Calculus and survivorship in medieval London: The association between dental disease and a demographic measure of general health

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Abstract

Objectives: Dental plaque is associated with a variety of systemic diseases and mortality risks in living populations. However, bioarchaeologists have not fully investigated the mortality risks associated with plaque (or its mineralized form, calculus) in the past. This study examines the relationship between survivorship and calculus in a medieval skeletal sample.

Materials and methods: Our sample (n = 1,098) from four medieval London cemeteries, c. 1000–1540 CE, includes people who died under attritional (normal) and catastrophic (famine and plague) conditions. The associations between age and the presence of dental calculus on the permanent left first mandibular molar are assessed using binary logistic regression and Kaplan–Meier survival analysis.

Results: The regression results indicate a significant negative relationship between age and calculus presence for individuals of all ages who died under normal mortality conditions and for adults who died under both normal and catastrophic conditions. Survival analysis reveals decreased survivorship for people of all ages with calculus under normal mortality conditions. Similarly, during conditions of catastrophic mortality, adult males with calculus suffered reduced survivorship compared to males without it, though there was no difference in survivorship between adult females with and without calculus.

Conclusions: These results suggest that, as in modern populations, calculus accumulation in the inhabitants of medieval London reflects a greater risk of premature death. The evaluation of calculus, a potential measure of underlying frailty, in the context of a demographic measure of general health suggests that it might provide insights into health in past populations.

KEYWORDS
binary logistic regression, bioarchaeology, mortality, paleodemography, paleopathology, survival analysis

1 | INTRODUCTION

This study examines the relationship between dental calculus and survivorship in medieval London. During life, dental calculus begins as dental plaque, a clear bacterial biofilm that coats the teeth. The biofilm is first formed when salivary proteins adhere to the teeth, protecting the enamel of the tooth from acid or bacterial demineralization (Siqueira, Custodio, & McDonald, 2012). Shortly after this protective pellicle forms, oral bacteria such as Streptococcus sanguis begin adhering to the tooth surface. Following the initial adhesion of pioneering bacteria to the enamel pellicle, other bacterial species colonize the plaque by attaching to the original layer of bacteria and bacterial biproducts (Rosan & Lamont, 2000). During life, dental plaque can accumulate, in some cases mineralizing periodically to become tartar or calculus. Dental calculus consists of mineral components, primarily calcium phosphates derived from saliva or gingival crevicular fluid, as well as organic and inorganic components introduced by bacteria, saliva, diet, or environmental exposure during or shortly after the mineralization process (Warinner, Speller, & Collins, 2015; White, 1991). The rate at which calculus and the overlying plaque accumulates varies among individuals and depends to a great extent on culturally-mediated oral hygiene practices, as well as factors like diet, oral fluid
alkalinity and composition, salivary flow rate, and hydration (Lieverse, 1999; Lieverse, Link, Bazaliyski, Gorinovoa, & Weber, 2007).

The accumulation of plaque is a serious matter in modern populations, as it has been connected to oral infections—such as caries and periodontal disease (Peterson et al., 2013; Wang et al., 2013)—as well as systemic health risks, such as coronary heart disease (DeStefano, And, Kahn, Williamson, & Russell, 1993), respiratory infections in the elderly (Sumi, Miura, Yukihiro, Nagaosa, & Nagaya, 2007), and all-cause mortality (i.e., all of the deaths that occur in a population or clinical study, regardless of cause; DeStefano et al., 1993; Jansson, Lavstedt, & Frithiof, 2002). In a longitudinal study of 1,390 Swedish adults without periodontal disease, Söder, Yakob, Meurman, Andersson, and Söder (2012) found dental plaque to be associated with a 79% increase in the liability of suffering premature death because of cancer. Males and females with less dental plaque were found to live 8.6 and 13.1 years longer, respectively, than those with more extensive plaque (Söder et al., 2012). Söder, Meurman, and Söder (2014) found that, when controlling for age, sex, dental visits, and other factors, a high calculus index (severity) score was associated with more than double (2.3x) the liability of suffering from premature death from heart infarction (p = .038). Another study, by Adolph et al. (2017), indicated that risks of all-cause, all-cancer, and noncardiovascular/noncancer mortality were higher for individuals with a high degree of gingival inflammation and an abundance of plaque matter and supragingival calculus.

Although dental plaque coats the teeth and covers all calculus deposits during life, this biofilm does not necessarily mineralize into calculus in all instances and does not preserve archeologically, making it unavailable for direct study by bioarchaeologists. In contrast, dental calculus is considerably more durable and has proven ubiquitous in the archeological record, occurring in human populations throughout history (Adler et al., 2013), as well as in the Neanderthals (Henry, Brooks, & Piperno, 2011) and Australopithecines (Henry et al., 2012). A recent surge in calculus studies facilitated by technological advances have dramatically expanded our understanding of health states (De La Fuente, Flores, & Moraga, 2012; Warinner et al., 2014; Warinner et al., 2015) and diets (Fox, Juan, & Albert, 1996; Warinner et al., 2014; Weyrich et al., 2017) in the past. However, these studies have primarily focused on identifying and analyzing the microscopic components of dental calculus, rather than the effects of those components on morbidity or mortality patterns at the population level.

