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Patterns of frailty in non-adults from medieval London☆

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ABSTRACT

Famine has the potential to target frail individuals who are at greater risk of mortality than their peers. Although children have been at elevated risk of mortality during recent famines, little is known about the risks posed to children during the medieval period. This study uses burials from the St. Mary Spital cemetery (SRP98), London (*c.* 1120–1540) to examine the relationships among non-adult age at death, burial type (attritional or famine), and four skeletal lesions (porotic hyperostosis, cribra orbitalia, linear enamel hypoplasia [LEH], and periosteal new bone formation). Hierarchical log-linear analysis reveals significant associations between famine burials and LEH, independent of age. Significant associations also exist between age and the presence of cribra orbitalia, porotic hyperostosis, and periosteal lesions, with all three lesions present in greater frequencies among older children and adolescents, independent of burial type. The LEH results suggest that early exposure to stressors increased frailty among non-adults in the context of famine. The associations between age and the other skeletal indicators suggest that, in both famine and non-famine conditions, frailer individuals died at younger ages and before skeletal lesions could manifest, while their less frail peers survived multiple physiological insults before succumbing to death at older ages.

1. Introduction

Famine, traditionally recognized solely as a period of food shortage and mass starvation, has recently received attention among social scientists as a complex convergence of factors causing excess mortality within a population (Horocholyn and Brickley, 2017). Scholars now recognize that a prolonged food shortage or nutritional deficiencies can be caused or worsened by social and political factors (e.g., war, market panic, communication or transport failure) as well as environmental factors (e.g., droughts, crop diseases), which collectively prompt excess mortality within the affected population (Sen, 1981; Morgan, 2013). In addition to food shortages and death by starvation, malnutrition is known to weaken the body's immune defenses, heightening its susceptibility to disease and parasitic infection (Walter and Schofield, 1989; Maharatna, 1996; Ó Gráda, 2007; Morgan, 2013). Thus, famine is better defined as a prolonged food deficiency caused by environmental, social, and political factors, which leads to a variety of physiological and social outcomes, such as malnutrition and starvation, increased infectious disease susceptibility and mortality, migration, and community breakdown. Famines were common in medieval London, due to urban growth and a heavy reliance on imported food from the surrounding rural areas (Dyer, 2002). Farr (1846) amassed data on famines throughout the medieval period (9th–15th centuries), finding that the English experienced approximately 10 years of famine per century. Changing weather conditions and climatic events resulted in crop failures and thus famines during this period. For example, a volcanic eruption in the tropics is implicated in the production of excessive rain and flooding and consequent famine in 1257–1258 in England. These famines were frequently exacerbated by pestilence or infectious disease (Scrimshaw, 1987; Campbell, 1992; DeWitte and Slavin, 2013). Mortality during the 1257–1258 famine, for example, was compounded by an outbreak of infectious disease in 1259, which further increased the death toll attributed to the famine in England's largest urban center (Stothers, 2000). Similarly, the Great Famine in England (1315–1317) was believed to be caused by heavy rains that devastated harvests from 1314 through 1317, but was worsened by market failure and grain hoarding (Kershaw, 1973; Campbell, 2010). In sum, the excess mortality associated with famines in London during the medieval period included disease-related deaths, in addition to those more directly linked to food scarcities and starvation. As the Great Famine of 1315–1317 demonstrates, political and economic factors could intensify famine characteristics like food deprivation and infectious disease, which often biases famine mortality against a society's marginalized individuals (Sen, 1981). Many of the individuals who perished during famine events were rural-urban migrants and the urban poor, who could not afford the exorbitant grain prices in London during a

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prolonged shortage (Farr, 1846; Stothers, 2000).

