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# Sex differentials in caries frequencies in Medieval London

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ABSTRACT

*Objective:* Tooth decay is one of the most common oral infections observed in skeletal assemblages. Sex differentials in caries frequency are commonly examined, with most studies finding that females tend to have a higher frequency of carious lesions (caries) compared to males. Less research has examined differences in caries between males and females with respect to age in past populations. Findings from living populations indicate that caries frequencies are higher in females, at least in part, because of the effects of estrogen and pregnancy. We are interested in the interaction of age, sex, and caries in medieval London, during a period of repeated famines, which might have exacerbated underlying biological causes of caries sex differentials.
*Design:* We examined caries in adults from two medieval London cemeteries dating to *c.* 1120–1539 AD: St. Mary Spital ($n = 291$) and St. Mary Graces ($n = 80$) to test the hypothesis that males and females have different caries frequencies irrespective of age. The association between maxillary molar caries and sex was tested using hierarchical log-linear analysis to control for the effects of age on caries frequencies.
*Results:* The results indicate a higher frequency of maxillary molar caries in females ($P < 0.00$), and that the age distribution of caries differs between the sexes ($P = 0.01$), with a consistent increase in frequency with age for females until late adulthood, but not males.
*Conclusions:* The difference in caries frequencies is not explained by differences in the age distributions of the sexes. Differences in the age patterns of caries for males and females could be the result of biological factors that present during reproductive age, differences in diet, or differential access to resources during famine.



## 1. Introduction

Tooth decay is one of the most common oral infections observed in both present day populations and bioarchaeological assemblages. Dental cariogenesis, commonly known as cavity formation, is the process by which focal demineralization of dental tissue occurs as a result of the activity of acidogenic bacteria in plaque; this process usually initially affects the enamel of the tooth and, subsequently, the underlying dentin (Featherstone, 2000). Teeth are often recorded and analyzed in bioarchaeological and paleopathological investigations because they are highly mineralized, making them more resistant to taphonomic factors, unlike bone tissue, which is less durable and highly susceptible to environmental changes after interment (Roberts & Cox, 2003). With the substantial quantity of teeth available in the archaeological record, dental health has been used as a proxy measure of general health levels in past populations in addition to diet, oral hygiene and other factors.

As with many other diseases (e.g., periodontal disease, cardiovascular disease, certain cancers, and autoimmune disorders), there is a difference between the sexes in the risk of developing carious lesions (hereafter referred to as caries). In both living and past populations, females tend to have a higher frequency of caries compared to males (Lukacs, 2008; Lukacs & Thompson, 2008; Roberts & Cox, 2003; Saunders, De Vito, & Katzenberg, 1997; Wasterlain, Hillson, & Cunha, 2009; Whittaker & Molleson, 1996). Findings from living populations indicate that caries frequencies are higher in females because of the complex effects of biological and behavioral differences between the sexes. Clinical literature attributes higher caries presence in females to physiological sex differences that have an indirect, though

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important, influence on dental health and oral ecology. Specifically, saliva type and quantity, higher estrogen levels, and hormonal fluctuation have been associated with an adverse impact on women's oral health, and thus caries rates (Lukacs, 2011b). Behavioral differences resulting from sexual division of labor have also been linked to increased rates of caries in females (Kelley, Levesque, & Weidl, 1991; Larsen, Shavit, & Griffin, 1991; Temple & Larsen, 2007). For example, in some cultures, males who are responsible for acquiring meat may be exposed to less cariogenic foods, compared to females who spend a majority of their time caring for and gathering cariogenic plants (Walker & Hewlett, 1990). Here, we examine sex differences in caries in medieval London to gain insights into the differential experiences of males and females during a period of important and wide-ranging demographic crises (e.g., famine and plague epidemics).