The observed associations between dental plaque or calculus and risks of morbidity and mortality in living populations raise the question of whether such associations existed in past populations and thus whether dental calculus might therefore be a useful indicator of health in bioarchaeological studies. Bioarchaeology and paleopathology, in general, face a significant challenge of defining health in a way that is consistent with definitions used in studies of living populations and is also feasible to assess using samples of human skeletal remains, which are biased for a variety of reasons and unlikely to be perfect representations of living populations (Milner, Wood, & Boldsen, 2008; Reitsema & McIvaine, 2014; Temple & Goodman, 2014). Bioarchaeologists must also grapple with the challenges posed by the osteological paradox, that is, the effects of heterogeneous frailty and selective mortality, and the possibility that skeletal lesions might not, in every context, indicate poor health, as is often assumed (DeWitte & Stojanowski, 2015; Wood, Milner, Harpending, & Weiss, 1992). In light of these challenges, one possible approach to assessing health in the past using human skeletal remains is to analyze skeletal pathology in the context of demographic information, such as life expectancy and risks of mortality, which are widely used as measures of the general, underlying health of living populations. Finding an association between dental calculus and mortality would potentially improve studies of health in the past given the relative ease of macroscopically identifying the presence of calculus and the fact that teeth preserve relatively well in the bioarchaeological record. An evaluation of this relationship is particularly timely given the recent surge of interest in dental calculus in paleogenomic and paleomicrobiomic studies.

Few studies have analyzed the relationship between calculus presence and mortality patterns in archeological samples. Scholars examining dental calculus prevalence in the archeological record have reported differences in presence or severity by age, but they rarely comment on the patterns in their discussions. Moreover, the nature of the associations observed often differs by study or skeletal collection, suggesting that the relationship between dental calculus and mortality is context-dependent. For example, a study of 791 individuals from the central highland and coastal regions of prehispanic Gran Canaria found significant associations between age at death and calculus deposition using Chi-square tests (χ² = 40.77, p < .001), between age at death and calculus deposition using stepwise logistic regression analysis (B = −0.47, Wald = 4.80, p = .027), and between age at death and the proportion of teeth with calculus deposition using Kruskal–Wallis tests (KW = 28.31, p < .001). Specifically, calculus deposition was more common in adults under 45 years of age compared to adults over 45 years of age (Delgado-Darias, Velasco-Vázquez, Arnay-de-la-Rosa, Martin-Rodríguez, & González-Reimers, 2006). In a different context—a study of 19th-century soldiers—Palubeckaitė et al. (2006) found no relationship between age at death and prevalence of calculus, although this particular finding may be related to the nature of their study population, which primarily consisted of males under 35 years of age who died of cold, hunger, and exhaustion in December of 1812. In contrast, a study of two cultural groups from the Cis-Baikal region of Siberia generally indicated higher calculus frequencies with increasing age at death for individuals between 20 and 50 years of age, coupled with a reduction in frequency thereafter for one of the groups (no calculus data were available for individuals aged 50+ years in the other group; Lieve et al., 2007). Similarly, a study of Late Antique (3rd–6th centuries AD) and Early Medieval (7th–11th centuries AD) Croatian populations found higher rates of calculus among older individuals (aged 36+ years, compared to individuals <35 years of age) during both periods (Šlaus, Bedić, Rajić Šikanjić, Vodanović, & Đomić Kunić, 2010). A study of individuals from the Greek colony of Apollonia (5th–2nd centuries BC) suggested an increase in the frequency of calculus with age when the data were analyzed at the level of the tooth (with a less-clear pattern of calculus presence when assessed among individuals; Keenleyside, 2008). Both Keenleyside (2008) and Šlaus et al. (2010) acknowledge the trend in their discussion briefly, describing a similar progressive accumulation of calculus...
with age identified in some modern populations (Beiswanger, Segreto, Mallatt, & Pfeiffer, 1989).

Studies of the relationship between sex and calculus formation have not revealed a consistent correlation. In living populations, some studies have suggested males are more likely to form calculus and accumulate a greater amount of calculus compared to females (Beiswanger et al., 1989; Buckley, 1980), but the results of other studies have not been consistent with this finding (Macpherson, Girardin, Hughes, Stephen, & Dawes, 1995). A similar pattern has been observed in archeological contexts, with some studies suggesting that males tend to develop calculus more readily than females. Evidence from the Mesolithic period in Ukraine suggests that males exhibited significantly higher observed incidences of calculus, which the authors suggest may reflect sex-based differences in access to and consumption of protein (Lillie & Richards, 2000). Studies from other archeological contexts have found a trend of increased dental calculus formation in males, but none of the results were statistically significant and, in one case, the relationship was not consistently observed for all the time periods analyzed (Delgado-Darias et al., 2006; Keenleyside, 2008; Šlaus et al., 2010). In summary, a variety of age- and sex-associated patterns of dental calculus presence or severity have been observed in bioarchaeological studies, but what is missing is an explicit evaluation of the effects of calculus presence on demographic outcomes, and by inference, general health in past populations.

In order to explore the relationship between dental calculus and risk of mortality in the past more explicitly, this study analyzes the association between macroscopically identified dental calculus and age at death using binary logistic regression and Kaplan–Meier survival analysis. In particular, this project examines how calculus accumulation is associated with the survivorship of individuals in medieval London. Previous research using medieval London cemetery samples has revealed a positive association between two other oral health indicators (dental carious lesions and periodontal disease) and mortality (DeWitte & Bekvalac, 2010). Demonstrating a similar association between dental calculus and mortality in medieval London would broaden our understanding of the links between oral health and general health in this particular context. By investigating the relationship between dental calculus and mortality directly, this study extends current research on the effects of oral health on systemic health in a novel context and evaluates the value of calculus as a macroscopic indicator of frailty and mortality risk in human remains recovered from bioarchaeological contexts.