Previous investigations of famine-related mortality among adults in medieval London have revealed associations between burial type—-specifically those individuals included in famine burials compared to individuals interred in attritional burials—and various osteological indicators of frailty, including femur length, linear enamel hypoplasia (LEH), and periosteal new bone formation (periosteal lesions). One study using skeletal material from St. Mary Spital cemetery (SRP98, *c.* 1120–1540) found that LEH in adults was significantly associated with famine burial (independent of age or sex), suggesting that early exposure to physiological stress increased the risk of mortality during famines experienced as an adult (Yaussy et al., 2016). Another study using the same skeletal assemblage found that a higher proportion of adults with short femora were included in famine burials (independent of age or sex), indicating that individuals who experienced early life physiological insults severe enough to impact growth were at increased risk of mortality during famines (DeWitte and Yaussy, 2017). In contrast, periosteal lesions on the tibia were significantly associated with non-famine (attritional) burials. This result might suggest that, during non-famine periods, individuals were better able to survive the factors that cause periosteal new bone formation long enough to develop these lesions, whereas individuals exposed to such factors in the context of nutritional stress and acute disease during famine periods died before such stressors formed (Yaussy et al., 2016; Jones et al., 2012). Although informative, these previous bioarchaeological studies of famine mortality in medieval London were restricted to adult skeletal remains, and have not provided any information about the risks experienced by children under famine conditions. A pair of studies examining victims of the Great Irish Famine (A.D. 1845–1852) suggested that mortality was particularly pronounced among non-adults (< 18 years old), especially among non-adults who exhibited skeletal indicators of physiological stress, such as scorbutic lesions, Harris lines, and growth retardation (Geber and Murphy, 2012; Geber, 2014). However, Geber (2014) cautiously highlights the context of the skeletal assemblage used for the studies, noting that the physical and psychosocial environments in a union workhouse likely impacted the patterns of morbidity and mortality observed in the sample. Consequently, the results of the Great Irish Famine studies are revealing, but not necessarily generalizable to populations from other temporal or geographic contexts.

Information from recent historical famines suggests that famine mortality exhibits peaks in the youngest and oldest age categories (Scrimshaw, 1987; Chamberlain, 2006; Morgan, 2013). Mortality during recent famines has been concentrated among children between the ages of 5–9 years and adults over the age of 45 years (Watkins and Menken, 1985), and this pattern is broadly consistent regardless of spatial, temporal, and cultural differences (Maharatna, 1996). Scholars suggest the most dangerous years for children to experience famine are the post-weaning years, when breast milk no longer confers nutritional and immunological benefits (Stuart-Macadam, 1995; Maharatna, 1996). However, though evidence suggests that post-weaning non-adults have been at greater risk of famine mortality in the last several centuries, little is known about the risks to non-adults during the medieval period. Much of the surviving historical documentation from this period is biased towards wealthy adult males (Kowaleski, 2013), and little is known about the health and mortality patterns of children at the time. However, skeletal samples can provide valuable information about the heterogeneity in frailty of non-adult individuals living during the medieval period (e.g., Lewis, 2002; Lewis and Gowland, 2007; Lewis, 2016). This study examines famine burials from medieval London and compares them to non-famine (attritional) burials from the same time periods. By using the available skeletal evidence, we recover data on a population that was widely omitted from historical documents and broaden our understanding of the selectivity of famines among children and adolescents in the past.

For this study, skeletal material from St. Mary Spital cemetery (SRP98, *c.* 1120–1540) is used to evaluate the associations between non-adult age at death, burial type (attritional or famine), and four skeletal indicators of exposure to physiological stress (porotic hyperostosis, cribra orbitalia, LEH, and periosteal new bone formation). Previous analyses of subadult data from St. Mary Spital by the Museum of London (Jones et al., 2012) revealed variable patterns of skeletal stress markers by age, burial type, and time period of use within the cemetery (see details below). In order to increase statistical power, we pool data across time periods. Further, we use an analytical approach (hierarchical log-linear analysis) that allows us to control for the potential effects of age on patterns of skeletal stress markers.

2. Materials and methods

2.1. Skeletal sample

The sample for this study come from the St. Mary Spital cemetery (SRP98), which was excavated by Museum of London Archaeology (MoLA) between 1998 and 2001. Associated with the Augustinian monastery and hospital of St. Mary Spital (founded in A.D. 1197 and closed in A.D. 1539), the cemetery was the final resting place for a diverse array of individuals, including hospital inmates, travelers, and wealthy benefactors. St. Mary Spital served London's ailing residents, but also provided alms to the poor, assistance to women in childbirth, shelter to pilgrims and migrants from the surrounding rural areas, and housing for orphans, widows, servants, and affluent elderly individuals (Thomas et al., 1997; Connell et al., 2012). Although only a portion of the cemetery could be excavated, 10,516 skeletons were recovered from the site, making SRP98 one of the largest excavated burial collections from Europe's medieval period. Archaeological context and a Bayesian approach to radiocarbon dating were used to divide the site into four phases: Period 14 (A.D. 1120–1200), Period 15 (A.D. 1200–1250), Period 16 (A.D. 1250–1400), and Period 17 (A.D. 1400–1539) (Sidell et al., 2007; Connell et al., 2012). In addition to the four chronological phases, MoLA used the number and arrangement of bodies in each grave to divide the interments into four distinct burial types. About half of the individuals buried in SRP98 were recovered from single graves (Type A), while the other half consisted of multiple interments arranged horizontally, vertically, or horizontally and vertically (Types B, C, and D, respectively) (Connell et al., 2012). Additional information about SRP98, as well as relevant images, site maps, and illustrations, can be found in the site report published by Connell et al. (2012).