Diet is an important factor to consider when exploring oral health, particularly dental caries, as food intake has a substantial effect on the etiology of caries (Rugg-Gunn & Hackett, 1993). For medieval London, we are fortunate to have a range of archaeological (i.e., faunal bones and pottery) and primary source evidence (i.e., household accounts) to understand diet in this period (Woolgar, Serjeantson, & Waldron, 2006). As is true today, medieval London drew on a vast hinterland to supply it with produce, animals, vegetables and cereals being brought into the city from the market gardens in the suburbs or further-afield (Galloway & Murphy, 1991). Its riverside location meant that fish (fresh or cured) were brought in via shipping from the English coast and continental Europe. Combined with the archaeological evidence for food preparation, cooking and storage, it is well-established that London had diverse food-ways, and was unique in England because of its access to a variety of local and exotic foods, reflecting the diversity of communities living in the city. This evidence also reveals that diets differed according to social status, with religious orders and higher status individuals (i.e., merchants) consuming higher quantities of meat and fish, with lower status people consuming what has been termed a 'rural diet' or a 'peasant diet' because it contained very low or no animal or fish protein and was mostly vegetable and cereal based (e.g., pottages) (Dyer, 1989).

In addition to archaeological and documentary evidence, there is limited isotopic data on diet in medieval London. To date, only one study has investigated dietary stable isotope values in medieval London (Lakin, 2008). This study, using rib samples from two medieval sites in London (St. Mary Spital and St. Nicholas Shambles) found that, in contrast to York (Müldner & Richards, 2007), there was considerable dietary heterogeneity in London, confirming the existing documentary and archaeological evidence. Lakin (2008) also identified two individuals who likely consumed a 'rural diet', as their dietary values matched the sampled faunal values. In contrast to the other sources of evidence, this study demonstrated that there were no statistically significant differences in isotope values among adult age groups (>18 years old). However, the majority of 18–25 year old females had more negative $\delta^{13}$N values compared to older females. Lakin (2008) suggests that this may reflect a number of factors: pregnancy, fasting, and rural-urban migration. At York, Müldner and Richards (2007) observed statistically significant differences between the sexes. This was not observed by Lakin (2008), however, who found that the absolute difference between the means for males and females was very small. It is important to note that the sample for Lakin's (2008) study included only individuals from Period 15 and a small number of individuals from Period 16 of St. Mary Spital (see details below), while this study includes individuals from Periods 14, 15, and 17.

Malnutrition has been shown to increase the risk of dental caries. Fasting reduces salivary flow rate, which is directly associated with increased risk of cariogenesis resulting from an increased rate of plaque formation (Johansson, Ericson, & Steen, 1984; Lingström & Moynihan, 2003). England and other regions in Europe experienced severe malnutrition resulting from a series of famines during the medieval period (*c.* 11–16th centuries CE) (Farr, 1846; Keys et al., 1950), which may have increased the prevalence of caries in the population, as malnutrition would have occurred across the entire population. For example, primary sources have noted that in 1258, 15,000 poor people died from famine in London. As deadly as famine was, people did survive medieval famines; in fact, some famine survivors have been identified as such in the East Smithfield Black Death cemetery from London (Antoine, Hillson, Keene, Dean, & Milner, 2005). Exposure to famine might have had long-term effects on health (DeWitte & Slavin, 2013). Episodic, severe malnutrition in the medieval period resulting from famine may have intensified biological and cultural causes of caries frequency differentials between males and females that are evident in contemporary populations.

It should be noted that London has always been a city of migrants. Primary sources and stable isotope data have shown that migrants from other parts of Britain and the near Continent lived in London (Kendall, Montgomery, Evans, Stantis, & Mueller, 2013). However, because of the general climatic deterioration suffered across Europe during the medieval period, episodes of famine were common throughout medieval Europe (Jordan, 1997), and therefore, the presence of migrants should not bias the results of our analysis of London material.

Previous work on the populations from St. Mary Spital and St. Mary Graces has examined sex differences in dental disease (Bekvalac & Kausmally, 2011; Connell, Gray Jones, Redfern, & Walker, 2012). However, neither publication examined the potential effect of age on patterns of caries as is done in this study. Our research examines the interaction of age, sex, and caries in medieval London, during a period of repeated famines, which might have exacerbated underlying biological causes of caries sex differentials.

## 2. Materials and methods

### 2.1. Skeletal samples

The two skeletal samples ($n = 371$) used in this study are drawn from medieval London cemeteries curated by the Centre for Human Bioarchaeology (CHB) at the Museum of London: St. Mary Spital dated to *c.* 1120–1539CE ($n = 291$) and St. Mary Graces dated to *c.* 1350–1538CE ($n = 80$).