# 2 | MATERIALS AND METHODS

## 2.1 | Skeletal samples

The skeletal samples \( n = 1,098 \) for this study come from four cemeteries that were in use during the medieval period in London: Guildhall Yard East, East Smithfield, St. Mary Graces, and St. Mary Spital. The Guildhall Yard East cemetery was in use from the 11th century through the early 13th century. The burials \( n = 34 \) used in this study come from two periods (Periods 10 and 11) that date to 1050–1150 and 1140–1230, respectively (Bowsher, Dyson, Holder, & Howell, 2007). The East Smithfield Black Death cemetery was established in the mid-14th century for the sole purpose of burying victims of the Black Death, which affected London from 1349 to 1350 (Grainger, Hawkins, Cowal, & Mikulski, 2008). This study includes a sample of 269 individuals from East Smithfield. The St. Mary Graces cemetery was associated with the Cistercian abbey of the same name and was used from 1350 until its closure in 1538. Included in the St. Mary Graces cemetery are victims of a later 14th century plague epidemic (the plague of 1361 or another outbreak that occurred after the Black Death). The plague burials are located in an area of the churchyard spatially distinct from the rest of the burials at St. Mary Graces; they are close to the Black Death burials in the underlying East Smithfield cemetery \( (c. 1349–1350) \) and far from the abbey. In contrast, the non-plague burials are located close to or within the Abbey \( (\text{Bos et al., 2016; Gl Christoph & Sloane, 2005; Grainger & Phillpotts, 2011; Sloane, 2011}) \).

Ancient DNA analyses have revealed the presence of DNA in an individual buried in the plague area of St. Mary Graces that is unique to Yersinia pestis—the bacterium that caused the earlier Black Death and continues to cause bubonic plague today (Bos et al., 2016), confirming archeological evidence that these burials contain plague victims. This study uses a combined sample of 181 individuals from St. Mary Graces, of which 76 are from the non-plague burials and 105 are from the plague burials. The samples selected from Guildhall Yard, East Smithfield, and St. Mary Graces include all the individuals excavated from those cemeteries for whom age at death could be estimated using the methods described below and who had permanent left mandibular first molars (LLM1s).

The St. Mary Spital (SRP98) cemetery was used throughout the medieval period, opening around 1120 and closing in 1539 (Connell, Jones, Redfern, & Walker, 2012). Bayesian radiometric dating was used to divide the St. Mary Spital burials into four distinct periods: Period 14 \( (c. 1120–1200) \), Period 15 \( (c. 1200–1250) \), Period 16 \( (c. 1250–1400) \), and Period 17 \( (c. 1400–1539) \) (Sidell, Thomas, & Bayliss, 2007). Additionally, the St. Mary Spital burials are categorized into four types: Type A (individual burials), Type B (small group burials with 2–7 bodies aligned horizontally), Type C (small group burials with 2–11 bodies stacked vertically in a single column), and Type D (larger group burials of 8–45 individuals and consisting of multiple rows of horizontally-arranged bodies stacked on top of each other). The Type D burials are believed to contain victims of famine-related catastrophic mortality, whereas Types A, B, and C are viewed as representing normal (“attritional”) mortality (Connell et al., 2012). During Period 16 \( (c. 1250–1400) \), there were several major demographic and subsistence crises in England, including the Great Famine of 1315–1317, during which an estimated 10–15% of the population of England and Wales died from starvation or disease (Campbell, 2016; DeWitte & Slavin, 2013); the Great Bovine Pestilence in 1319–1320, which killed 62% of bovine populations and led to dairy resource scarcities that lasted until the early 1330s (DeWitte & Slavin, 2013; Jordan, 1996; Slavin, 2012); and the Black Death in 1348–1350, which killed 30–60% of the population. The current study uses individuals from St. Mary Spital for whom ages were estimated (using the methods described below) for previous research that focused on pre- vs. post-Black Death trends in demography and on patterns of selective mortality during medieval famine events (DeWitte, 2014, 2018;
DeWitte & Wood, 2008; Yaussy, DeWitte, & Redfern, 2016). Because it is currently not feasible to distinguish between famine and plague burials from Period 16, and the possibility that Type A burials from this period might include famine or plague victims, the burials from this period were excluded from the sample. Thus, this study uses burials just from Periods 14 (n = 139), 15 (n = 297), and 17 (n = 178) from St. Mary Spital.

2.2 | Dental calculus

The dental calculus data used for this study were collected by researchers at Museum of London Archeology (MoLA) and were obtained from the Wellcome Osteological Research Database (WORD). The severity and location of calculus deposits were recorded in WORD following Brothwell (1981). For this study, individuals with calculus severity scores (1 = slight, 2 = medium, and 3 = heavy) were combined following Brothwell (1981). For this study, individuals with calculus deposits were recorded in WORD obtained from the Wellcome Osteological Research Database (WORD). The severity and location of calculus deposits were recorded in WORD obtained from the Wellcome Osteological Research Database (WORD). The severity and location of calculus deposits were recorded in WORD obtained from the Wellcome Osteological Research Database (WORD).

