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Linear Enamel Hypoplasia and Age-at-Death at Medieval (11th–16th Centuries) St. Gregory's Priory and Cemetery, Canterbury, UK

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ABSTRACT Linear enamel hypoplasia (LEH) is a macroscopically detectable band-like dental defect, which represents localized decrease in enamel thickness caused by some form of disruption to a child's health. Such dental deformations are utilized in osteoarchaeological research as permanent markers of childhood physiological stress and have been extensively studied in numerous ancient human populations. However, currently there is no such data for medieval populations from Canterbury, UK. Here, LEH is examined in the context of age-at-death in human burials from the medieval St. Gregory's Priory and adjacent cemetery (11th–16th centuries), Canterbury, UK. The cemetery and Priory burials represented lower ($n = 30$) and higher status ($n = 19$) social groups, respectively.

Linear enamel hypoplastic defects were counted on mandibular and maxillary anterior permanent teeth ($n = 374$). The age and sex of each skeleton were estimated using standard methods. Differences in LEH counts, age-at-death, and LEH formation ages were sought between the two social groups. Results indicate significantly greater frequencies of LEH in the Cemetery (mean = 17.6) compared to the Priory (mean = 7.9; $t = -3.03$, df = 46, $p = 0.002$). Adult age-at-death was also significantly lower in the Cemetery (mean = 39.8 years) compared to the Priory burials (mean = 44.1 years; $t = 2.275$, df = 47, $p = 0.013$). Hypoplasia formation ages differed significantly between the Priory (mean = 2.49 years) and Cemetery (mean = 3.22 years; $t = 2.076$; df = 47; $p = 0.034$) individuals.

Results indicate that childhood stress may reflect adult mortality in this sample, and that the wellbeing of individuals from diverse social backgrounds can be successfully assessed using LEH analyses. Results are discussed in terms of the multifactorial etiology of LEH, as well as weaning-related LEH formation. Copyright © 2012 John Wiley & Sons, Ltd.

Key words: linear enamel hypoplasia; age-at-death; social status; medieval Canterbury

Introduction

Childhood physiological stress can disturb enamel formation, producing localized hypoplastic defects that can emerge on the outer tooth surface (Hillson, 1992; Larsen, 1997; Reid & Dean, 2000, 2006; Hubbard *et al.*, 2009). These malformations occur in several forms (e.g. irregular depressions, pitting, or furrowing) (Hillson & Bond, 1997), but linear enamel hypoplasia (LEH) is the most commonly reported (Hillson, 1996; Griffin & Donlon, 2008). The health of archaeological samples of modern human populations can be deduced from LEH analyses (Larsen, 1997; Roberts & Manchester, 2005), because of the non-specific nature of this dental pathology (Goodman & Armelagos, 1985). Although many aetiological explanations, such as childhood disease (e.g. measles) and malnutrition (Goodman & Armelagos, 1988; Larsen, 1997; Roberts & Manchester, 2005), as well as weaning (Blakey *et al.*, 1994), and accidental consumption of toxins (Neiburger, 1990) have been put forward as factors underlying LEH formation, it can be difficult to identify these causes in human archaeological samples. Thus, the majority of prior research has focused on LEH as a permanent marker of 'general' childhood physiological stress (e.g. Rose *et al.*, 1978; Goodman & Armelagos, 1988; Wright, 1997; Palubeckaitė, 2001; Šlaus *et al.*, 2002;

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King *et al*., 2005; Boldsen, 2007; Griffin & Donlon, 2007; Mays & Barber, 2008; Dabbs, 2011; Krenz-Niedbała & Kozłowski, 2011).