#### 2.1.1. St. Mary Spital (*c.* 1120–1539)

St. Mary Spital (site code: SRP98) was one of England's largest medieval hospitals. It was founded in the twelfth century and was in use until its dissolution in the 16th century (Thomas, Sloane, & Phillpotts, 1997). The stipulations of its foundation charter make it unique in London, because it was charged with hosting and caring for pilgrims and the infirm, and providing care to pregnant women and the offspring of those who died in childbirth (Calendar of Close Rolls 1339-41, 600 cited in Sheppard, 1957). The associated cemetery, which was in use from the 12–16th centuries, contains individuals of all age ranges, from neonates to elderly adults, who were from the city, suburbs, and the infirmary (Connell et al., 2012).

Excavations of St. Mary Spital revealed 10,516 individuals, over half of the estimated 18,000 or so individuals that archaeologists estimated were originally buried in the cemetery (Connell et al., 2012). Of the individuals excavated from St. Mary Spital, 6,950 were 35 percent complete and had regions of the skeleton suitable for estimating age or sex, of which 5,387 individuals of all ages were recorded by the Museum of London Archaeology into the

Wellcome Osteological Research Database (WORD) and are thus available to researchers. This study examines a sample of 291 adults (167 males and 124 females) from the collection spanning *c.* 1120–1539CE. Using high-precision Bayesian radiocarbon dating within a well-defined stratigraphic framework, the cemetery has been classified into four distinct chronological phases: 1120–1200CE (Period 14), 1200–1250CE (Period 15), 1250–1400CE (Period 16), and 1400–1539CE (Period 17) (Sidell, Thomas, & Bayliss, 2007). Individuals from Period 16 were excluded from this study because excess mortality that occurred during the Black Death could potentially affect normal patterns of mortality and oral health that are presumably evident throughout the remaining periods of use within the St. Mary Spital cemetery. The Spitalfields Osteology Team previously collected the demographic (age and sex) and caries data used for this study.

### 2.1.2. St. Mary Graces cemetery (*c.* 1350–1538)

St. Mary Graces cemetery (site code: MIN86) is associated with the Abbey of St. Mary Graces in London, and was located northeast of the Tower of London (Grainger & Hawkins, 1988). The St. Mary Graces cemetery was in use after the Black Death from 1350 until 1538 (it is not divided into temporal phases like St. Mary Spital). Individuals interred in St. Mary Graces included members of the general population of London, as well as monks and important lay people associated with the Cistercian Abbey (Grainger & Hawkins, 1988). Monks and important lay people were buried within the Abbey's church and chapels, and members of the general population were interred in the associated cemetery (Grainger & Hawkins, 1988; Rogers & Waldron, 2001). Excavation of St. Mary Graces in the 1980s revealed 133 skeletons from within the Abbey church and chapels and 310 within the larger lay cemetery (Grainger & Hawkins, 1988). This study includes a sample of 80 adults (59 males and 21 females) from St. Mary Graces. CHB researchers at the Museum of London collected the demographic and caries data used for this study (Bekvalac & Kausmally, 2011). We have pooled data from St. Mary Spital (Periods 14, 15, and 17) with that from St. Mary Graces.

### 2.2. Sex determination and age estimation

Sex was determined using sexually dimorphic skeletal features of the pelvis and skull, as these are the most reliable parts of the skeleton for sex determination. Museum of London Archaeology (MoLA) and the Centre for Human Bioarchaeology (CHB) visually assess a total of fourteen skeletal features of adult individuals (18 years or older) to determine sex (Powers, 2008). Sexually dimorphic features of the skull include the supraorbital ridge, mastoid process, inion protuberance, nuchal crest, frontal shape, zygomatic root, and gonial shape, following standards provided in Brothwell (1981),Ferembach, Schwindezky, and Stoukal (1980), and Bass (1995). Sexually dimorphic features of the pelvis include the greater sciatic notch, preaurciular sulcus, ventral arc, medial portion of the pubis, subpubic angle, subpubic concavity, and median ischiopubic ridge, following standards outlined by Phenice (1969). When present, multiple skeletal indicators were used in sex determination. Only individuals assigned a sex or probable sex were considered for this study; thus, only adults were included in the samples.

