bonferroni adjustment was applied (Field, 2009: 372–373) and only SPSS adjusted *P* values were considered (these are backward corrected *P* values, i.e. the *P* values are multiplied by the total number of possible pairs). Along with the Kruskal-Wallis test, a number of descriptive statistics such as Mean (i.e. statistical model of the centre of the distribution of the scores; Field, 2009: 789), Median (i.e. the middle score of a set of ordered observations; Field 2009: 789), and histograms showing the distribution of the data for each group were performed. This was carried out to provide greater insight into the nature of the data and also to aid the interpretation of the results. All statistical analyses were performed using SPSS Statistics 26.

3. Results

Having developed a method to measure tooth wear rate in different pig assemblages, we applied it to a specific case study, where previous historical and archaeological research suggested that an overall change in pig diet was likely. This concerned the comparison between the English Late Medieval and Early Modern periods. The chronological periods by which the data were divided are explained in the Materials section. The average wear rates (AWR) for each site and phase can be found in Table 1 (online supplementary material).

The results for the combination of M_1/M_2 are shown in Table 3. Only sites with data from at least two of the three chronological phases are included; as such, West Cotton, Little Pickle, and Flaxengate were excluded, as they only provided data for one phase. Of the entire sample, Hereford, Launceston, Great Linford, Wharram Percy, and Shapwick are the sites that could provide data for all three chronological phases.

Table 6
Results of Kruskal-Wallis test for M_1/M_2 (wear *versus* eruption) when run on the Late Medieval- Early Modern samples (three phases).

Null Hypothesis Testing: The distribution of scores is different between periods		
Sites	Sig.	Decision
Hereford	.136	Reject the null hypothesis.
Winchester	.893	Reject the null hypothesis.
Launceston Castle	.352	Reject the null hypothesis.
Norwich Castle	.539	Reject the null hypothesis.
Dudley Castle	1.000	Reject the null hypothesis.
Wharram Percy	.436	Reject the null hypothesis.
Shapwick	.708	Reject the null hypothesis.
The Shires (St. Peter's Lane + Little Lane)	.264	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is 0.050.

Table 7
Results of Kruskal-Wallis test for M_2/M_3 (wear *versus* eruption) when run on the Late Medieval-Early Modern samples (three phases). *P* values equal or below 0.05 are highlighted in grey.

Null Hypothesis Testing: The distribution of scores is different between periods		
Sites	Sig.	Decision
Hereford	.298	Reject the null hypothesis.
Winchester	.378	Reject the null hypothesis.
Launceston Castle	.815	Reject the null hypothesis.
Norwich Castle	.009	Reject the null hypothesis.
Dudley Castle	1.000	Reject the null hypothesis.
Great Linford	.174	Reject the null hypothesis.
Wharram Percy	**.003**	Retain the null hypothesis.
Shapwick	.157	Reject the null hypothesis.
The Shires (Little Lane)	.766	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is 0.050.

Table 8
P values for the combination M_2/M_3 (wear *versus* eruption) when pairwise comparisons were carried out on Wharram Percy. The probability level is determined as follows: *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), n.s. = not significant.

Pairwise Comparisons for Wharram Percy Significance values have been adjusted by the SPSS Bonferroni correction for multiple tests.			
Sample	**Sig.**	**SPSS Bonferroni Adj. Sig.**	**Probability Level**
Later Middle Ages-16th century	.550	1	n.s.
Later Middle Ages-Post 16th century	.049	.147	n.s.
16th century-Post 16th century	.001	**.002**	**

Each row tests the null hypothesis that Sample 1 and Sample 2 distributions are not the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is 0.05.

Table 9
Results of Kruskal-Wallis test for all combinations when run on the merged Late Medieval-Early Modern samples (three phases).

Null Hypothesis Testing: The distribution of scores is different between periods		
Sites	Sig.	Decision
All Late Medieval-Early Modern sites M_1/M_2 (all)	.255	Reject the null hypothesis.
All Late Medieval-Early Modern sites M_2/M_3 (all)	.204	Reject the null hypothesis.
All Late Medieval-Early Modern sites M_1/M_2 (wear *versus* eruption)	.716	Reject the null hypothesis.
All Late Medieval-Early Modern sites M_2/M_3 (wear *versus* eruption)	.187	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is 0.050.

Table 3 shows that there is no statistically significant difference between the different phases for most of the sites considered. The exceptions are represented by the sites of Great Linford, Wharram Percy, and Shapwick, which have a significant *P* value (i.e. $\leq$0.05). Since these sites had data for all three chronological phases, to understand which combination of phases have provided a significant *P* value, we must look at the pairwise comparison results generated by the Kruskal-Wallis test, so that Bonferroni adjusted *P* values for each comparison in each site can be evaluated. Table 4 shows that after the Bonferroni adjustment, only two of the three sites, Great Linford and Wharram Percy, have a significant *P* value, and both for the same comparison: Later Middle Ages-16th century. However, the level of probability of these values is not especially high.

Table 10
Results of Kruskal-Wallis test for the combination M_1/M_2 (all) and M_2/M_3 (all). For both combinations, wear data from the English sites merged by chronological phase (Later Middle Ages, 16th century, and Post 16th century) are compared to wear data from the outgroups. *P* values equal or below 0.05 are highlighted in grey.

Null Hypothesis Testing: The distribution of scores is different between periods		
Combinations	Sig.	Decision
M_1/M_2 (all)	**.000**	Retain the null hypothesis.
M_2/M_3 (all)	**.000**	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is 0.050.

Table 11
P values for the combination M_1/M_2 (all) when pairwise comparisons were carried out between our main datasets and the outgroups. The probability level is determined as follows: *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), n.s. = not significant.

Pairwise Comparisons for M_1/M_2 (all)
Significance values have been adjusted by the SPSS Bonferroni correction for multiple tests.

Samples	**Sig.**	**SPSS Bonferroni Adj. Sig.**	**Probability level**
Durrington Walls VS Later Middle Ages	.000	.001	***
Durrington Walls VS 16th century	.003	.072	n.s.
Durrington Walls VS Post 16th century	.434	1	n.s.
Heybridge VS Later Middle Ages	.901	1	n.s.
Heybridge VS 16th century	.980	1	n.s.
Heybridge VS Post 16th century	.312	1	n.s.
Crypta Balbi 7th-8th century VS Later Middle Ages	.000	.000	***
Crypta Balbi 7th-8th century VS 16th century	.000	.000	***
Crypta Balbi 7th-8th century VS Post 16th century	.001	.041	*
Crypta Balbi 9th-10th century VS Later Middle Ages	.785	1	n.s.
Crypta Balbi 9th-10th century VS 16th century	.908	1	n.s.
Crypta Balbi 9th-10th century VS Post 16th century	.378	1	n.s.
Wild boars VS Later Middle Ages	.000	.001	***
Wild boars VS 16th century	.002	.050	*
Wild boars VS Post 16th century	.454	1	n.s.