Unlike the smaller B and C burial types, the multi-layered Type D burials held as many as 45 individuals and were hastily dug to accommodate a sudden rise in mortality within a period of days. Therefore, the Type ABC burials are described in the SRP98 site report as "the attritional group", and the Type D burials are referred to as "the catastrophic group" (Connell et al., 2012; Jones et al., 2012). There is no indication that the Type D burials exhibit more evidence of interpersonal violence than the Type ABC burials, which suggests that the mass burials were not used to inter the victims of warfare. Rather, the demographic profile of the Type D burials matches what would be expected during a famine event (i.e., mortality increases among non-adults and the elderly) (Jones et al., 2012). Although osteological age estimation methods have prevented an estimate of the mortality peak among older adult individuals, the Type D (famine) burials contain a greater proportion of non-adults compared to the Type A (attritional) burials (Table 1 provides the age-distributions in Type A and Type D burials in the Periods used in this study, as detailed below). In addition to the osteological data, radiocarbon dating shows that many of the Type D burial pits were dug prior to historically-documented outbreaks of plague in London, such as the Black Death of 1348–1350 (Jones et al., 2012). Instead, the dates of the Type D burials closely coincide with famines recorded by Farr (1846). For example, two mass burial pits from Period 14 were dated to *c.* 1155–1165, which closely coincides with a famine that occurred in 1162. Likewise, mass burials from Periods 15 and 16 were dated to *c.* 1235–1255, matching two closely-

Table 1
Demographic profiles for non-adult age categories and adults (18+ years of age) in Period 14, 15, and 17 (the attritional sample only includes Type A burials).

Age Category	Number of Attritional Burials	Frequency of Attritional Burials	Number of Famine Burials	Frequency of Famine Burials	*p*-value	
Perinatal – 1 year	23	2.4%	13	1.1%	< 0.001	< 0.001
1–5 years	13	1.3%	9	0.8%		
6–11 years	31	3.2%	101	8.6%		
12–17 years	88	9.1%	149	12.8%		
Adult	814	84%	897	76.7%		–
Total	969	100%	1169	100%		

spaced famines in 1252 and 1257–1258. Finally, the mass burials from Period 17 align with at least nine separate instances of famine in 1401, 1416, 1434, 1439, 1440, 1486, 1491, 1497, and 1521, supporting the assertion that the Type D pits were dug to accommodate famine-related mortality (Sidell et al., 2007; Jones et al., 2012).

This study evaluates the relationships among burial type (attritional vs. famine), non-adult age at death, and the presence or absence of porotic hyperostosis, cribra orbitalia, LEH, or periosteal lesions on the tibia, to determine whether there are significant associations between burial type and skeletal lesions that exist in the absence of an age effect. To ensure the analyses compared strictly attritional and catastrophic burials, we conservatively included only the Type A (attritional) and Type D (famine) burials. This approach is consistent with previous publications examining the relationship between skeletal indicators and famine burials in adults from SRP98 (Yaussy et al., 2016). Further, because the focus of these analyses is how earlier life insults influenced risk of famine mortality in later childhood and adolescence, the site phase (Period 16) that includes the Black Death (which occurred between A.D. 1349–1350 in London) was excluded from the study. Although some of the Type D burials from Period 16 (A.D. 1250–1400) are unassociated with the catastrophic mortality caused by the Black Death (or subsequent plague epidemics, such as those in 1361–1362, 1369, 1375, and 1391), the mass burials associated with plague and those associated with famines within the period (e.g., England's Great Famine of 1315–1318) cannot be feasibly distinguished at this time. Therefore, only data from Period 14 (A.D. 1120–1200), Period 15 (A.D. 1200–1250), and Period 17 (A.D. 1400–1539) are used in this study, as these periods either pre-date (Periods 14 and 15) or post-date (Period 17) the major 14th-century plague outbreaks in London.

2.2. Age estimation

All data for this study were previously collected by researchers at MoLA and were obtained from the Wellcome Osteological Research Database (WORD). Inclusion in WORD is limited to those individuals from SRP98 who are at least 35 percent complete and exhibit those skeletal features necessary to estimate age and (in adults) sex. For those individuals who fulfilled these inclusion criteria, non-adult ages at death (perinatal, 1–6 months, 7–11 months, 1–5 years, 6–11 years, and 12–17 years) were estimated by MoLA using conventional methods based on diaphyseal length, dental development and eruption, and epiphyseal fusion (Powers, 2012). When necessary, age categories were combined to ensure sufficient sample sizes for analysis. Adults are included in Table 1 only to evaluate differences in the non-adult vs. adult composition of the attritional and famine burials from Periods 14, 15, and 17; adults were not included in the hierarchical log-linear analyses.