Numerous studies have examined the relationship between hypoplastic defects and stress in the context of social status from archaeological sites (e.g. Lanphear, 1990; Cucina and Işcan, 1997; Cucina, 2002; Starling & Stock, 2007; Tomczyk *et al*., 2007; Mayes & Barber, 2008; Dabbs, 2011). A variety of themes have been covered, including: LEH prevalence correlated with weaning and differences in subsistence strategies (Lanphear, 1990); varied population stress levels associated with cultural amelioration (Dabbs, 2011); high status or more 'privileged' ancient groups affected by LEH (Cucina and Işcan, 1997; Mayes & Barber, 2008); or links between LEH and periods of food scarcity (Tomczyk *et al*., 2007). When examined in the context of age-at-death, LEH records also show positive associations, implying that severe childhood stress can affect longevity (e.g. Šlaus *et al*., 2002; Palubeckaitè *et al*., 2002; King *et al*., 2005; Boldsen, 2007; Armelagos *et al*., 2009). However, not all projects implement consistent methodological controls when collecting LEH data. For example, in order to avoid bias and increase sample size some studies choose to use only one tooth (often from one side of the jaw) (e.g. Boldsen, 2007), but this restricts addressing potential systemic stress. Often, more specific tooth types (e.g. anterior dentition only) or jaw sides are chosen and control for dental calculus, but not wear is implemented (or at least reported) (e.g. Šlaus *et al*., 2002; Palubeckaitè *et al*., 2002). Only a few studies report complete exclusion of heavily worn dentition and analyze specific tooth types that display minimal attrition and dental calculus (in some cases, the latter is manually removed for the purpose of analysis) (e.g. Cucina, 2002; Griffin & Donlon, 2007). When examining stress markers registered in teeth, it is indeed of importance to assign as many methodological controls as possible to account for age-related tooth loss and dental wear, and also identify systemic stress by comparing more than one tooth type (e.g. King *et al*., 2005), particularly when two or more groups are contrasted.

It is clear that osteoarchaeology has seen an abundance of research analyzing LEH in relation to other factors in a variety of past populations. However, no prior published analyses considered addressing (potential) childhood stress and possibly linked social status in human groups of medieval Canterbury (Kent, UK) (Figure 1). Historical aspects of medieval British societies allow constructing hypotheses that aim to study any links between health and stress as the Middle Ages were dominated by feudalism and the church, causing populations to divide into different socio-economic 'classes' (Hull, 1989). Consequently, these were reflected in the quality of life led by individuals representing different status groups, as demonstrated in the accelerated spread of infectious disease (such as leprosy) (Roberts & Manchester, 2005) and restricted access to exclusive types of foods (Dyer, 2003) in lower ranking individuals (Hull, 1989). Thus, results of a carefully controlled study carried out on two distinct archaeological groups, dated to the medieval period (11^{th} – 16^{th} centuries) from Canterbury (UK) are here reported. It is hypothesized

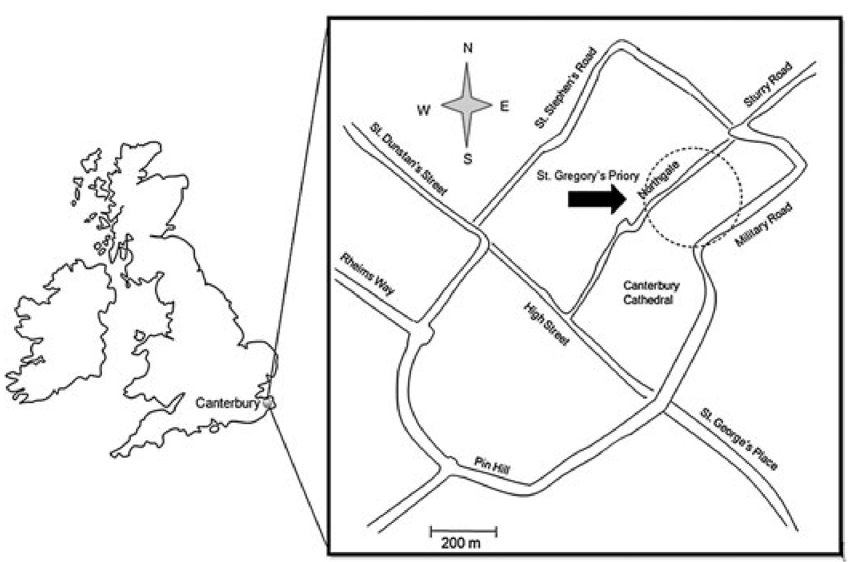

Figure 1. Approximate location of St. Gregory's Priory in contemporary central Canterbury, UK.

that adult age-at-death estimates, LEH counts, and LEH age formation estimates can aid the identification of stress and mortality caused by differences in social status.