Each row tests the null hypothesis that Sample 1 and Sample 2 distributions are not the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is 0.05.

The same test was carried out for the combination of M_2/M_3. As previously done, only sites with data from at least two relevant chronological phases were included. Table 5 shows that there is no statistical difference between wear scores of different phases for any of the sites. These results confirm what was partially noticed with the combination M_1/M_2: the wear scores, when chronological periods are compared, are not significantly different.

As mentioned in Methods, the eruption sequence is largely stable in a population and should, therefore, be marginally subjected to individual variation. Consequently, the tooth combinations in which one of the teeth is in one of Ewbank et al.'s eruption stages (i.e. C to U) probably represent the most reliable data in the use of tooth wear rate.

As a consequence, the Kruskal-Wallis test was also performed on selected mandibles where one of the molars was still erupting. The sample size is inevitably substantially reduced (Table 2). Table 6 shows the results for the combination of M_1/M_2.

The results indicate that there are no significant differences between wear scores of different phases of any of the archaeological sites. Therefore, the null hypothesis, according to which the distribution of scores is different across phases, can be rejected. It is important to consider that the reduced sample size makes it harder for the test to produce a significant value.

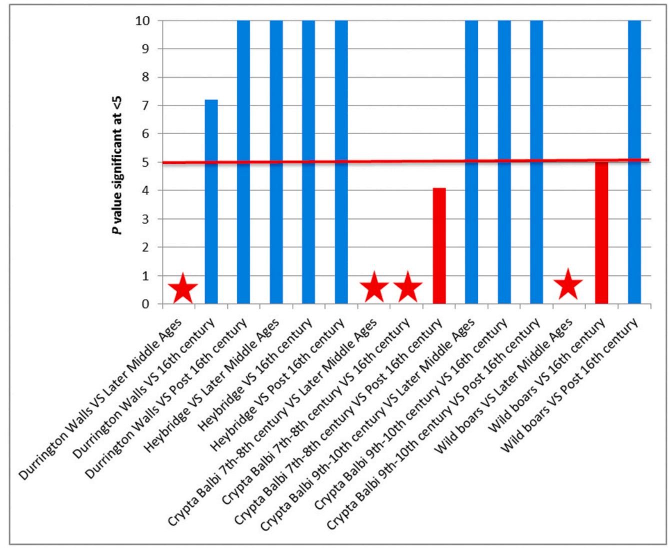


Fig. 3. Histogram showing all the *P* values for each pair of sites compared, for the combination M_1/M_2 (all). The red color highlights the pairs which have provided significant *P* values (*) while the red star highlights highly and very highly significant *P* values (**, ***). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 7 shows the results when selected mandibles for the combination of M_2/M_3 were tested. The results are consistent with what was previously seen with the combination M_1/M_2: no statistically significant differences are present between scores of different phases for most sites. The only exception is represented by the site of Wharram Percy, which has provided a highly significant *P* value.

Table 8 shows which phase-comparison has provided a significant *P* value for the Wharram Percy sample, and this is the 16th century-Post 16th century comparison.

To provide a large-scale approach and increase sample size, data from different sites were combined and compared by chronological phase. Table 9 shows that despite the sample size has greatly increased, there is no evidence for any statistically significant difference between periods for any tooth combination used.

There is, therefore, no evidence of a significant change in the rate of pig tooth wear between Medieval and Modern times in England. An important implication of this result is that kill-off patterns based on dental wear should be comparable between periods, as the rate of wear does not seem to affect distributions substantially.

However, before this concept could be more universally applied, it is necessary to compare our English Medieval and Early Modern data with those from several substantially different populations, here regarded as outgroups. Wear rate data from the outgroups were added to the analysis to be compared with data from the English Medieval and Early mMdern phases. Table 10 shows that, with the addition of the outgroups, in both combinations, there is very strong evidence ($P \leq 0.001$) to suggest a difference between at least one pair of groups.

Table 11 shows the results of each group-comparison for the combination of M_1/M_2. It can be seen that, except for Heybridge and Crypta Balbi 9th-10th century, the outgroups are all significantly different from the Later Middle Ages sample. In addition, both Crypta Balbi 7th-8th century and the wild boars sample provided significant results, even

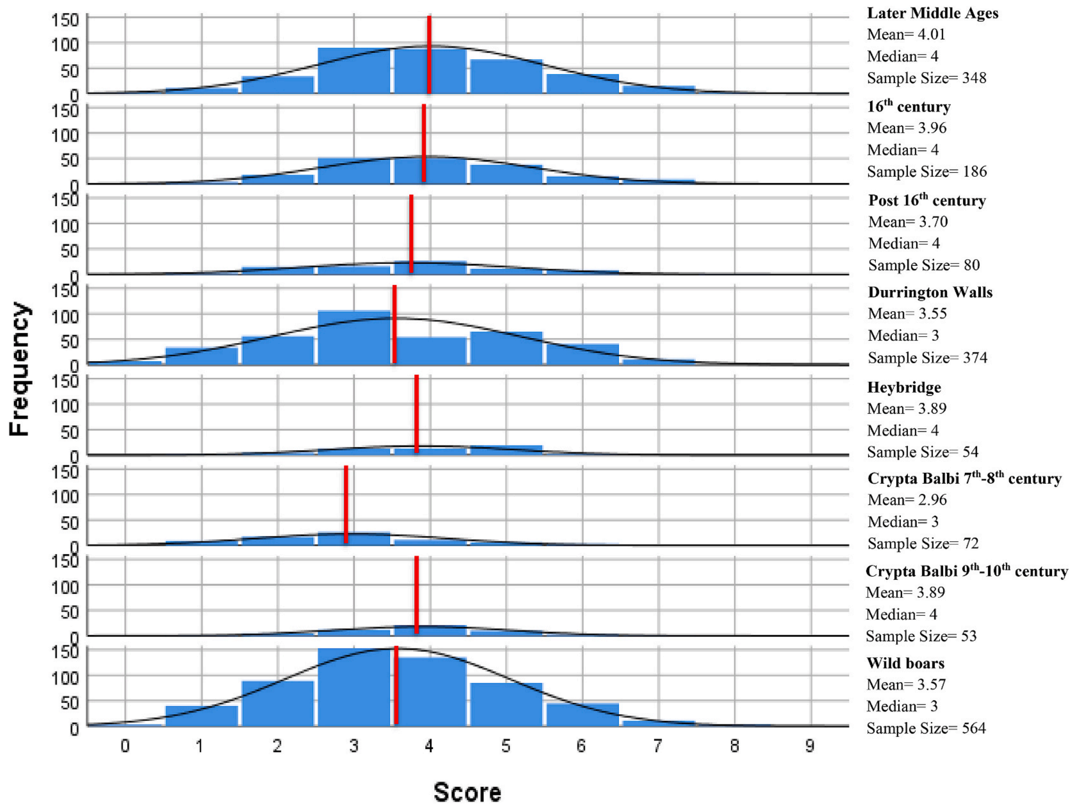


Fig. 4. Histogram showing the spread of data for each group for the combination M_1/M_2 (all). The red vertical line shows the Mean while the black line shows the distribution curve for each sample. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 12
P values for the combination M_2/M_3 (all) when pairwise comparisons were carried out on the entire sample including the outgroups. The probability level is determined as follows: *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), n.s. = not significant.