2.3 | Age estimation

Ages were estimated for all individuals in this study by the authors. Adult age at death was estimated using transition analysis. Transition analysis uses maximum likelihood estimation to produce point estimates of age for even the oldest individuals in a collection. This method avoids several of the shortcomings of conventional age estimation methods, such as broad terminal age categories and mimicry of the age-at-death distribution of the known-age reference sample. Additionally, transition analysis accommodates the fragmented skeletal remains and small sample sizes typical of bioarchaeological collections (Boldsen, Milner, Konigsberg, & Wood, 2002). For this study, transition analysis was applied to skeletal age indicators on the pubic symphysis and the iliac auricular surface and to cranial suture closure as described by Boldsen et al. (2002), and the Anthropological Database, Odense University (ADBOU) Age Estimation software was used to determine individual ages-at-death (using an informative prior distribution of ages at death based on data from 17th-century Danish rural parish records). Ages for nonadult individuals (i.e., those individuals for whom all epiphyses had not yet fused) were estimated based on epiphyseal fusion, and dental development and eruption (Buikstra & Ubelaker, 1994; Gustafson & Koch, 1974; Moorrees, Gran, Lebret, Yen, & Fröhlich, 1969; Scheuer & Black, 2000; Scheuer, Musgrave, & Evans, 1980; Smith, 1991).

2.4 | Sex determination

Sex was determined for adults based on sexually dimorphic features of the skull and pelvis using the standards described in Buikstra and Ubelaker (1994). The following dimorphic features of the skull and pelvis were scored: glabella/supraorbital ridge, supraorbital margin, mastoid process, external occipital protuberance/nuchal crest, mental eminence, ventral arc of the pubis, subpubic concavity, ischiopubic ramus ridge, and the greater sciatic notch.

2.5 | Binary logistic regression and Kaplan–Meier survival analysis

The association between age at death and calculus presence was analyzed using binary logistic regression and Kaplan–Meier survival analysis with SPSS version 25. Both analyses were conducted on the full combined sample ("all sites", i.e., all sites and all burial types; n = 1,098) and two different subsamples that were selected to represent attritional (normal) and catastrophic (famine, plague) mortality. The "attritional" sample (n = 421) includes the Guildhall Yard East burials, the nonplague burials from St. Mary Graces, and the Type A/B/C burials from St. Mary Spital. The "catastrophic" sample (n = 677) includes the East Smithfield burials, the plague burials from St. Mary Graces, and the Type D burials from St. Mary Spital. Following initial analyses that included all ages, these analyses were repeated with subsamples limited to individuals above the age of 20 years in each of the "all sites," "attritional," and "catastrophic" samples, for the reasons described below. Given the possibility of sex differences in dental calculus, analyses were also performed separately on the adult females and males from the "all sites" (female n = 279, male n = 323), "attritional" (female n = 116, male n = 125), and "catastrophic" (female n = 163, male n = 198) samples.
3 | RESULTS

The age-at-death distributions of individuals with and without dental calculus within each of the “all sites,” “attritional,” and “catastrophic” samples are shown in Table 1. In each case, the frequency of dental calculus increases with age up to a certain point in adulthood (the timing of peak frequency varies across samples) and then declines. In all samples, frequencies of calculus are lowest among individuals ages 0–9.99 years, and the frequencies for individuals above the age of 60 are lower than they are for any other age category except the youngest (0–9.99). Chi-square analyses (Table 2) of sex differences in the frequency of dental calculus reveal consistently higher frequencies of calculus in females across all samples, but the observed difference between the sexes is significant only for the “all sites” sample. The results of binary logistic regression are shown in Table 3. Analyses of (a) the complete sample (“all sites”) with all ages and pooled-sexes included and (b) the female-only catastrophic sample do not reveal a significant relationship between age and the presence of dental calculus. However, analysis of the “catastrophic” sample with all ages and pooled-sexes included reveals a significant positive relationship between calculus presence and age, whereas analyses of all other subsamples (attritional sample with all ages, all subsamples of adults ages 20+) reveal significant negative relationships between age and calculus presence.

The Kaplan–Meier survival analysis results are shown in Table 4, and the corresponding survival curves are shown in Figures 1–12. Survival analyses of the complete (“all sites”) sample and the catastrophic sample, each with all ages included, do not reveal a significant difference in survivorship between individuals with and without calculus. Analysis of the attritional sample with all ages included does reveal significantly lower survivorship for individuals with calculus compared to those without calculus, though, as is also true for the “all sites” and “catastrophic” samples, the 95% confidence intervals for mean survival time for males with and without calculus, and the survival curves do not cross over (Figures 4 and 5). There is, however, overlap of the 95% confidence intervals and a crossover of survival curves (again in the mid- to late-20s) between those adults with and without calculus in the “catastrophic” sample. The sex-specific Kaplan–Meier analyses reveal significantly higher survivorship for both males and females without dental calculus compared those with dental calculus in nearly every case. The only exception to this general pattern was observed for adult females in the catastrophic sample. In this case, there was no significant difference in estimated survivorship between females with and without dental calculus and there is substantial overlap in the corresponding 95% confidence intervals for mean survival time. For males in the catastrophic sample, survivorship was higher for males without dental calculus, but there is an overlap in the 95% confidence intervals for mean survival time for males with and without dental calculus and the corresponding survival curves overlap until the late 20s.