Materials and methods

Study population

Medieval human skeletal remains recovered at the St. Gregory's Priory and a nearby Cemetery in the Northgate area of Canterbury (Kent, UK) (Figure 1), were examined. St. Gregory's Priory was established in the 11th century by Lanfranc, the Archbishop of Canterbury, and it functioned until the early 16th century (Woodcock, 1956:xi; Tatton-Brown, 1995; Hicks & Hicks, 2001). Historical and archaeological textual records imply that there was a distinct divide in the socio-economic status between individuals buried within the cemetery and those occupying St. Gregory's Priory (Tatton-Brown, 1995; Hicks & Hicks, 2001). The Priory was established for the clergy to minister to the sick and provide burial for financially depleted members of the medieval society in the associated cemetery. Therefore, burials examined in this study represented two distinct social groups, higher (Priory $n = 19$) and lower status (Cemetery $n = 30$), as inferred from burial location (Hicks & Hicks, 2001). The Priory originally contained a considerably small amount of burials due to its historical context. Furthermore, excluding juvenile remains and applying restrictive dental controls means that this study evaluates a limited sample size, but on the other hand, it presents a carefully controlled methodological approach.

Osteological and statistical procedures

Adult age-at-death and sex were estimated following standard osteological methods (Buikstra & Ubelaker, 1994). In total, 374 (maxillary and mandibular) permanent canines and incisors were examined, as approximately 4.6% teeth were missing due to ante- or post-mortem loss as identified from empty tooth sockets. Posterior tooth rows were excluded from analyses, because they exhibit age-related occlusal attrition in adult samples (Miles, 1962; Hillson, 1996). Focusing on anterior dentition allowed for comparisons of the same tooth types across the board. In order to ensure that anterior wear did not skew results by erasing evidence of any formed defects, only comparably worn teeth displaying minimal amount of calculus (i.e. unmasking hypoplastic defects) were examined, further reducing sample size. This was achieved by ensuring that only maximum one third of the occlusal tooth section (after intermediate, preceded by cervical) was worn down in all studied individuals.

Hypoplastic defects were counted following the 'Field method' (Hassett, 2011) (Figure 2), which involves identifying lines macroscopically (Buikstra & Ubelaker, 1994; Brickley & McKinley, 2004). The anterior surface of each tooth with detected LEH was examined using a standard magnifying glass to minimize under- or over-estimating of LEH total counts for each tooth. A hypoplastic line was counted only if it extended horizontally across the labial tooth surface, measuring a minimum three quarters in length (e.g. Griffin & Donlon, 2008). Following this, the location of lines was compared to the timings of anterior tooth growth diagrams devised by Reid and Dean (2000; 2006) to estimate the age of LEH formation. Although many prior LEH publications have used other sources of LEH age determination, such as tooth mineralization stages by Bass (1995) (e.g. Boldsen, 2007) or a more conventional method by Massler *et al.* (1941) (e.g. Palubeckaitè *et al.*, 2002; Krenz-Niedbała & Kozłowski, 2011); Reid and Dean's (2000, 2006), work on tooth formation times is based on histological examinations that take into account the so-called hidden (appositional) enamel (King *et al.*, 2002) providing a reliable source for obtaining LEH formation age. A criterion identifying systemic stress was set to be confirmative if two or more teeth exhibited simultaneously forming LEH bands (e.g. Palubeckaitè *et al.*, 2002; King *et al.*, 2005).

Statistical analyses were performed in SPSS/PASW 18.0. It was impossible to explore sex differences as female skeletons were a minority in each group. This has resulted in pooling sexes together. Due to high and comparable records of presence of LEH in both groups, no statistical tests were run to determine disparities in prevalence as identified by dental defect presence or absence, rather differences in the frequencies (e.g. Boldsen, 2007; Griffin & Donlon, 2008) of hypoplasia and age-at-death, as well as hypoplastic line formation ages were sought using an independent samples t-test.