Pairwise Comparisons for M_2/M_3 (all)
Significance values have been adjusted by the SPSS Bonferroni correction for multiple tests

Samples	Sig.	SPSS Bonferroni Adj. Sig.	Probability level
Durrington Walls VS Later Middle Ages	.000	.000	***
Durrington Walls VS 16th century	.000	.000	***
Durrington Walls VS Post 16th century	.000	.002	**
Heybridge VS Later Middle Ages	.014	.403	n.s
Heybridge VS 16th century	.001	.032	*
Heybridge VS Post 16th century	.007	.205	n.s.
Crypta Balbi 7th-8th century VS Later Middle Ages	.000	.003	**
Crypta Balbi 7th-8th century VS 16th century	.000	.000	***
Crypta Balbi 7th-8th century VS Post 16th century	.001	.014	*
Crypta Balbi 9th-10th century VS Later Middle Ages	.047	1	n.s.
Crypta Balbi 9th-10th century VS 16th century	.004	.109	n.s.
Crypta Balbi 9th-10th century VS Post 16th century	.021	.581	n.s.
Wild boars VS Later Middle Ages	.000	.000	***
Wild boars VS 16th century	.000	.000	***
Wild boars VS Post 16th century	.000	.000	***

Each row tests the null hypothesis that Sample 1 and Sample 2 distributions are not the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.

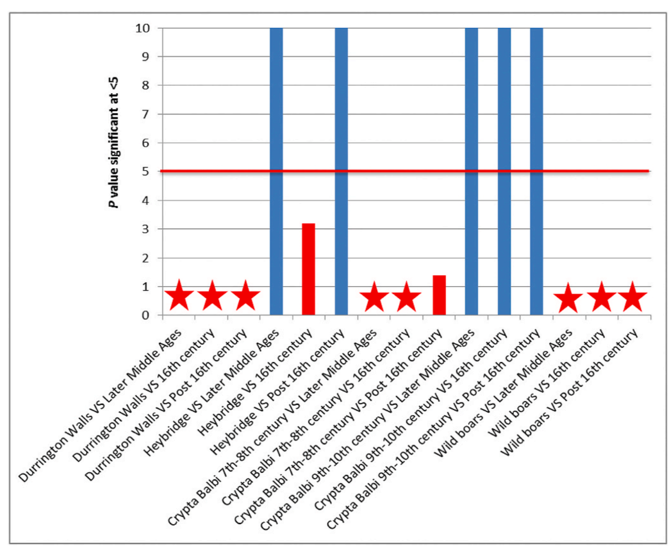


Fig. 5. Histogram showing all the *P* values for each pair of sites compared, for the combination M_2/M_3 (all). Colours and symbols as explained in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

though of different magnitude, when compared to 16th century values. The Post 16th century phase is, only in one case, significantly different from the outgroups but, the small sample size from this phase reduces the likelihood of the test producing a significant result.

Fig. 3 graphically shows all the *P* values obtained for each comparison made. *P* values have been transformed from decimal to integer numbers to facilitate the legibility of the diagram. For this and the

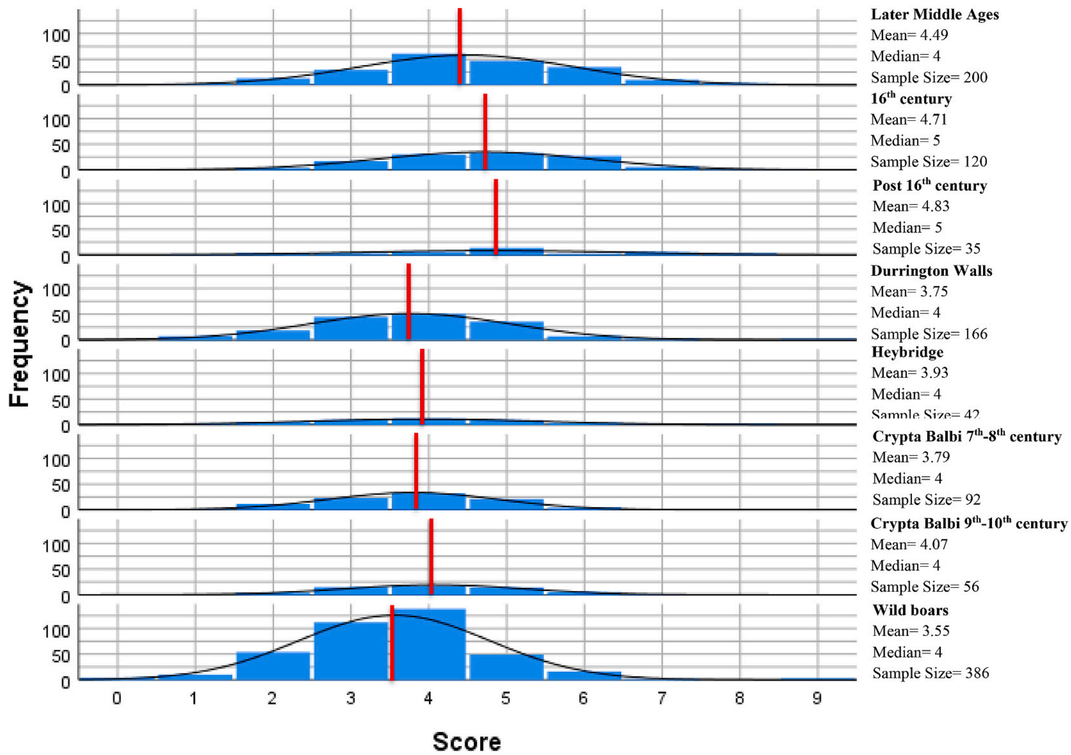


Fig. 6. Histogram showing the spread of data for each group for the combination M_2/M_3 (all). The red vertical line shows the Mean while the black line shows the distribution curve for each sample. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

following figures, the *P* value significance is set at ≤5. To facilitate visual representation, values on the horizontal axis have been capped at 10. It can be seen that the Crypta Balbi 7th-8th century sample has provided very highly significant *P* values when compared to the sample from the Late Middle Ages and the 16th century material. A similar pattern can also be identified for both Durrington Walls and the modern wild boar sample; both samples gave very highly statistically significant results when compared to the Later Middle Ages ($P \leq 0.001$). When compared to the 16th century sample only the wild boar sample gave a significant value ($P \leq 0.05$).