The MoLA and CHB estimate age-at-death of adult individuals using four nonmetric methods: molar tooth wear (Brothwell, 1981), pubic symphyseal morphology (Brooks & Suchey, 1990), iliac auricular surface morphology (Lovejoy, Meindl, Pryzbeck, & Mensforth, 1985), and costo-chondral morphology of the rib (Işcan, Loth, & Wright, 1984; Işcan, Loth, & Wright, 1985). When possible, all of the techniques, or multiple techniques, are used to estimate age (Powers, 2008). Based on the techniques used for adult age estimation, MoLA and the CHB assign each adult to one of the following age-at-death categories: 18–25 years, 26–35 years, 36–45 years, 46 years and older, or adult (i.e., individuals with too few age indicators available to allow for a more precise age-group, but


**Fig. 1.** Superior view of a mandible from St. Mary Spital cemetery with an example of a carious lesion present on the superior aspect of the second left mandibular molar. Scale in centimeters.

who are estimated to be greater than 18 years of age at death). This study includes only those individuals assigned to the first four categories (i.e., we exclude those who were simply assigned an age of "adult"). Further, age categories 36–45 years and 46 years and older were pooled into a 36 years and older age category for this study to fulfill the conditions required to perform hierarchical log linear analysis (i.e., all expected frequencies should be greater than 1, and 80% should be greater than or equal to 5).

### 2.3. Dental caries

The recording methods used by MoLA and the CHB classify teeth as absent or present at the level of the individual tooth socket, which is described as the "dental location" in their database (Powers, 2008). Teeth scored as "present" include those that are loose (i.e., teeth that are observable but lack a socket due to post-mortem damage) (Powers, 2008). All observable teeth were scored for caries presence. MoLA and the CHB record caries at the level of the individual tooth, and include the position and severity of the lesion on the tooth (Powers, 2008). Caries are assessed visually and scored as "present" if destruction of the enamel or dentin can be seen (Fig. 1). Only cavitated lesions were scored as "present" for caries. MoLA and the CHB record caries by severity using the following categories: enamel destruction only, destruction of dentin with pulp chamber not exposed, destruction of dentin with pulp chamber exposed, and gross destruction with crown largely destroyed (Powers, 2008). For this study, the presence of at least one carious lesion on the tooth, no matter the severity category, is scored as "present" for caries. This study uses only data on tooth presence and caries presence from maxillary molars in order to maximize sample sizes for the statistical analyses, and to minimize overestimation of caries presence as would likely occur if we included more tooth categories given our criterion for caries absence, detailed below. An individual was assigned a score of "present" for caries if at least one maxillary molar exhibited a carious lesion. However, an individual was scored as "absent" for caries only if all six maxillary molars were present and lacked caries. Though this might lead to overestimates of caries frequencies (as the criterion for presence is less stringent than that for absence), it does reduce the possibility of false negatives (i.e., scoring individuals who had caries on missing teeth as "absent" for caries). Moreover, our goal is to examine sex differences in caries, and we are thus less concerned with the frequency values themselves or the distribution of caries in the dental arcade (these data are already published; see Bekvalac & Kausmally, 2011; Connell et al., 2012).

Analyses of caries must take into account the commonly observed pattern of an increase in caries prevalence with increasing age (Hillson, 2001). Age-related changes, including oral hygiene behavior and changes in diet, have been associated with increased caries frequencies for both sexes (Lukacs & Thompson, 2008). Most notably, the accumulation of years of exposure to oral pathogens increases an individual's inflammatory status, which, in turn, increases risk of caries. Increased susceptibility to caries with increased age could thus obscure the actual relationship between sex and caries frequency. Differences in age distributions between males and females (such as a higher proportion of older females than males in a sample) can potentially influence the observed patterns of caries frequency differences between the sexes. Thus, statistical analyses must account for age in order to avoid confounding age differences for sex differences in assessing caries frequencies. Therefore, this study uses hierarchical log-linear analysis, which allows for the evaluation of associations among more than two variables. Here, we use hierarchical log-linear analysis to determine if there is a significant association between caries and sex that exists in the absence of an age effect.

### 2.4. Hierarchical log-linear analysis

Preliminary assessment of independence regarding caries frequencies and sex was determined using a Chi-square test. Hierarchical log-linear analysis was subsequently used to evaluate the associations among caries, sex, and age within the cemeteries using SPSS version 21. Hierarchical log-linear analysis is suitable for this study because all the data included are either categorical (i.e., age category) or binary (i.e., sex) variables. Moreover, this approach tests the significance of the interaction for all of the variables in question (i.e., caries, sex, and age), in addition to the significance of all other lower order interactions (e.g., between age and sex, between sex and caries, and between age and caries). Non-significant interactions with a $P$-value greater than 0.05 are removed using backwards elimination.