2.3. Skeletal indicators of stress

Data on the skeletal indicators of exposure to physiological stress used in this study (cribra orbitalia, porotic hyperostosis, periosteal new bone formation, and LEH) were also obtained from WORD. Cribra orbitalia and porotic hyperostosis are characterized by porotic lesions on the orbital roofs and cranial vault, respectively. The lesions result from expansion of the diploë and resorption of the outer table of the skull due to bone marrow hypertrophy (Stuart-Macadam, 1992; Ortner, 2003; Walker et al., 2009). Often, these lesions are attributed to anemia, particularly iron-deficiency anemia. However, there is evidence that iron deficiency inhibits marrow hypertrophy and thus would not cause marrow expansion (Walker et al., 2009; however, cf. Oxenham and Cavill, 2010 and McIlvaine, 2015). Moreover, studies have demonstrated that inflammation, osteoporosis, and rickets are also potential sources of porotic lesions (Wapler et al., 2004). In this study, we make no attempt to determine the etiologies of cribra orbitalia or porotic hyperostosis in our sample, but instead use them as nonspecific indicators of exposure to physiological disturbances during early childhood development (both cribra orbitalia and porotic hyperostosis form predominantly between the ages of 6 months to 12 years of age; Mittler and Van Gerven, 1994). Only those individuals with preserved, scorable skeletal elements were included in the analyses. Porotic hyperostosis was scored as present in WORD when micro- or macroporosity was observed on one or more cranial vault bones. Of the cranial vault bones, the parietals were most commonly preserved and scored for porotic hyperostosis, and provided the largest sample size for analysis of porotic hyperostosis presence (i.e., only individuals with the right, left, or both parietals were included). For cribra orbitalia, WORD (Connell and Rauxloh, 2013) provides lesion scores of 1–5 (1 = "capillary like impressions on the bone", 2 = "scattered fine foramina", 3 = "large and small isolated foramina", 4 = "foramina have linked into a trabecular structure", 5 = "outgrowth in trabecular form from the outer table surface") based on the grading system of Stuart-Macadam (1991). The scores for both cribra orbitalia and porotic hyperostosis were collapsed into scores of "0" for absent and "1" for present for the analyses used in this study. We have conservatively considered orbital lesions of types 0 and 1 to be "absent" (i.e., no cribra orbitalia), while orbital lesions of types 2–5 were considered "present".

Linear enamel hypoplasias (LEH) are produced when enamel formation is disrupted by stressors such as infection or malnutrition (and in some cases, trauma to the jaw; see Andreasen and Ravin, 1973), leaving permanent horizontal lines or pits on tooth enamel (Goodman et al., 1980; Larsen, 1997; White et al., 2011). Enamel formation on the permanent teeth occurs during childhood, meaning that physiological insults during early life leave an enduring record of disruption. LEH are considered a nonspecific indicator of stress (Ortner, 2003), so no attempt was made in this study to determine the specific etiology or source of the lesions. LEH were identified macroscopically on the mandibular canines and were scored as present ("1") if at least one defect was visible under good lighting and absent ("0") if no defects were visible to the naked eye. The mandibular canines have a relatively long developmental time span (enamel forms on the mandibular canine from approximately age 6 months to 6 years of age; Reid and Dean, 2006) and are highly sensitive to physiological disturbance and frequently exhibit hypoplastic defects, which suggests that they are a good indicator of insults that occur early in life (Goodman et al., 1980, 1985).

Periosteal new bone formation (periosteal lesions) is a response to trauma or inflammation generally (Weston, 2008; White et al., 2011), and can occur at any point during the lifespan (i.e., it is not restricted to childhood disturbances as is often the case with the other lesions included in this study). As with the other skeletal lesions examined in this

Table 2
Results of Chi-square analyses of the association between burial type and presence of skeletal indicator.