Fig. 4 shows the distribution of scores for each site, along with their Mean, for the combination M_1/M_2. All groups have an approximate unimodal distribution, which means that they can be fairly well characterised by the position of their Means. The Later Middle Ages group, along with the 16th century group, the Heybridge sample, and the Crypta Balbi 9th-10th century sample have similar Mean values, which range from 3.89 to 4.01. On the other hand, the Post 16th century group, Durrington Walls, and the wild boar sample have Means in the 3.55 to 3.70 range. The Mean is significantly lower for the Crypta Balbi 7th-8th century, which barely reaches 3.

If we consider the Mean as an average indication of the speed of wear of an assemblage, Crypta Balbi 7th-8th century shows a slower rate of wear compared to the other groups, and a significantly slower rate of

Table 13
Results of Kruskal-Wallis test for the combination M_1/M_2 and M_2/M_3 (wear *versus* eruption). For both combinations, wear data from the English sites merged by chronological phase (Later Middle Ages, 16th century and Post 16th century) are compared to wear data from each outgroup. *P* values equal or below 0.05 are highlighted in grey.

Null Hypothesis Testing: The distribution of scores is different between periods

Combinations	Sig.	Decision
M_1/M_2 (wear *versus* eruption)	**.008**	Retain the null hypothesis.
M_2/M_3 (wear *versus* eruption)	**.000**	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is 0.050.

Table 14
Significant *P* values for the combination M_1/M_2 (wear *versus* eruption) when pairwise comparisons were carried out on the entire sample including the outgroups. The probability level is determined as follows: *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$), n.s. = not significant.

Pairwise Comparisons for M_1/M_2 (wear *versus* eruption)
Significance values have been adjusted by the SPSS Bonferroni correction for multiple tests

Samples	**Sig.**	**SPSS Bonferroni Adj. Sig.[a]**	**Probability level**
Durrington Walls VS Later Middle Ages	.238	1	n.s.
Durrington Walls VS 16th century	.192	1	n.s.
Durrington Walls VS Post 16th century	.999	1	n.s.
Heybridge VS Later Middle Ages	.091	1	n.s.
Heybridge VS 16th century	.080	1	n.s.
Heybridge VS Post 16th century	.595	1	n.s.
Crypta Balbi 7th-8th century VS Later Middle Ages	.001	.025	*
Crypta Balbi 7th-8th century VS 16th century	.001	.021	*
Crypta Balbi 7th-8th century VS Post 16th century	.010	.292	n.s.
Crypta Balbi 9th-10th century VS Later Middle Ages	.768	1	n.s.
Crypta Balbi 9th-10th century VS 16th century	.816	1	n.s.
Crypta Balbi 9th-10th century VS Post 16th century	.551	1	n.s.
Wild boars VS Later Middle Ages	.029	.815	n.s.
Wild boars VS 16th century	.025	.686	n.s.
Wild boars VS Post 16th century	.595	1	n.s.

Each row tests the null hypothesis that Sample 1 and Sample 2 distributions are not the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is 0.05.

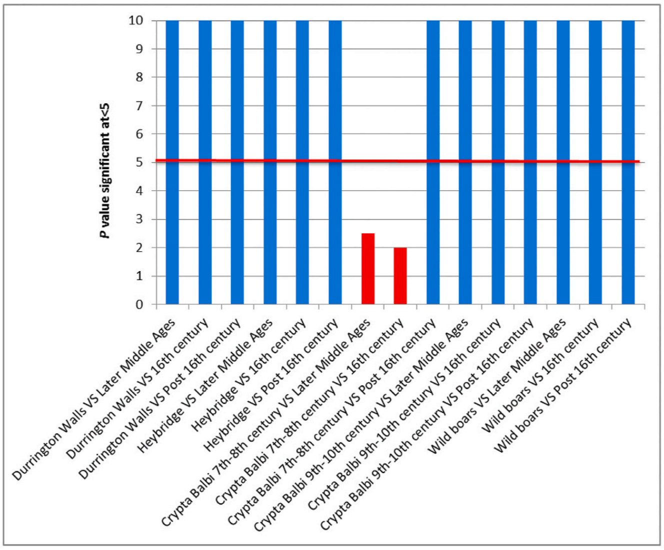


Fig. 7. Histogram showing all the *P* values for each pair of sites compared, for the combination M_1/M_2 (wear *versus* eruption). Colours and symbols as explained in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

wear when compared to the Later Middle Ages and 16th century samples.

Table 12 shows which pair-comparisons have provided significant *P* values for the combination of M_2/M_3. The results indicate, largely consistently with what was seen with the previous combination, that in all cases, the outgroups, except for Crypta Balbi 9th-10th century, are significantly different from the Medieval and Early Modern English datasets. The site of Heybridge is the least different the outgroups.

Fig. 5 graphically shows all the *P* values for the combination M_2/M_3 obtained for each pair-comparison made, transformed as explained for Fig. 3. As previously seen with the combination M_1/M_2, Durrington Walls, Crypta Balbi 7th-8th century and the modern wild boars are the groups that have provided significant *P* values. These values are mostly very highly significant and, as such, the combination M_2/M_3 seems to provide stronger evidence for the existence of a difference between the samples than the combination M_1/M_2.

Fig. 6 shows the distribution of data for the combination M_2/M_3 for each group, along with their Mean. The Mean values for the Later Middle Ages, the 16th century, and the Post 16th century group are the highest, ranging between 4.49 and 4.83 (the highest).

On the other hand, all the other sites have a lower Mean value ranging from 3.55 (the lowest) to 4.07. This pattern accurately mirrors the results from the Kruskal-Wallis test: Durrington Walls, Crypta Balbi 7th-8th century and the modern wild boars, which have provided the lowest Mean values, are significantly different from the Later Middle Ages, the 16th century and the Post 16th century samples, which have the highest Mean values. If we consider the Mean as an average indicator of the tooth wear rate for a sample, it emerges that most outgroups have a slower rate of attrition than the Medieval and Early Modern samples. Heybridge appears to be closer to the Medieval and Early Modern sites, but less so than in the M_1/M_2 comparison. Crypta Balbi 9th-10th century plots in the same area as Heybridge but its relatively small sample size probably explains the lack of significant differences with the Medieval and Early Modern groups.