## 3. Results

The age-at-death distributions of males and females in the sample are provided in Fig. 2, and they reveal only slight differences in the frequencies of males and females throughout

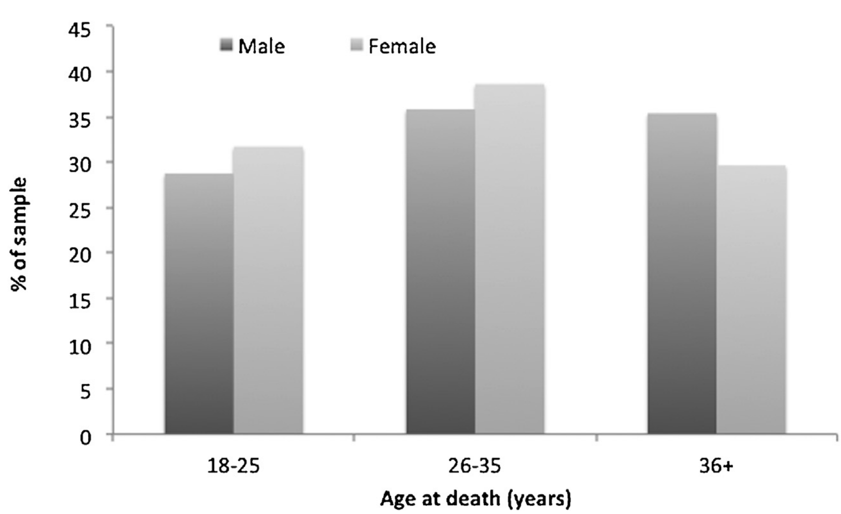


**Fig. 2.** Age-at-death distributions (by percent of sample) of males and females in the St. Mary Graces and St. Mary Spital pooled sample.

**Table 1**
Caries frequencies of males and females by age-group for St. Mary Spital and St. Mary Graces combined.

| Age | Sex | No caries | Caries | % with Caries |
|---|---|---|---|---|
| 18–25 | Male | 47 | 18 | 28 |
| | Female | 14 | 32 | 70 |
| | Both | 61 | 50 | 45 |
| 26–35 | Male | 25 | 56 | 69 |
| | Female | 17 | 39 | 70 |
| | Both | 42 | 95 | 69 |
| 36+ | Male | 28 | 52 | 65 |
| | Female | 7 | 36 | 84 |
| | Both | 35 | 88 | 72 |
| Total | Male | 100 | 126 | 56 |
| | Female | 38 | 107 | 74 |
| | Both | 138 | 233 | 63 |

adulthood, and that the shape of the distributions are similar between the sexes. Dental caries frequencies among males and females in both the cemeteries are shown in Table 1. The frequency of caries is higher in females than in males for all age groups except 26–35 when the frequencies of caries are comparable.

A preliminary Chi-square test was used to assess whether there is an association between sex and caries frequencies in the cemeteries. The results indicate that caries presence is not independent of sex ($P = 0.01$) (Table 2).

The results from the hierarchical log-linear analysis of the associations among age at death, sex, and caries are shown in Table 3. The results reveal a significant three-way association among sex, age, and caries, which suggests that the age distribution of caries frequencies significantly differs between the sexes. The percent of caries within each age category among males and females is shown in Fig. 3, and it reveals an increase in caries frequency with age among females through late adulthood (>36 years of age at death), while the frequency of caries in males decreases with age. The results of the hierarchical log-linear analysis also indicate that sex and caries are significantly associated, which is not surprising given that a relationship between sex and caries had already been established with the preliminary Chi-square test. The maxillary molar caries frequency is higher in females. Age and caries are also significantly associated, and as can be seen in Table 1, the frequency of caries increases with age. Sex and age are not significantly associated, which indicates that the age distributions of males and females are not significantly different. Given that the age distributions of the sexes do not differ, the significant three-way interaction among age, sex, and caries suggests that the difference in caries frequencies is not explained by differences in the age distributions between the sexes. That is, the frequency of caries is not higher in females because there is a higher frequency of older females compared to older males.