	Famine	Attritional	*p*-value
Linear Enamel Hypoplasia (n = 223)	55.2%	43.8%	0.100
Periosteal New Bone Formation (n = 292)	7.5%	8.6%	0.753
Porotic Hyperostosis (n = 344)	8.4%	11.8%	0.320
Cribra Orbitalia (n = 305)	48.1%	35.8%	0.045

study, we do not attempt to discern the specific etiology of periosteal lesions. Instead, we use periosteal lesions as a general indicator of disease, chronic or acute infection, or physiological insult. Moreover, because we consider individuals with specific diseases (e.g., leprosy or treponemal infection) to be physiologically frail relative to their peers, we did not differentially diagnose these conditions and did not exclude individuals with them from our analyses. We analyzed data from non-adults possessing at least two-thirds of either tibia. The tibia was used in this study because it is more likely than other skeletal elements to present with periosteal lesions. The anterior tibia has little soft tissue between it and the external environment, making it susceptible to repeated injury and bacterial infection. In addition, the tibia's slow immune response and elevated osteogenic potential make it likely to develop periosteal new bone in response to acute insult or chronic infection (Gallay et al., 1994; Roberts and Manchester, 2007; Klaus, 2014). Periosteal lesions were scored as absent ("0") if no new bone formation was visible to the naked eye, and present ("1") if any new bone formation was observed on the anterior tibial diaphysis.

To ensure sufficient sample sizes, each skeletal indicator was analyzed separately, meaning that all non-adults with the appropriate skeletal element were considered for analysis of that lesion type. In other words, all individuals with the right, left, or both orbital roofs were examined for cribra orbitalia (n = 305). Likewise, individuals with the right, left, or both parietals were examined for porotic hyperostosis (n = 344), individuals with the right, left, or both tibiae were examined for periosteal new bone formation on the anterior surface of the diaphysis (n = 292), and individuals with the right, left, or both mandibular canines were examined for LEH (n = 223).

2.4. Hierarchical log-linear analyses and Chi-square analyses

Chi-square analyses were conducted to preliminarily examine the associations between age and burial type and between skeletal indicator presence and burial type, as well as the direction of differences in the event that significant differences were indicated by hierarchical log-linear analyses. Given our relatively small sample sizes (as are typical of bioarchaeological studies) and because of the issues associated with conventional null hypothesis significance testing and *p*-values (see for example, Lang et al., 1998; Cohen, 2011; Trafimow and Marks, 2015), we are wary of relying too heavily on p-values to interpret our findings. However, we consider *p*-values equal to or less than 0.1 as indications of associations that are worthy of additional consideration.

The interactions among non-adult age at death, famine or attritional burial, and each skeletal stress indicator were analyzed using hierarchical log-linear analysis, which allows us to test the significance of all three-way interactions, as well as other, lower order interactions (e.g., the two-way interaction between skeletal stress indicator presence and burial type). Hierarchical log-linear analysis allows for the evaluation of the associations among more than two categorical or binary variables, so it is possible to determine whether there are significant associations between burial type and skeletal stress markers that exist in the absence of an age effect. Non-significant interactions among variables were removed via backwards elimination with a statistical significance criterion of 0.01. We note that we selected this relatively conservative criterion for elimination in the hierarchical log-linear analyses in order to reveal the maximum number of significant associations. As with the Chi-square analyses, we considered *p*-values at or below 0.1 to be suggestive of a trend when evaluating the results of the hierarchical analyses.

3. Results

The age-at-death distributions for the attritional and famine burials from SRP98 Periods 14, 15, and 17 are shown in Table 1 (note: these data are not limited to individuals scored for skeletal stress indicators and thus the sample sizes are larger than those used for hierarchical log-linear analyses). Comparisons of the distributions including and excluding the adult age category reveal significant differences ($p < 0.001$ in each case). There is a higher proportion of non-adults in the famine burials compared to the attritional burials, and among the non-adults, there is a lower proportion of those ages 0–5 and a higher proportion of those between 6–17 years in the famine burials compared to the attritional burials.

As shown in Table 2, the Chi-square analyses indicate a positive association between famine burial and the presence of LEH and between famine burial and the presence of cribra orbitalia. Periosteal new bone formation and porotic hyperostosis did not exhibit a significant association with burial type.

A summary of the hierarchical log-linear results is presented in Table 3. There is no significant three-way association among age, burial type, and skeletal indicator for any of the four skeletal indicators of stress included in this study. Among the two-way associations we tested, there is a higher frequency of LEH in the famine burials compared to attritional burials (55.2% vs. 45.8%; $p = 0.094$), and this association exists independent of an age effect. The hierarchical log-linear analysis results also suggest that the apparent significant association between burial type and cribra orbitalia presence (a higher frequency in the famine burials, 48.1% vs. 35.8%) is actually an artifact of a significant association between age and cribra orbitalia presence ($p < 0.001$) and a significant difference in the age distributions between the two burial types when the data are limited to those individuals who were scored for cribra orbitalia ($p = 0.021$). When analyzed independently of age, there is no significant association between burial type and cribra orbitalia ($p = 0.299$).