4 | DISCUSSION

4.1 | Dental calculus and age

The binary logistic regression results reveal significant negative associations between dental calculus and age for most, but not all, of the

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sex</th>
<th>Calculus absent</th>
<th>Calculus present</th>
<th>Chi-square p</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sites</td>
<td>Female</td>
<td>79 (28.3%)</td>
<td>200 (71.7%)</td>
<td>.039</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>117 (36.2%)</td>
<td>206 (63.8%)</td>
<td></td>
</tr>
<tr>
<td>Attritional</td>
<td>Female</td>
<td>24 (20.7%)</td>
<td>92 (79.3%)</td>
<td>.187</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>35 (28%)</td>
<td>90 (72%)</td>
<td></td>
</tr>
<tr>
<td>Catastrophic</td>
<td>Female</td>
<td>55 (33.7%)</td>
<td>108 (66.3%)</td>
<td>.135</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>82 (41.4%)</td>
<td>116 (58.6%)</td>
<td></td>
</tr>
</tbody>
</table>

% = percentages of individuals within each category with or without dental calculus.
samples used in this study. Specifically, for adults in general (regardless of mortality conditions) and for the attritional sample including individuals of all ages, the regression results suggest that frequencies of dental calculus decrease significantly with age. The major exceptions to this pattern are the findings for the catastrophic sample that includes nonadults, in which case the regression results indicate a significant increase in dental calculus with age, and for adult females in the catastrophic sample, for which no significant association between dental calculus and age was found. As described above, and as seen in Table 1, frequencies of dental calculus are at their lowest among nonadults ages 0–9.99 across all samples. There is a substantial increase in frequencies among individuals ages 10–19.99, and thereafter frequencies remain high, with minor fluctuations, throughout most of adulthood until age 60. Thereafter, calculus frequencies decline rapidly, though they never decline to the levels observed among individuals of the earliest age category.

Previous studies have produced conflicting results regarding the relationship between calculus presence and age in modern populations. Scholars studying populations in the continental United States have found a positive relationship between calculus and age, suggesting that calculus accumulates over a lifetime (Beiswanger et al., 1989; Miller, Brunelle, Carlos, Brown, & Lee, 1987). However, other authors have suggested that the relationship may be context-dependent. In a study of individuals from modern-day Winnipeg, Canada and Glasgow, Scotland, only the Winnipeg data revealed a statistically significant positive correlation between age and calculus score (Macpherson et al., 1995). Likewise, a study comparing Sri Lankan tea laborers and Norwegian individuals suggested that dental calculus only accumulated in the population without access to regular dental care (Ånerud, Löe, & Boysen, 1991). Several years later, White (1997) would reiterate this result in a review of the literature, stating that, with regular oral hygiene, supragingival calculus is first observed in early adolescence and does not increase significantly with age. In contrast, individuals who are members of cultures in which there are no regular oral hygiene practices, supragingival and subgingival calculus can be expected to begin accumulating shortly after or within a decade of tooth eruption and will generally increase with age.

### TABLE 3

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sex/age</th>
<th>Odds ratio</th>
<th>95% CI</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sites</td>
<td>All ages and sexes</td>
<td>1.002</td>
<td>0.994–1.009</td>
<td>.623</td>
</tr>
<tr>
<td></td>
<td>Adults</td>
<td>0.971</td>
<td>0.961–0.982</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>Adult females</td>
<td>0.972</td>
<td>0.955–0.990</td>
<td>.002</td>
</tr>
<tr>
<td></td>
<td>Adult males</td>
<td>0.972</td>
<td>0.959–0.985</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Attritional</td>
<td>All ages and sexes</td>
<td>0.984</td>
<td>0.973–0.995</td>
<td>.005</td>
</tr>
<tr>
<td></td>
<td>Adults</td>
<td>0.944</td>
<td>0.927–0.961</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>Adult females</td>
<td>0.934</td>
<td>0.906–0.963</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>Adult males</td>
<td>0.952</td>
<td>0.931–0.974</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>All ages and sexes</td>
<td>1.011</td>
<td>1.001–1.022</td>
<td>.032</td>
</tr>
<tr>
<td></td>
<td>Adults</td>
<td>0.983</td>
<td>0.969–0.998</td>
<td>.027</td>
</tr>
<tr>
<td></td>
<td>Adult females</td>
<td>0.995</td>
<td>0.968–1.023</td>
<td>.708</td>
</tr>
<tr>
<td></td>
<td>Adult males</td>
<td>0.980</td>
<td>0.962–0.997</td>
<td>.025</td>
</tr>
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### TABLE 4

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sex/age</th>
<th>Calculus absent</th>
<th>Calculus present</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sites</td>
<td>All ages and sexes</td>
<td>26.49 (24.55–28.43)</td>
<td>27.0 (25.94–28.05)</td>
<td>.529</td>
</tr>
<tr>
<td></td>
<td>Adults</td>
<td>42.27 (39.66–44.89)</td>
<td>34.87 (33.59–36.14)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>Adult females</td>
<td>39.75 (35.86–43.65)</td>
<td>34.00 (32.39–35.61)</td>
<td>.004</td>
</tr>
<tr>
<td></td>
<td>Adult males</td>
<td>44.05 (40.54–47.57)</td>
<td>35.77 (33.80–37.74)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Attritional</td>
<td>All ages and sexes</td>
<td>33.45 (28.88–38.02)</td>
<td>27.81 (26.16–29.46)</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>Adults</td>
<td>53.30 (48.41–58.19)</td>
<td>35.89 (33.89–37.88)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>Adult females</td>
<td>53.72 (46.52–60.92)</td>
<td>35.25 (32.62–37.87)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>Adult males</td>
<td>52.99 (46.13–59.85)</td>
<td>36.70 (33.66–39.74)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>All ages and sexes</td>
<td>23.79 (21.83–25.74)</td>
<td>26.34 (24.98–27.70)</td>
<td>.248</td>
</tr>
<tr>
<td></td>
<td>Adults</td>
<td>37.48 (34.74–40.22)</td>
<td>34.03 (32.39–35.67)</td>
<td>.013</td>
</tr>
<tr>
<td></td>
<td>Adult females</td>
<td>33.66 (30.04–38.28)</td>
<td>32.94 (30.99–34.90)</td>
<td>.591</td>
</tr>
<tr>
<td></td>
<td>Adult males</td>
<td>40.24 (36.43–44.05)</td>
<td>35.05 (32.46–37.63)</td>
<td>.015</td>
</tr>
</tbody>
</table>