As previously mentioned, the testing of tooth combinations where one of the teeth was in one of Ewbank et al.'s eruption stages has the potential to provide the most reliable results in the study of tooth wear rate; at the expense, however, of sample size. We ran the Kruskal-Wallis test on selected mandibles for the outgroups, treated as individual groups, and the Medieval and Early Modern sites, which were combined by chronological phase.

Table 13 shows that, when the test was run, *P* values are significant for both tooth combinations, confirming the presence of a genuine

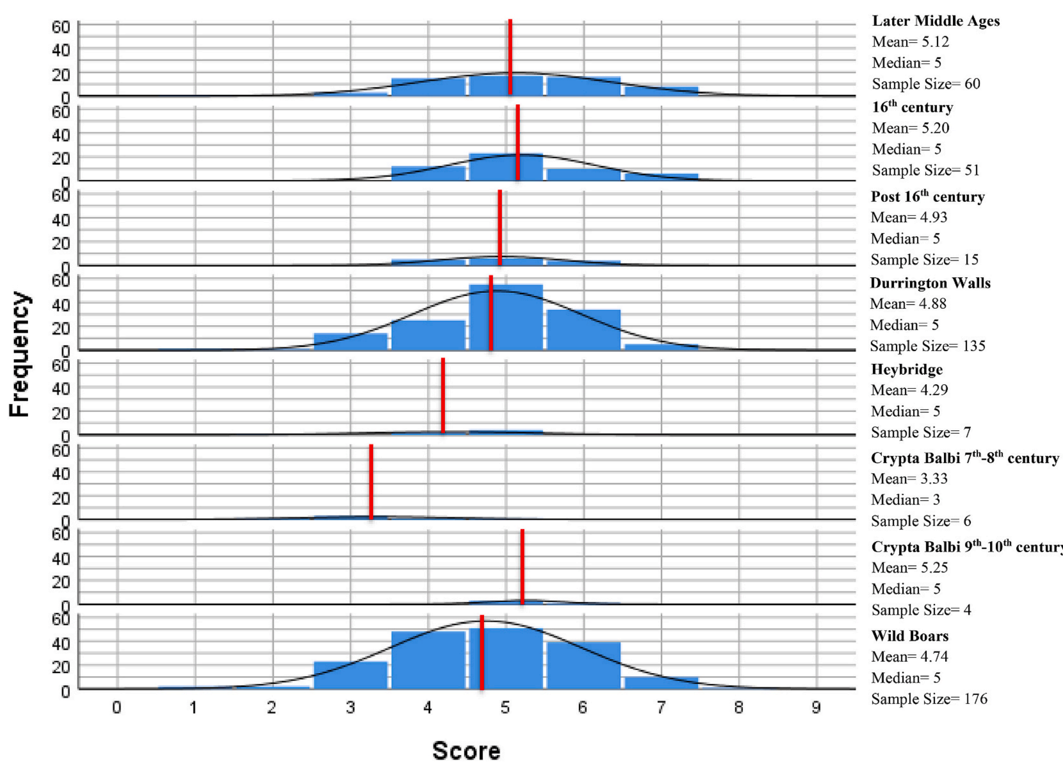


Fig. 8. Histogram showing the spread of data for each group for the combination M_1/M_2 (wear *versus* eruption). The red vertical line shows the Mean while the black line shows the distribution curve for each sample. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 15
Significant *P* values for the combination M_2/M_3 (wear *versus* eruption) when pairwise comparisons were carried out on the entire sample including the outgroups. The probability level is determined as follows: *** = very highly significant ($P \leq 0.001$), ** = highly significant ($P \leq 0.01$), * = significant ($P \leq 0.05$).

Pairwise Comparisons for M_2/M_3 (wear *versus* eruption)
Significance values have been adjusted by the SPSS Bonferroni correction for multiple tests

Sample	Sig.	SPSS Bonferroni Adj. Sig.	Probability level
Durrington Walls VS Later Middle Ages	.005	.132	n.s.
Durrington Walls VS 16th century	.003	.081	n.s.
Durrington Walls VS Post 16th century	.001	.037	*
Heybridge VS Later Middle Ages	.825	1	n.s.
Heybridge VS 16th century	.715	1	n.s.
Heybridge VS Post 16th century	.175	1	n.s.
Crypta Balbi 7th-8th century VS Later Middle Ages	.001	.022	*
Crypta Balbi 7th-8th century VS 16th century	.000	.014	*
Crypta Balbi 7th-8th century VS Post 16th century	.000	.007	**
Crypta Balbi 9th-10th century VS Later Middle Ages	.074	1	n.s.
Crypta Balbi 9th-10th century VS 16th century	.053	1	n.s.
Crypta Balbi 9th-10th century VS Post 16th century	.009	.246	n.s.
Wild boars VS Later Middle Ages	.000	.000	***
Wild boars VS 16th century	.000	.000	***
Wild boars VS Post 16th century	.000	.000	***

Each row tests the null hypothesis that Sample 1 and Sample 2 distributions are not the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is 0.05.

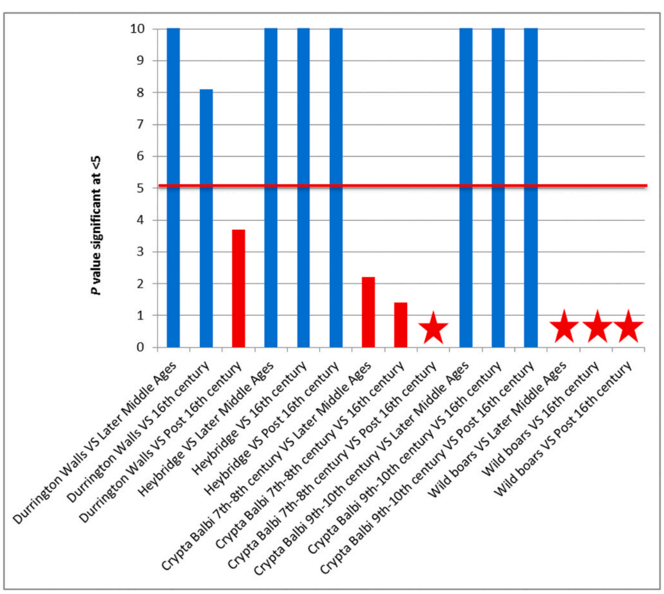


Fig. 9. Histogram showing all the *P* values for each pair of sites compared, for the combination M_2/M_3 (wear *versus* eruption). Colours and symbols as explained in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

difference between at least one pair among the compared groups.

Table 14 shows which pair-comparisons have provided significant *P* values for the combination M_1/M_2 (wear *versus* eruption) while Fig. 6 visually shows these results. However, *P* values have been transformed as explained for Fig. 3.