As with the Chi-square analyses, hierarchical log-linear analyses reveal that periosteal new bone formation and porotic hyperostosis were not significantly associated with burial type. In addition, the non-adult age at death categories analyzed in this study were not

Table 3
Results of hierarchical log-linear analysis of the associations among age, burial type, and skeletal indicator.

	Variable	*p*-value
Linear Enamel Hypoplasia (LEH)	Burial Type × Age × LEH	0.983
	Age × LEH	0.660
	Burial Type × LEH	0.094
	Burial Type × Age	0.299
Periosteal New Bone Formation (PNBF)	Burial Type × Age × PNBF	0.688
	Age × PNBF	0.076
	Burial Type × PNBF	0.765
	Burial Type × Age	0.907
Porotic Hyperostosis	Burial Type × Age × Porotic Hyperostosis	0.460
	Age × Porotic Hyperostosis	0.007
	Burial Type × Porotic Hyperostosis	0.370
	Burial Type × Age	0.603
Cribra Orbitalia	Burial Type × Age × Cribra Orbitalia	0.989
	Age × Cribra Orbitalia	< 0.001
	Burial Type × Cribra Orbitalia	0.299
	Burial Type × Age	0.021

significantly associated with either the famine or attritional burial types among those scored for LEH, periosteal new bone formation, and porotic hyperostosis (though, as noted above, there is a difference in age distributions in general and among those scored for cribra orbitalia). Lastly, the presence of periosteal new bone formation on the tibiae, porotic hyperostosis, and cribra orbitalia were all associated with age, independent of burial type. Periosteal lesions on either tibia ($p = 0.076$) and porotic hyperostosis on either parietal bone ($p = 0.007$) were most common in the oldest non-adult age at death category (12–17 years). Likewise, cribra orbitalia on either orbital roof ($p = 0.000$) was most frequent in an older age category (6–11 years; 60.0%), although the oldest age category (12–17 years) did not show a comparably high frequency of cribra orbitalia presence (40.4%) and was most similar to the pattern observed in the middle age category (1–5 years; 40.0%).

4. Discussion

The differences in age-distributions between the famine and attritional burials are broadly what we expect based on previous findings in more recent contexts, suggesting specifically, that children faced disproportionate risks of mortality during famines (the same has also been observed for elderly people in recent famines, though our focus here is on non-adults and thus we have not detected a differential effect at late adult ages). For example, as detailed above, in several cases of modern famines, some of the greatest proportional increases in mortality occurred among children between the ages of 5–9 years (Watkins and Menken, 1985), and it has been suggested that the post-weaning years—when the nutritional and immunological benefits of breast milk are no longer available—are associated with elevated vulnerability for children during famine (Stuart-Macadam, 1995; Maharatna, 1996).

The positive association between LEH and famine burials suggests that early exposure to physiological insults affected frailty, and thus morbidity and mortality, particularly in the context of famine in medieval London. As mentioned above, Jones et al. (2012) previously examined frequencies of LEH among non-adults in SRP98, but did not find a consistent (or consistently significant) pattern of association between LEH and burial type across or within Periods. According to Jones, there were higher frequencies of LEH in general in famine burials in Periods 14 (A.D. 1120–1200) and 17 (A.D. 1400–1539). In Period 15 (A.D. 1200–1250), however, there were higher frequencies of LEH in famine burials only among older non-adults (aged 6–17 years); by contrast, LEH frequencies were actually higher in attritional burials among children ages 1–5 years in Period 15. By pooling data across Periods, we obtain a broader view of these associations, and have sample sizes sufficient for controlling for age. The results of this study suggest that non-adults who experienced physiological disturbances during development severe enough to interfere with enamel formation were more likely to die during conditions of famine than was true under normal conditions of mortality. This association between LEH presence and famine mortality supports bioarchaeological studies of the developmental origins of health and disease hypothesis (DOHaD, also known as the fetal origins or Barker hypothesis), which suggests that fetal and early life insults (evinced here by enamel hypoplasia) impact the individual's phenotype or immunological competence, influencing frailty and later morbidity and mortality (Armelagos et al., 2009). As we have argued for a similar association between short femora in adults and famine burial in SRP98 (DeWitte and Yaussy, 2017), this does not mean that LEH was not also associated with elevated risks of mortality under normal, non-famine conditions in this population. Rather, these results might reflect an exacerbation of underlying vulnerabilities in the face of starvation and attendant infectious diseases during times of medieval famine that elevated the mortality risks of relatively frail individuals even higher than they would have been during non-famine years. In other words, though the causes of mortality (e.g., infectious diseases) might have been largely the same for non-adults during famine and non-famine periods, the risk of mortality associated with those causes was perhaps heightened during famine periods for individuals who had experienced earlier life physiological insults evinced by LEH.