## 4. Discussion

The results from this study concerning sex differences in caries frequencies are consistent with observations made for the majority of both living and past populations; specifically, there is a higher frequency of caries in females than males. This study shows that in medieval samples from London, females have a higher frequency of caries irrespective of an age effect, suggesting that females have a higher risk of developing carious dental lesions.

Diet is a crucial determinant of cavity formation, or cariogenesis. Diet in medieval Europe, by present-day standards, was generally unbalanced with insufficient intake of protein, lipids, minerals, and vitamins (Dyer, 1983; Larsen et al., 1991). Bread and grains made up the majority of an individual's diet, up to 70 percent of food intake according to some sources (Boldsen, 2005; Cruz, Repetto, Morera, & Tarli, 1993). Increased carbohydrate consumption has been associated with an increase in caries frequencies (Varrela, 1991; Vodanović, Hrvoje, Mario, & Željko, 2005). Cariogenic foods are those with a high fermentable carbohydrate content that reduce pH levels, which breaks down enamel, creating an ideal environment for cariogenesis to occur (Schmidt, 1998). Sugar, a food commonly linked to cariogenesis, was not commonly consumed in England (Moore & Corbett, 1973). Thus, the high frequency of dental caries in medieval populations can likely be attributed to the heavy reliance on grains. Larsen (1995) argues that females in past populations, being the preparers of the food, had greater access to caries-promoting foods. Females in medieval England, were responsible for the preparation of meals for the household (Markham & Best, 1986; Mount, 2014), which may have given them better access to cariogenic foods and thus increased their risk of developing caries.

As mentioned previously, during the medieval period, Europe experienced numerous episodes of famine, which was an inevitable effect of bad harvests, grain shortages, and subsequent high prices (Farr, 1846). People living in London would have experienced elevated risk of famine because, as an urban center, London was dependent on outside sources for food (Dyer, 2002) and had a high population density, particularly as people migrated to the city because its religious institutions would have provided alms for the poor (Dyer, 1983). Clinical and epidemiological research has established an association between malnutrition and changes in the oral environment that increase the risk of developing dental caries (Psoter, Reid, & Katz, 2005). Additionally, fasting reduces salivary flow rate, which is directly associated with increased risk of cariogenesis because of an increased rate of plaque formation (Johansson et al., 1984; Lingström & Moynihan, 2003), A meta-analysis of dental caries prevalence in living populations in South Asia found that females exhibited a higher caries prevalence compared to males, which Lukacs (2011a) attributes to cultural practices that result in diet restriction and frequent fasting for females. The malnutrition experienced by medieval Londoners as a result of famine may have exacerbated pre-existing dietary and biological differences between sexes that could cause caries.

**Table 2**
Results from Chi-square test of caries frequencies between male and females from St. Mary Spital and St. Mary Graces.

| | No lesion | Lesion | $n$ | %with lesion |
|---|---|---|---|---|
| Male | 100 | 126 | 226 | 56 |
| Female | 38 | 107 | 145 | 74 |
| | 138 | 233 | 371 | 63 |
| | | | $\chi^2$ | 1.06 |
| | | | $P$ | 0.01 |

**Table 3**
Results of hierarchical log-linear analysis of the association among caries, sex, and age in St. Mary Spital and St. Mary Graces.

| Variables | $P$ |
|---|---|
| Age × sex × caries | 0.01 |
| Age × sex | 0.17 |
| Age × caries | 0.00 |
| Sex × caries | 0.00 |

Moreover, an association has also been found between childhood malnutrition and increased caries rates in adulthood (Alvarez, 1995; Psoter et al., 2005). Malnutrition during childhood causes salivary gland hypofunction that continues into adolescence, causing increased risk of dental caries (Psoter, Spielman, Gebrian, St Jean, & Katz, 2008). Multiple famines of varying severity occurred in England between 1120 and 1539, with 27 famines documented by Farr (1846) alone. Thus it would be possible for childhood malnutrition to have affected the adults buried in both St. Mary Spital and St. Mary Graces.

Behavioral differences in oral hygiene may have contributed to caries prevalence and thus sex differentials of caries frequency in these cemeteries. Access to dental care could have been different for men and women. Professional dental practices included tooth extraction and herbal treatments for teeth with severe carious lesions. Evidence of differential access to these resources for men and women could not be found in the literature. However, Mikikimin, Herlihy, Udovitch, and Lopez (1978) contend that females might not have been able to partake in professional dental care since barbershops, the primary resource for tooth extraction, were mostly frequented by males.