The group Crypta Balbi 7th-8th century *versus* Later Middle Ages and Crypta Balbi 7th-8th century *versus* 16th century are the two combinations that provide significant *P* values (Fig. 7). However, the level of probability is not especially high. The combination M_1/M_2 (wear *versus* eruption) therefore suggests a small number of statistically significant differences. The smaller sample size may be the reason behind this result.

Fig. 8 shows, with a series of histograms, the distribution of scores and the Mean values for the combination M_1/M_2 (wear *versus* eruption) for each sample. The Later Middle Ages, 16th century, Post 16th century, and Crypta Balbi 9th-10th century have Mean values ranging from 4.93 to 5.25. Durrington Walls, Heybridge, and the modern wild boar group have lower Mean scores, ranging from 4.29 to 4.88. The lowest Mean score belongs to Crypta Balbi 7th-8th century, which is also the sample that has provided the only significant *P* values with the Kruskal-Wallis test when compared to the Later Middle Ages and 16th century groups (highest Mean values). The Crypta Balbi 7th-8th century pigs, therefore, are confirmed as the animals with the slowest rate of wear. The trend identified for the full sample is confirmed by this analysis but is generally less pronounced as it is detrimentally affected by smaller sample size.

Table 15 shows the pair-comparisons that provided significant *P* values when the combination M_2/M_3 (wear *versus* eruption) was analysed. As opposed to the combination M_1/M_2 (wear *versus* eruption), the combination M_2/M_3 (wear *versus* eruption) has not only produced more statistically significant comparisons but also provided *P* values with a high or very high level of probability.

Once again, most of the outgroups, except for Heybridge and Crypta Balbi 9th-10th century, are shown to be different from the Medieval and Early Modern samples. Both Crypta Balbi 7th-8th century and the modern wild boar sample have given significant *P* values when compared to the Later Middle Ages, the 16th century, and the Post 16th century samples. However, the modern wild boar sample seems to the most different of the outgroups. Durrington Walls, on the other hand, has provided only one significant *P* value when compared to the Post 16th century sample (this could be a consequence of the smaller sample size for this tooth combination at the site).

Fig. 9 shows graphically the *P* value reported in Table 16. *P* values have been transformed, as explained in Fig. 3.

Fig. 10 shows the distribution of each sample along with the Mean, for the combination of M_2/M_3 (wear *versus* eruption). The Later Middle Ages, 16th century, Post 16th century, and Heybridge samples have the highest Mean values, ranging from 5.07 to 5.76. The Mean value is lower for Durrington Walls, Crypta Balbi 7th and 8th century and the modern wild boar samples, ranging from 4.06 to 4.52. The Mean for the Crypta Balbi 9th-10th century seems to fall in between these two groups. If we consider the Mean as a value that quantifies the average speed of wear of a sample, what emerges from this analysis is that Durrington Walls, Crypta Balbi 7th-8th century, and the modern wild boar sample have a slower speed of wear compared to the other groups.

The analysis carried out on the Medieval and Early Modern sites and the outgroups has shown that, while there is a certain level of stability in the rate of pig tooth wear for the English Medieval and Early Modern samples, when these are compared with the outgroups, differences in the rate of wear emerge. These results are also confirmed when individual English Late Medieval and Early Modern sites were compared to the outgroup samples (for more details see Supplementary Material 2). These differences, which are more strongly expressed when the combination M_2/M_3 is used, seem to suggest that most of the outgroups, with the possible exception of Crypta Balbi 9th-10th century and Heybridge, have a slower wear rate than the Medieval and Post Medieval samples.

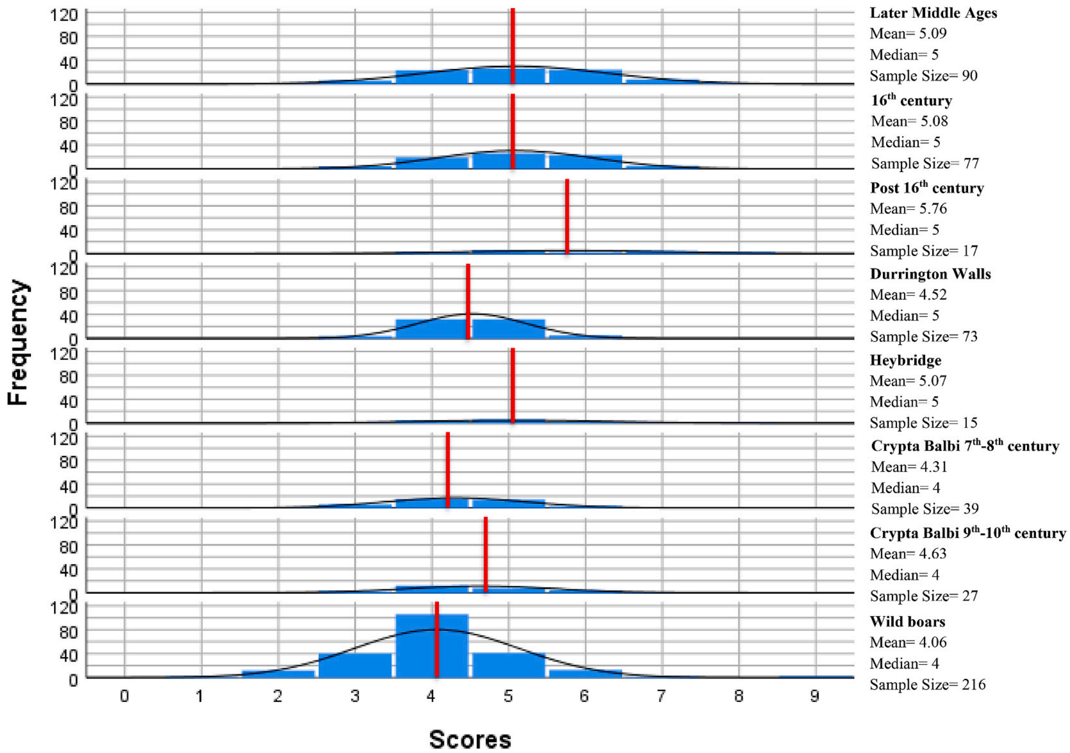


Fig. 10. Histogram showing the spread of data for each group for the combination M_2/M_3 (wear *versus* eruption). The red vertical line shows the Mean while the black line shows the distribution curve for each sample. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

4.1. Assessment of the wear rate in our samples

The core aim of this paper was to propose a simple, and therefore accessible, method to measure wear rate in pig teeth from archaeological sites. Once the method was developed (cf. Methods, Section 2.2), it was important to apply it to a real archaeological case study, to explore the extent to which it could be effective (cf. Results, Section 3).