Mean survival times (mean ages at death) in years are shown with 95% confidence intervals in parentheses.
FIGURE 2 Kaplan–Meier survival curves for the "attritional" sample with all ages included

FIGURE 3 Kaplan–Meier survival curves for the "catastrophic" sample with all ages included

FIGURE 4 Kaplan–Meier survival curves for the "all sites" sample for individuals ages 20+ years

FIGURE 5 Kaplan–Meier survival curves for the "attritional" sample for individuals ages 20+ years

FIGURE 6 Kaplan–Meier survival curves for the "catastrophic" sample for individuals ages 20+ years

FIGURE 7 Kaplan–Meier survival curves for the "all sites" adult female sample
until about 30 years of age (White, 1997). The calculus frequencies observed in our samples appear to follow a similar trend, at least until age 60.

In general, individuals from medieval London did not receive regular, effective dental care. Although medieval Europeans viewed clean, white teeth and fresh breath as desirable, dental cleaning was not common (Newman, 2001). Among the few medieval texts to mention teeth cleaning, the medical treatise “Chirugia Magna” of Guy de Chauliac advocates removing heavy deposits of calculus with a file (Anderson, 2004). Overall however, methods for removing plaque and calculus were not widely used. The dental hygiene practiced by most individuals amounted to picking food out from the teeth, whereas more “refined” individuals may have used mouth rinses or gargles of wine or vinegar periodically, scrubbed their teeth with cloths while bathing, or chewed on reedy plants known as “mallows” (Newman, 2001). A lack of consistent, effective dental treatment likely allowed the accumulation and retention of dental calculus leading up to and continuing throughout most of adulthood. The relatively low

![Kaplan-Meier survival curves for the “all sites” adult male sample](image8)

![Kaplan-Meier survival curves for the “all sites” adult female sample](image9)

![Kaplan-Meier survival curves for the “attritional” adult male sample](image10)

![Kaplan-Meier survival curves for the “attritional” adult female sample](image11)

![Kaplan-Meier survival curves for the “catastrophic” adult male sample](image12)

![Kaplan-Meier survival curves for the “catastrophic” adult female sample](image13)
frequencies of calculus among individuals above the age of 60 in our samples suggests that individuals without calculus were more likely to survive to the latest adult ages. The regression results might reflect the effects of selective mortality, that is the disproportionate deaths of frail individuals (with dental calculus) during early and middle adulthood and thus the production of late-age cohorts with relatively little calculus.

4.2 | Dental calculus and survivorship

The Kaplan–Meier survival analyses reveal a consistent negative association between calculus presence and survivorship for adults in both atrialtrional (normal) and catastrophic conditions (i.e., periods of famine and plague) in medieval London. These findings suggest the accumulation of dental calculus is associated with relatively high underlying frailty and thereby enhanced risks of mortality in medieval London. The possible inclusion of false-negatives for dental calculus (i.e., individuals who had dental calculus at the time of death but were not scored as “present” for the pathology because of its loss during excavation, washing, or handling during research projects) means that we might have underestimated the true difference in survivorship between those with and without dental calculus. This does not pose a concern, as it suggests that the differences in survivorship might have been even more dramatic than indicated by the results of our analyses.

The relationship between the accumulation of dental calculus and systemic health and risk of mortality suggested by our findings—and that has been observed in studies of living people—is likely indirect and may be related to the density of microorganisms that colonize plaque and calculus deposits. Estimates of bacterial magnitude have exceeded $10^{11}$ microorganisms per milligram of dental plaque, with over 400 different bacterial species inhabiting the biofilm (Li, Kolteveit, Tronstad, & Olsen, 2000; Paster et al., 2001). Although healthy individuals often present with the same oral microorganisms as those with oral infections, it is a shift in the microbial ecology of dental plaque from gram-positive, aerobic flora to gram-negative, anaerobic flora that signals a transition from a healthy to diseased mouth (Moutsopoulos & Madianos, 2006). Increases in the number of bacteria colonizing the plaque biofilm provide more opportunities for bacteria or bacterial components such as endotoxins and outer membrane proteins to enter the bloodstream and migrate to distant portions of the body, causing or affecting susceptibility to systemic disease. Such an increase in bacteria in the oral biofilm can also lead to inflammation that has both local and distant effects that can produce negative health outcomes.