The results for LEH and cribra orbitalia are consistent with our previous study of skeletal lesions among adults in this cemetery (Yaussy et al., 2016). As in our previous study, we found that cribra orbitalia was not associated with either the famine or attritional burial types (independent of an age effect), and we suggested that cribra orbitalia may not be as sensitive an indicator of frailty as LEH in the context of medieval London. Although not addressed in our previous study, porotic hyperostosis on the parietal bones also appears to follow this pattern and is not clearly informative about frailty in this context. As was true with the findings for LEH, Jones et al.'s (2012) analyses of these lesions in SRP98 did not reveal consistent patterns (nor consistently significant differences) between burial types. For example, in that study, for both indicators, there was little difference in the frequencies observed in the famine and attritional burials in Period 15 (A.D. 1200–1250). However, contrary to our results, previous analyses of the non-adults from Period 14 (A.D. 1120–1200) suggested a trend of higher frequencies of cribra orbitalia and porotic hyperostosis among famine burials. Overall, the results obtained by Jones et al. (2012) and the results obtained by this study underscore the assertion that cribra orbitalia and porotic hyperostosis are not consistently informative about frailty in the context of medieval London.

In contrast to our previous study of adults from SRP98 (Yaussy et al., 2016), we did not find an association between periosteal new bone formation and attritional burials among non-adults from SRP98. In our previous paper, we suggested that the positive association between attritional burial and age among adults reflected relatively low frailty, and that high frequencies of periosteal lesions among individuals in attritional burials indicated an ability to survive physiological disturbances long enough to form periosteal new bone (Yaussy et al., 2016). Our results are bolstered by previous evidence that suggests periosteal lesions among adults represent the accumulation of nonlethal physiological insults over a relatively long life (Grauer, 1993; DeWitte, 2014). In contrast, non-adults die after a relatively short life, limiting the period during which they can survive nonlethal physiological insults and accrue periosteal lesions. This may explain why periosteal new bone formation was not significantly associated with either burial type (famine or attritional) among the non-adults from SRP98. We note that Jones et al. (2012) found conflicting patterns among the Periods; analysis by Period did not reveal a consistent pattern of association between periosteal new bone formation and burial type or age.

The observed two-way associations between age and several of the analyzed skeletal indicators (cribra orbitalia, porotic hyperostosis, and periosteal lesions) are perhaps not surprising, particularly if we heed the recommendations of Wood et al. (1992) and avoid making strictly binary interpretations of the presence of skeletal lesions (i.e., we should not assume in all cases that a lack of lesions indicates low frailty and vice versa). The presence of periosteal new bone on the tibiae was significantly associated with the oldest age group (12–17 years), which could indicate that older non-adults from medieval London who survived injury or infection earlier in life accrued periosteal lesions over time. Studies of periosteal lesions among adult individuals (e.g., Grauer, 1993; DeWitte, 2014; Yaussy et al., 2016), suggest that periosteal lesions may signal relatively low frailty, as only individuals with relatively low frailty could survive physiological insults (sufficient to cause periosteal lesions) that proved lethal to frailer individuals. Although all the non-adults in the St. Mary Spital collection eventually died for one reason or another, the older individuals that survived all previous lesion-causing insults to reach adolescence may have been less frail than their peers that died at younger ages and before lesions could develop. Assessment of this hypothesis, however, is limited by the nature of the WORD data, which does not consistently specify the activity of the recorded periosteal lesions (healed vs. active). It would be of interest for future studies to examine whether periosteal lesions among adolescents in the St. Mary Spital sample were primarily healed rather than active, which would suggest that these individuals were less frail than their peers with active lesions and survived earlier episodes of stress that caused periosteal new bone formation. An alternative explanation for the higher frequency of periosteal lesions among adolescents compared to their younger peers could be that this pattern reflects the difficulty with which pathological new bone formation is identified in non-adults. In individuals under 4 years of age, the disorganized, porous appearance of woven bone deposited because of trauma or infection may be, at least in some cases, indistinguishable from the woven bone associated with the normal process of appositional growth (Ortner, 2003; cf. Ribot and Roberts, 1996). Therefore, the higher frequency of periosteal lesions among adolescents may be an artifact of the macroscopic detection methods employed by this study, rather than a true indication of age-related frailty among non-adults.