The case study allowed us to address two core research questions. Firstly, we wanted to assess the degree of variability in the tooth wear rate of the various assemblages we studied. Secondly, we wanted to investigate whether any potential differences could be linked to changes in dietary regimes, as known from the literature dealing with the Late Medieval and Early Modern periods in England (cf. Introduction, Section 1).

Microwear studies have demonstrated that there is a relationship between types of food ingested and wear patterns in teeth (Mainland, 1998, 2003; Merceron et al., 2010), though it is unknown to what extent this also affects macrowear. Larsson et al. (2005) found craniofacial and dentofacial differences in modern pigs fed on very different diets. According to their research, the occlusal attrition on the lower molars was extreme in pigs fed on a hard diet, rich in silicates. However, it is important to consider that these modern animals were fed on highly different diets: a hard diet, requiring very high chewing activity, and a soft diet, which was almost liquid. Such a dichotomy in feeding regimes would not have existed in the past: during the pannage season, pigs fed on woodland resources but, during the rest of the year, alternative food sources were used. When pigs began to be more regularly penned throughout the year, they were fed on a variety of foods, taking advantage of their adaptability (Grigson, 1982; Schley and Roper, 2003). The diet of Medieval and Early Modern pigs, despite gradually shifting through time from a more foraging-based diet to a more human-controlled diet, was more diversified than that of the animals featured in Larsson et al.'s experiment.

The analysis of our Medieval and Early Modern assemblages, based on both tooth wear rate (TWR) and average wear rate (AWR) has not highlighted noticeable differences in the speed of wear, at both the level of the site and the broad chronological periods. Generally, differences in tooth wear rates were statistically insignificant. This does not mean that no differences occurred, but simply that these were not of a scale that would seriously affect the comparability of age profiles. The degree of variability and difference in and between the compared groups was, however, difficult to assess as, due to the novelty of the approach, we did not have a yardstick to compare them with. This is why we also analysed tooth wear rates in several outgroups to provide further elements of comparison.

When we introduced a number of tooth wear datasets from substantially different pig populations into the analysis, highly significant differences emerged between some of the outgroups and the core investigation samples. This showed that the potential degree of variability in pig tooth wear rates was much greater than we could assess through the analysis of the English Medieval and Early Modern samples.

Table 16 summarises the differences that emerged between the core sample and the outgroups and highlights how the outgroups, with the possible exception of Crypta Balbi 9th-10th century and Heybridge,

Table 16
Summary of the probability levels from the Kruskal-Wallis test and the AWR values for each tooth combination for the whole sample including the outgroups. Probability levels are as explained in Table 4.

Medieval and Early Modern Sites (M_1/M_2 all)				
Outgroups	Later Middle Ages 4.01	16th century 3.96	Post 16th century 3.70	AWR
Durrington Walls	***	–	–	**3.55**
Heybridge	–	–	–	**3.89**
Crypta Balbi 7th-8th century	***	***	*	**2.96**
Crypta Balbi 9th-10th century	–	–	–	**3.89**
Wild boars	***	*	–	**3.57**
Medieval and Early Modern Sites (M_2/M_3 all)				
Outgroups				
	4.49	**4.71**	**4.83**	**AWR**
Durrington Walls	***	***	**	**3.75**
Heybridge	–	*	–	**3.93**
Crypta Balbi 7th-8th century	**	***	*	**3.79**
Crypta Balbi 9th-10th century	–	–	–	**4.07**
Wild boars	***	***	***	**3.55**
Medieval and Early Modern Sites (M_1/M_2 wear *versus* eruption)				
Outgroups				
	5.12	**5.20**	**4.93**	**AWR**
Durrington Walls	–	–	–	**4.88**
Heybridge	–	–	–	**4.29**
Crypta Balbi 7th-8th century	*	*	–	**3.33**
Crypta Balbi 9th-10th century	–	–	–	**5.25**
Wild boars	–		–	**4.74**
Medieval and Early Modern Sites (M_2/M_3 wear *versus* eruption)				
Outgroups				
	5.09	**5.08**	**5.76**	**AWR**
Durrington Walls	–	–	*	**4.52**
Heybridge	–	–	–	**5.07**
Crypta Balbi 7th-8th century	*	*	**	**4.31**
Crypta Balbi 9th-10th century	–	–	–	**4.63**
Wild boars	***	***	***	**4.06**

have consistently lower average wear rates (AWRs for each site per chronological phase and tooth combination are given in Supplementary Material 3). This means that their molars wore more slowly than in the Medieval and Early Modern samples.

These differences must be partly due to variable diets, but it is worth considering that Medieval and Early Modern English pigs, likely to have been subjected to different dietary regimes, did not display such degrees of difference. It is therefore likely that there are other contributing factors. One of these could potentially be a difference in tooth eruption times between wild boar and 'primitive' domestic pigs on the one hand and 'improved' breeds on the other, which was suggested by old literature (e.g. Brown, 1882; Nehring, 1888; Simonds, 1854). However, Legge's (2013) comprehensive review has shown that there is insufficient evidence to support such a claim. Additionally, our estimates of wear speed are based on relative differences between teeth, rather than absolute values. Consequently, to explain differences in tooth wear rate between populations based on differences in eruption timings, it would be necessary not just for such timings to be different for the whole dentition, but also that the delay in the eruption of a molar in comparison to another would need to be variable. In other words, we would need that in one population the second molar erupted, for instance, four months after the first and in another, the delay would have to be of eight months. Such variation is not inconceivable, but, currently, there are no data supporting it. Future studies may provide the opportunity to review this subject further but, based on current evidence, this does not seem to be the most likely explanation for the variation in tooth wear rates.

Another possibility is represented by differences in the histological properties (hardness and thickness of the enamel in particular) of the molars of wild boars, primitive domesticates, and improved animals; or even just different populations and breeds. This would affect wear rates, as a thicker and harder enamel would slow down the process of dentine exposure. Studies on the histological variation of animal teeth are few (cf. Grüneberg, 1952; Robinette et al., 1957), and none focus on pig teeth. However, those studies do point out that histological intraspecific variation does occur.

In their natural environment, wild boars are opportunistic omnivores, and feed predominantly on plants, including roots, fruits, stems and leaves, and acorns and beechmast when available (Hamilton et al., 2009). With such feeding habits, heavily based on hard food with a highly abrasive component, it would make sense, from an adaptive point of view, for the wild boar teeth to be resistant to wear. The constant abrasion produced by the process of mastication should not cause a rapid loss of enamel and dentine, compromising the ability of the animal to process food and, therefore, survive. This premise could explain why the AWR for the modern wild boar sample used in this study is among the lowest, while the AWRs for the English historical sites are higher. The animals from the Late Medieval and Early Modern period sites had been subjected to millennia of human selection and may have developed a thinner enamel which was subject to more rapid wear. Thick enamel, like long snout or large tusks, no longer represented an adaptive advantage and therefore it may have stopped being selected for. Additionally, these pigs, even those still kept free-range according to the pannage system, no longer had a possibility of interbreeding with wild boars, as these were extinct in Britain by that time (Albarella, 2010).