Though dental procedures and physical insults to the oral epithelium can afford bacteria (or components thereof) in dental plaque access to the bloodstream briefly, this pathway usually poses no significant danger and threats are rapidly eliminated by the reticuloendothelial system (Li et al., 2000). However, as mentioned above, the accumulation of plaque is associated with the development of other oral health disorders, such as gingivitis and periodontal disease (periodontitis). Gingivitis is an inflammation of the gingiva (gum), and periodontitis is an infection that causes inflammation and destruction of gum tissue (gingivitis), the periodontal ligament, root cementum, and alveolar bone. Gingivitis and periodontitis are caused by bacteria present in dental plaque (e.g., Porphyromonas gingivalis and Tannerella forsythia, previously known as Bacteroides forsythus), and likely explain the connection between plaque and calculus accumulation and systemic disease and mortality (Socransky, Haffajee, Cugini, Smith, & Kent Jr., 2005). Once infected, the inflamed and ulcerated oral epithelium provides a direct route to the bloodstream for bacteria and bacterial bioproducts. In addition to bacterial components (e.g., lipopolysaccharide or LPS), periodontal disease allows locally-produced proinflammatory mediators (e.g., interleukin-(IL-1)$\beta$, tumor necrosis factor-$\alpha$ (TNF-$\alpha$), IL-6, and prostaglandin E2 (PGE2)) to pour into the bloodstream, initiating responses in more distant tissues (Gemmel, Marshall, & Seymour, 1997; Loos, 2005; Loos, Craandijk, Hoek, Wertheim-van Dijlen, & van der Velden, 2000; Moutsopoulos & Madianos, 2006). The dissemination of bacteria and their bioproducts into the bloodstream have the added effect of inducing systemic-level infection responses that may instigate or affect the progression of cardiovascular diseases (for reviews of the evidence, see Dietrich, Sharma, Walter, Weston, & Beck, 2013; Dietrich et al., 2017), chronic obstructive pulmonary disease (Liu et al., 2012; Wang et al., 2009; Zeng et al., 2012), pneumonia (Awano et al., 2008; El Attar, Zaghloul, & El Menoufy, 2010; Scannapieco & Mylotte, 1996; Sharma & Shamsuddin, 2011; Terpenning et al., 2001), and diabetes (Bissett, Stone, Rapley, & Preshaw, 2013; Borgnakke, Ylstalo, Taylor, & Genco, 2013; Lalla et al., 2007; Nelson et al., 1990; Taylor, Burt, Becker, Genco, & Shlossman, 1998). For example, platelet aggregation can be induced by oral bacteria such as P. gingivalis and S. sanguis or by the proinflammatory immune cytokines generated in response to them, affecting the formation of thrombi in the arteries and veins (Herzberg & Meyer, 1996). In addition, studies have demonstrated an association between periodontal disease and Alzheimer’s disease (Kamer et al., 2008; Shaik et al., 2014; Singhrao, Harding, Poole, Kesanvalu, & Crean, 2015; Watts, Crimmins, & Gatz, 2008), kidney disease (Fisher, Taylor, West, & McCarthy, 2011; Kshirsagar et al., 2009), negative pregnancy outcomes (Boggess, Beck, Murtha, Moss, & Offenbacher, 2006; Canakci et al., 2004; Jarjoura et al., 2005; Lopez, Smith, & Gutierrez, 2002; Moore et al., 2004; Offenbacher et al., 1996), and various types of cancer (Fitzpatrick & Katz, 2010; Javed & Warnakulasuriya, 2016; Maisonneuve, Amar, & Lowenfels, 2017; Meyer, Joshipura, Giovannucci, & Michaud, 2008; Shi et al., 2018; Zeng et al., 2016).

Our findings of negative associations between dental calculus and survival are consistent with previous findings in the context of medieval London of elevated risks of mortality associated with periodontal disease and dental caries (DeWitte & Bekvalac, 2010). Thus, our study provides further confirmation of the interconnection between oral health and general health in past populations, but perhaps more importantly (given the previously established associations between the two) highlights the potential use of dental calculus in studies of health in the past. Not all stress markers can be assessed for all individuals in all skeletal assemblages because of the fragmentary nature of some skeletal remains, postmortem damage, or other factors. Indeed, the second author was originally motivated to assess the association between calculus and survival in part because many individuals in samples from medieval London could not be scored for linear enamel hypoplasia (a commonly used indicator of stress) because their enamel surfaces were partly or wholly obscured by dental calculus. Further, not all investigators have collected or will collect data on the same pathologies or stress markers because of project-specific
interests or time constraints. Thus, we argue that evaluating the risks of mortality or survivorship associated with a variety of skeletal stress markers is of great utility to bioarchaeologists, as such analyses will potentially increase the number of stress markers informative about frailty that we can use for assessing health in the past. Though our finding of a possible association between oral health and general health is not in and of itself novel, this is the first study to demonstrate an association between dental calculus and survival in a bioarchaeological context and therefore may motivate other scholars to include dental calculus in the array of stress markers they use in studies of past populations.

We might not be able to determine the exact mechanisms linking dental calculus accumulation and reduced survivorship in the past, as there are numerous health conditions that can potentially mediate the association between calculus and early death, many of which are undetectable in human skeletal remains. Further, the etiology of calculus is complex and affected by a number of factors, including individual variation in salivary flow, hydration, calcium, and phosphate levels in body fluids, mineral content of drinking water, dental wear, various aspects of diet, and oral hygiene practices (Lieverse, 1999). As such, this study does not claim that the severity of calculus accretion is reflective of frailty, or that the accumulation of calculus and the development of oral and systemic disease is solely related to oral hygiene practices. Instead, our study highlights the potential utility of dental calculus as an indicator of frailty in general in bioarchaeological studies and underscores the importance of incorporating demographic measures in studies of health in the past. We do not suggest that the formation of dental plaque and dental calculus is necessarily a causative factor in elevating risks of mortality. Rather, we think it is more likely that the results of this study suggest that the presence of dental calculus—regardless of severity or primary cause—may reflect a disruption of individual homeostasis and an underlying frailty that could prove useful in bioarchaeological studies of health and risk of mortality in the past.