Previously, anthropologists have emphasized behavioral and dietary differences between males and females to explain higher frequencies of caries in females in both contemporary and past populations, minimizing or ignoring the substantial influence of biological factors such as pregnancy (see Lukacs & Largaespada, 2006). However, a survey of clinical literature supports an association between cariogenesis and physiological and hormonal differences between the sexes in addition to diet and behavior (Lukacs, 2011b). Furthermore, Lakin's (2008) biochemical analysis of individuals from St. Mary Spital found little difference in stable isotope values between males and females (i.e., females and males had similar diets), suggesting that other factors, such as physiological differences, may have more of an effect on differences of caries frequency between the sexes seen in medieval London.

Research has demonstrated that "caries rates increase proportionally with increasing estrogen levels, whereas increasing androgen levels have no effect" (Lukacs & Largaespada, 2006, p. 554). Males typically have extremely low levels of estrogen, while females have significantly higher levels of estrogen throughout the life cycle (Worthman, 1995). Moreover, females experience peak levels of estrogen in response to the menstrual cycle, puberty, and pregnancy (Meistrich, Trostle, Brock, Jagiello, & Vogel, 1981). Lukacs (2008) contends that during pregnancy, females undergo hormonal fluctuations that influence dietary preferences and immunological competence that can result in adverse dental health. During pregnancy, estrogen levels substantially increase more than at any other time during life, and this has been found to result in increased caries. Fluctuation in estrogen levels modifies the composition of saliva that decreases the ability of saliva to buffer against specific bacteria linked to the development of dental caries (Villagrán, Linossier, & Donoso, 1999). In the case of medieval London, it is possible that famine experienced by Londoners during the medieval period may have disproportionately affected the oral health of females at childbearing ages, as malnutrition increases risk of cariogenesis, discussed above. Because of these differences, attention must be given to the elevated risk of dental caries for reproductive-aged women, particularly consideration of the malnutrition women may have experienced during famine. Further investigation into maternal mortality and fertility rates of medieval London cemeteries may elucidate patterns of female reproduction and increased dental caries frequencies.

Saliva has been found to have a direct influence on the health of the oral cavity by flushing away debris and sugars from the mouth, protecting the outer enamel surface by coating teeth, and preventing pathogens from colonizing the oral cavity. Sex differences have been identified in both the composition and flow rate of saliva, with females having a dramatically lower salivary flow rate as a result of smaller salivary glands and higher estrogen levels. Reduced salivary flow rate in postmenopausal females has also been recognized (Friedlander, 2002), which may be a contributing factor to the steady increase of caries frequencies with age for the females of medieval London.

It is important to mention that the sex differences in caries in St. Mary Spital and St. Mary Graces may actually be an artifact of variation in frailty rather than a direct indicator of sex differences in caries in the once-living cemetery population. For example, females may have had higher frailty than males, which could have resulted in more females with caries interred in these cemeteries and thus included in this analysis. However, Dewitte (2010) found, using