The high frequency of cribra orbitalia and porotic hyperostosis among older children and adolescents agrees with reports from other archaeological samples (e.g., Fairgrieve and Molto, 2000; Salvadei et al., 2001; Facchini et al., 2004). The presence of these skeletal indicators is often attributed to iron-deficiency anemia caused by dietary deficiency, diarrheal diseases, parasitic infection, or other factors. In addition to high nutritional demands among rapidly growing children, the diet of medieval Londoners generally was predominated by iron-deficient cereals, especially among the poor who could not afford meat until the later medieval period (Dyer, 1998). Without adequate food supplementation after weaning, high nutritional demands, deficient dietary intake, persistent diarrheal diseases, and high pathogen loads could have predisposed non-adults to porotic lesions as they approached adulthood. However, the development of new cribra orbitalia lesions may also be dependent upon non-adult age, further explaining the trend in lesion presence by age at death. Our results are consistent with Stuart-Macadam's (1985) hypothesis that cribra orbitalia is a childhood condition. The youngest group of non-adults analyzed in this study (largely composed of neonates) may have been protected from anemia-related hypertrophy by iron stores amassed in utero, which are typically exhausted within the first 6 months of life (Institute of Medicine, 2001). Non-adults older than 6 months are at risk of iron deficiency, since breastmilk is not sufficient to meet the dietary needs of these infants without complementary food supplementation (Institute of Medicine, 2001). In medieval England, weaning typically took place at 1 to 2 years of age (Fildes, 1986), further increasing the risk of iron-deficiency anemia. Breastmilk would often be supplemented with animal milk or other liquids, which may have promoted gastrointestinal bleeding or chronic diarrhea (Stuart-Macadam, 1995; Lewis, 2007). The dramatic increase in cribra orbitalia from the neonatal/infant age group to the young child (1–5 years at death) is likely connected to this period of persistent iron deficiency and physiological insult, and has been recognized in previous bioarchaeological studies (e.g., Mittler and Van Gerven, 1994). However, the highest frequency of cribra orbitalia lesions was among older children (6–11 years at death), with a slight decrease in lesion presence in the adolescent group (12–17 years at death). The adolescent group may not exhibit as high a rate of cribra orbitalia presence because of the nature of the marrow in the medullary cavities of the orbital roofs. By age 12, portions of red (erythropoietic) marrow have been converted to inactive yellow marrow, and, as a result, anemia-induced erythropoiectic marrow hypertrophy in adolescents does not exceed the capacity of the medullary cavity and generate cribra lesions, as it does in younger non-adults (Stuart-Macadam, 1985). Because non-adults in the oldest age group may have experienced iron-deficiency anemia and increased risk of death without exhibiting skeletal lesions, it may be that cribra orbitalia is not a sensitive indicator of frailty among adolescents.

It is also possible that changes to the immune system throughout the non-adult period had an effect on frailty and mortality risk, and thus could have influenced the age-related lesion patterns observed in the SRP98 skeletal assemblage. Newborn infants and very young children (i.e., the youngest age categories used in this study, < 1 year and 1–5 years at death), exhibit a more pronounced T-helper 2 (Th2) and diminished T-helper 1 (Th1) response to infection compared to older non-adults and adults (Dowling and Levy, 2014). As a result, early life Th1-specific responses to bacterial or viral infections are impaired relative to Th2-specific responses to foreign threats such as extracellular parasites (Mosmann and Coffman, 1989). Many young non-adults during the medieval period succumbed to disease before skeletal lesions could manifest (Redfern, 2012), suggesting that the association between age and lesion presence for cribra orbitalia, porotic hyperostosis, and periosteal new bone formation (independent of burial type) may be due to age-related immune system deficiencies and disease risk among the youngest non-adults. In other words, though lesions like cribra orbitalia and porotic hyperostosis still indicate frailty associated with malnutrition, blood loss, or a heavy pathogen load during childhood (Stuart-Macadam, 1992), the individuals exhibiting these lesions also had to survive long enough to develop a bony response to physiological disturbance. Therefore, the older children and adolescents with skeletal lesions were perhaps frail, but they may have been relatively less frail than the youngest non-adults who perished before these lesions could manifest.

5. Conclusion

This study suggests that exposure to certain physiological insults in early childhood impacts frailty in later childhood and adolescence, contributing to patterns of mortality during famines. Our results demonstrate an association between LEH presence and inclusion in famine burials. However, the results of this study also suggest that not all skeletal lesions are equally sensitive or can be considered reliable gauges of frailty in this context. Cribra orbitalia, porotic hyperostosis, and periosteal new bone formation were not associated with either the attritional or famine burial types, but were more frequently associated with older age at death, suggesting that nonspecific lesion presence in older non-adults may signal relatively low frailty among older individuals compared to younger individuals who died before any lesions could develop.

Conflicts of interest

None.

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