As seen in Table 4, the magnitude of the difference in survivorship between individuals with and without dental calculus is greater for the attritional sample compared to the catastrophic sample. Further, the 95% confidence intervals for mean survival time for those in the catastrophic sample with and without dental calculus overlap, but there is no overlap in the 95% confidence intervals for mean survival time for those with and without dental calculus in the attritional sample. This difference between the attritional and catastrophic samples likely parallels findings from a previous study of the effect of prior exposure to physiological stress on risks of mortality during the Black Death and under normal, pre-Black Death conditions (DeWitte & Wood, 2008). In that previous study, the results of hazards analysis suggested that during the Black Death, people who had skeletal markers of exposure to physiological stress (linear enamel hypoplasia, cribra orbitalia, porotic hyperostosis, and periostea new bone formation) suffered higher risks of mortality during the epidemic compared to their age-peers who lacked the stress markers. The same general pattern of elevated risks of mortality associated with the presence of stress markers was observed in the normal mortality sample. However, the estimated differences in risk of death between those with and without stress markers were higher in the normal mortality sample compared to the Black Death sample. All together, these results suggest that the Black Death disproportionately killed people who were already in poor health, mirroring the selectivity that occurred under conditions of normal medieval mortality. However, it might have been the case that many relatively healthy people, who would have been unlikely to die under normal mortality conditions (and without skeletal stress markers), also succumbed to the Black Death. The deaths of relatively healthy people during the Black Death could have reduced the observed differences in risks of death between those with and without lesions in the Black Death sample compared to what was estimated for the normal mortality sample. As can be seen in Table 4, we found in this study that the estimated mean survival time for individuals with dental calculus is similar between the catastrophic and attritional samples, both when individuals below the age of 20 are included and excluded from analysis. Where the two samples differ substantially is with respect to the estimated mean survival time of individuals without dental calculus; it is much higher in the attritional sample compared to the catastrophic sample. This result might reflect the fact that mortality crises like famines and the Black Death killed selectively, but did not discriminate as strongly between individuals with high and low frailty as occurred under conditions of normal medieval mortality.

### 4.3 Sex differences

The higher observed frequency of dental calculus in females compared to males in our study is inconsistent with other studies that found greater calculus formation among males. Diet is one factor that may have influenced differential calculus deposition between the sexes, with evidence from animal studies suggesting that diets high in fat, carbohydrates (Smith, Baer, King, & White, 1963) or protein (Baer & White, 1966) increases calculus formation. However, existing historical data for medieval England are limited and do not clarify if one sex had preferential access to certain types of food. Although stable isotope analyses of skeletal material have provided useful information about diet during the medieval period, few studies have yielded results suggesting substantial dietary differences between males and females. A study of nitrogen and carbon isotope ratios by Müldner and Richards (2007) suggested that women consumed less marine foods than men in northern England during the 13th–16th centuries. However, there were no significant differences between males and females from the same household or status group, suggesting the pattern may relate to dietary differences between laypeople and members of the local monastic order, rather than sex-influenced access to high fat or protein food sources. Additionally, a study of two more 13th–16th-century sites from northern England suggested no difference in access to marine foods between males and females (Mays, 1997). In the absence of dietary differences between males and females, a variety of other factors involved calculus formation may differ by sex. In particular, females have lower mean salivary flow rates compared to males, likely because of their smaller salivary glands and estrogen-mediated suppression of saliva flow (Bergdahl, 2000; Dodds, Johnson, & Yeh, 2005; Dowd, 1999; Percival, Challacombe, & Marsh, 1994). However, according to Dawes (1970), increased salivary flow rates should result in increased salivary protein and calcium
concentrations, as well as increased alkalinity in the oral cavity, which, in turn, would correspond to increased calculus formation. Consequently, sex-based differences in salivary flow do not explain the higher frequency of calculus formation in females compared to males in our study. In sum, conflicting findings among studies of differential calculus formation between males and females might indicate that there is regional, temporal, or cultural variation in differences between the sexes with respect to the risk of forming dental calculus.

In this study, most of the sex-specific survival analyses indicate a negative association between calculus presence and survivorship for adult males and females. The exception to this is presented by females in the catastrophic sample. The results suggest that in the catastrophic sample, there was significantly reduced survivorship for males with calculus compared to males without calculus, but there was no significant difference between females with and without dental calculus. The similar estimated mean survival times for females in the catastrophic sample with and without calculus is consistent with previous findings from DeWitte (2010) that might suggest that the Black Death discriminated less strongly between females with and without pre-existing health conditions than was true for men.

5 | CONCLUSION

The results of this study suggest the accumulation of dental calculus during life was positively associated with frailty and negatively associated with survivorship in medieval London. In both attritional and catastrophic burials, adults with dental calculus had significantly lower survivorship and died at younger ages compared to individuals without dental calculus. However, an overlap in the 95% confidence intervals associated with survival time for individuals with dental calculus in the catastrophic burials might suggest that the distinction between those with and without calculus was less dramatic during mortality crises. Because calculus deposits take time to accrete, the presence of macroscopically identifiable calculus may indicate a long-term oral infection burden as well as possible related systemic disease burdens similar to those experienced by modern populations. This study demonstrates that, regardless of the cause of mortality, the presence of dental calculus can be informative about general health risks experienced by members of past populations that may serve as a marker of relatively high frailty in isolation or incorporated into health or frailty indices.

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