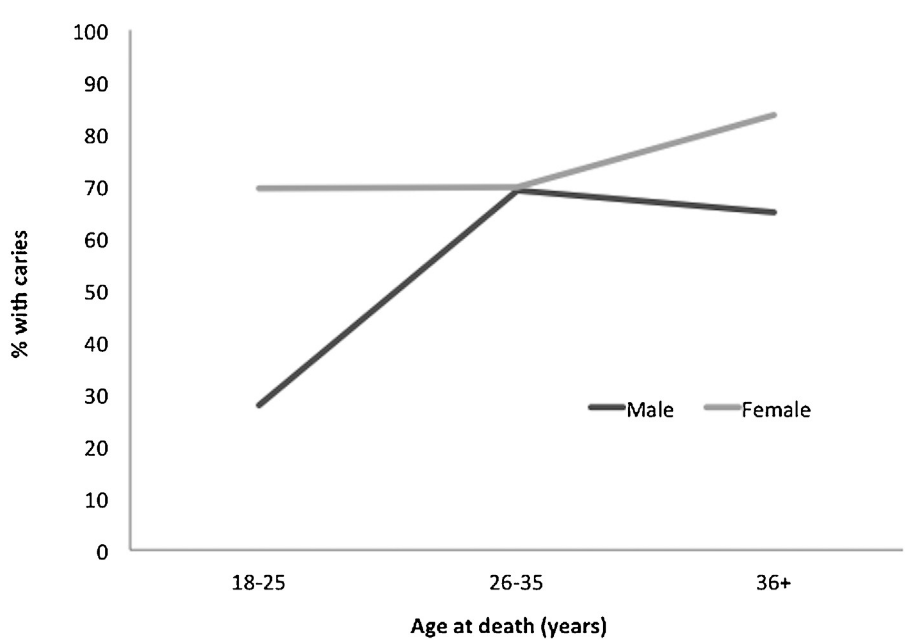


**Fig. 3.** Percent of individuals with caries by age at death category for males and females in the pooled St. Mary Graces and St. Mary Spital sample.

samples from medieval London, that females who experienced physiological stress during life were more likely to resist dying than males who experienced similar levels of stress, which indicates that males were frailer than females. If males were in fact more frail than females in the St. Mary Spital and St. Mary Graces populations, males with caries might have been more likely to die than females with caries, which would increase the proportion of males with caries in the sample used for this study. If this were the case, that would suggest there was an even larger gap between male and female caries rates in the once-living population than was estimated in this study; that is, the sex differential observed in these samples might be an underestimate of the true differences in caries frequencies.

We must also consider the potential effect of antemortem tooth loss on the results of this study. Nelson, Lukacs, and Yule (1999) have noted that antemortem tooth loss (AMTL) is often the result of caries and abscess formation, and have shown that AMTL, if not controlled for, can result in underestimation of caries prevalence. If, in the medieval London population, AMTL was more common in males, the results of this study might be an artifact of elevated tooth loss in males rather than reflecting true differences in caries frequencies between the sexes. On the other hand, greater AMTL in females could result in underestimation of caries frequencies in females, and thus underestimation of the true difference in caries frequencies between the sexes. Because we are concerned with the difference in caries frequencies between the sexes, rather than general caries prevalence per se, we conducted a Chi-square test to assess the difference in AMTL frequencies between males and females in our sample. We found that there was no significant difference in AMTL between the sexes ($P = 0.72$). Thus, the results of our study are not likely confounded by AMTL.

Finally, the use of only the maxillary molars for this study could introduce bias in the form of an overestimation of caries frequencies given that previous work has found higher rates of caries in cheek-teeth (Connell et al., 2012; Hillson, 2001). However, as noted above, the possibility of overestimating caries frequencies does not limit this study given that our focus is on comparing age-patterns of caries between the sexes and not on the actual frequencies themselves.

## 5. Conclusion

The results of this study suggest that, for these skeletal collections from London, caries frequency and sex are significantly associated, with a higher frequency of caries in females. Moreover, the association between caries frequency and sex is not explained by differences in the age distribution of the sexes.

Clinical and epidemiological studies in living populations and bioarchaeological studies of dental caries frequencies in past populations show that females usually have higher caries rates than males. St. Mary Spital and St. Mary Graces are particularly interesting for an investigation of sex differentials in caries frequency because of the occurrence of multiple famines during the medieval period in London. Because of the adverse effect of malnutrition on oral health, famine experienced by Londoners during this period might have exacerbated sex differences in caries frequencies.

This study also underlines the importance of considering biological factors that may contribute to sex differentials in dental caries. Bioarchaeological studies concerning dental caries tend to oversimplify causal factors of dental caries and ignore intrinsic biological differences that contribute to sex differences in caries frequencies (Lukacs & Largaespada, 2006). Cultural and behavioral sex differences are often the favored explanations for sex differentials in caries rates in the past. Biological factors, however, play an important role in the complex etiology of dental caries, and these factors should be considered in conjunction with behavioral differences that stem from a result of sexual division of labor. Future work might incorporate influences of maternal mortality and fertility with female caries frequencies to elucidate biological factors concerning this dental pathology. Moreover, the incorporation of stable isotope data to determine sex differentials of diet within this collection could also be informative, as these data could clarify dietary differences between sexes, substantiate historical and stable isotope evidence concerning diet and potentially malnutrition differences between males and females in medieval London.

## Conflict of interest

None.

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## Ethical approval

None.

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