To understand why both Durrington Walls and Crypta Balbi 7th and 8th century have provided low AWR values, we need to consider the pig management adopted at each site. In Neolithic Britain, domestic pigs most likely shared the same habitat with their wild progenitors. The association of domestic pigs with human settlements was most likely loose and, as such, pigs shared very little of the human food-chain (Hamilton et al., 2009). This loose husbandry regime meant that the animals were free to roam in the woodland, making human control over their reproductive behaviour impossible. In other words, they were free to frequently interbreed with the wild stock. Given this premise, it is possible that Neolithic pigs, even though domestic, could retain 'wild' histological traits due to the frequent contribution of wild boar to the gene pool. It is difficult to make any specific consideration about pig husbandry techniques for Durrington Walls, as the site was focused on consumption rather than production. Isotopic analysis has demonstrated that animals bred in other areas were brought to the site to be slaughtered (Evans et al., 2019; Madgwick et al., 2019; Viner et al., 2010). Biometrically, the pigs from Durrington Walls have been proven to be largely domestic (Albarella and Payne, 2005), but it is possible that, because of the frequent introgression with wild boar, they retained the 'wild' histological components which, in turn, would explain the low AWR. For domestic pigs, these animals are also rather large, which supports the view of some potential interbreeding with wild boar (Viner, 2011; Viner-Daniels, 2014). We must also consider that the Durrington Walls pigs are several millennia older than those of our core case study, and therefore they were less modified from the original wild boars.

The case of the site of Crypta Balbi in Rome is rather different. The zooarchaeological study of the pig bones from this site has revealed an interesting biometric pattern (Albarella et al., 2019). Both pig post-cranial bones and teeth increased in size in the 7th and 8th century while, in the following 9th and 10th centuries, they decreased. Since the size increase affected both post-cranial bones and the more conservative teeth, the phenomenon has been explained with a possible genotypic change. Following the collapse of the Empire, the city of Rome changed significantly and, in this context, it is likely that the sty keeping regimes usually adopted in Roman times were less strictly practiced. As such, locally raised free-range pig herds entered into regular contact with the larger wild boar and interbred. This would explain the size increase of the 7th-8th century. On the contrary, the reduction in the size of the pigs in the 9th-10th century has been linked to a better enforced reproductive separation from the wild. Our results fit very well with this interpretation: the animals from Crypta Balbi 7th and 8th century, which were likely mixed with wild stock, have a slower AWR, more similar to the AWR of the modern wild boar sample than to the animals from 9th-10th century Rome and the English Medieval and Early Modern sites.

Among the outgroups, the Late Iron Age and Romano-British site of Heybridge has revealed a wear rate that is only slightly lower than that from the English Medieval and Early Modern sites. The Heybridge pigs are likely to have been domestic (Johnstone and Albarella 2015). We know from archaeological (Carandini and Ricci, 1985; King, 1985), textual (Columella, 1977; Varro, 1935) and artistic evidence (MacKinnon, 2001) that the Romans kept pigs in a variety of ways, including in sties. A microwear study conducted by Wilkie et al. (2007) on the pig teeth from Heybridge confirms that the latter was most likely the case at that site: the micro-patterns and structures observed on the occlusal surface are indicative of consumption of soft textured foods with limited access to soil for rooting, and were interpreted as consistent with sty keeping. A closely controlled husbandry regime, where there was very little opportunity for the domestic pigs to interbreed with wild stock, is consistent with our results: the pigs from Heybridge have shown to have a faster AWR, generally more similar to the AWR values of the Medieval and Early Modern samples.

In conclusion, it seems plausible that the slower AWR obtained for some of the outgroups is due to the existence or retention of wild histological traits that made the teeth of these pig populations more resistant to wear. However, this is just a working hypothesis and it would be of great interest to establish whether such traits can be histologically identified and to elucidate the processes through which they are inherited. We hope that our study will act as a springboard for further studies to be carried out and additional evidence to be gathered on this topic.

4.2. *Reflections on the proposed methodology to measure tooth wear rate*

O'Connor (2003: 163–164) highlighted very effectively one of the main problems affecting all methodologies based on tooth wear to reconstruct mortality profiles when he wrote: "*the attribution of calendar ages to mandibles on the basis of the state of attrition attained by the teeth at the time of death depends on the assumption that attrition is sufficiently constant between samples and between modern and archaeological material to allow us to make comparison*".

Therefore, it should be clear that to improve the reliability of our comparisons of kill-off patterns, we need to establish whether tooth wear rates are comparable between assemblages. The method presented in this paper offers an opportunity to do so. We suggest that the calculation of tooth wear rates (TWR) and average wear rates (AWR) should become standard practice in zooarchaeological analysis, at least in those cases where there are enough mandibles to attempt the reconstruction of a mortality curve. The system can be also easily extended to maxillary teeth, for instance by using Wright et al.'s (2014) wear recording system as a base, and to other species. In fact, we do have work in progress on cattle to do exactly that (Hood et al. in prep).

Ideally, it is desirable to provide different values for the M_1/M_2 and M_2/M_3 pairs, as done in this paper. This provides better resolution and also the opportunity to monitor potential differences between the two pairs, which may be related to changes that occurred during the animals' lives (e.g. in diet, environmental conditions, husbandry practices, etc.). However, to increase sample size – unfortunately, at the expense of resolution – researchers may also want to consider combining data from the two pairs.

Our English Medieval and Early Modern case study has provided reassuring evidence, indicating that the wear rates in the two periods are not sufficiently different from each other to invalidate a comparison of age profiles. However, comparisons with outgroups have alerted us to the fact that more substantial differences can occur between pig populations, especially when wild and domestic, and/or pigs from very different periods are compared. Wild boar tooth samples may give the impression to be younger than domestic pigs, when differences in wear patterns may be merely a consequence of a slower wear rate. Therefore, *a priori* assumption of equal wear rates would be unwise and verification is needed in all cases.

Our work has also shown that, although differences in diets will certainly affect the speed of wear, these do not seem to represent the most important factor. Differences between pig populations, possibly related to their genetic make-up and population histories may well be the most important underlying reasons behind variability in wear rates. This will, however, need to be verified by further research. The key purpose of this paper is rather to provide an appropriate and user-friendly methodology to establish the speed of tooth wear in pigs and emphasise, through examples, the need to undertake this analysis to formulate reliable archaeological interpretations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2021.105331.

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