Results

Descriptive statistics are available in Tables 1–3. Presence of hypoplasia was recorded in the vast majority of individuals, with only two samples from the cemetery and four from the Priory displaying entirely unaffected dentition. The highest counts of lines were noted for upper left central incisor and both lower canines in the Cemetery (Table 2), whereas individuals from the Priory exhibited the highest numbers of hypoplastic lines on the upper left central incisor and lower right canine (Table 2). More hypoplastic bands were recorded among the Cemetery

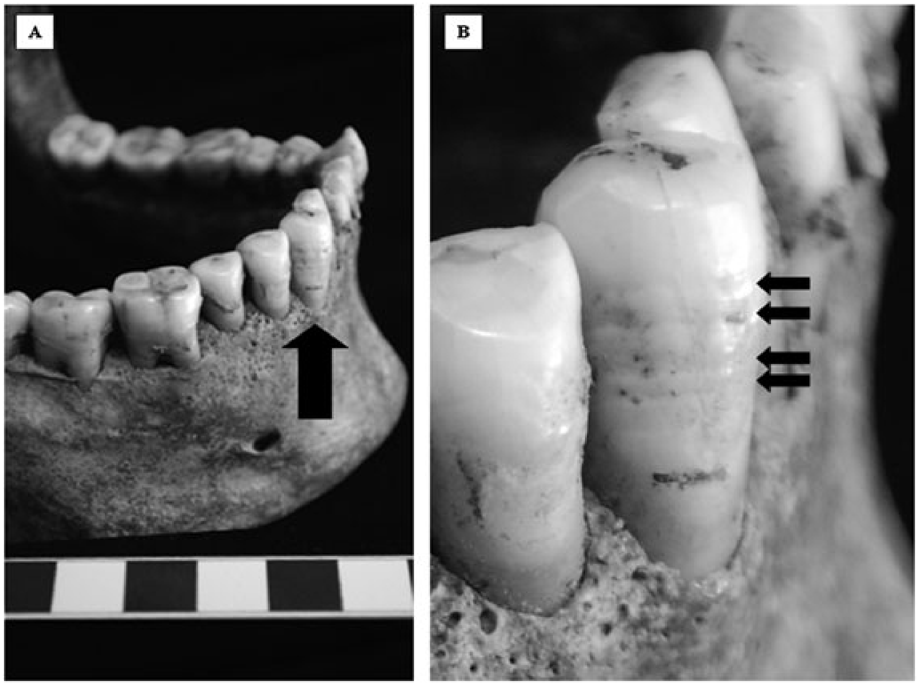

Figure 2. A. Mandible of an adult male displaying LEH on his right canine. B. Mandibular right canine displaying four LEH.

Table 1. Sex and age-at-death descriptive statistics for Cemetery and Priory individuals

Status	Sex	*n*	Min. age-at-death	Max. age-at-death	Mean age-at-death	Standard Deviation
Cemetery	♀	7	27.0	48.1	37.58	7.12
	♂	23	30.0	52.1	40.48	5.73
	Total	30	27	52.1	39.8	6.08
Priory	♀	6	29.5	50.4	40.03	8.21
	♂	13	35.5	55.3	46.01	5.79
	Total	19	29.5	55.3	44.15	7.02

individuals (mean = 17.6) than those from the Priory (mean = 7.9) (Table 3). An independent samples *t*-test produced statistically significant results ($t = -3.03$, df = 45.815, $p = .002$, one-tailed). Age-at-death estimates differed significantly between Cemetery (mean = 39.8 years) and Priory (mean = 44.1 years) samples (t = 2.275, df = 47, $p = 0.0135$, one-tailed) (Table 1). Finally, hypoplastic band formation ages also differed significantly between the groups (Cemetery mean = 3.22; Priory mean = 2.49; t = 2.076, df = 47, $p = 0.034$ one-tailed) (Table 3).

Discussion

The results from this study support the notion that a low socio-economic status can negatively affect an individual's wellbeing and lead to a disrupted enamel formation during childhood, and consequently a shortened longevity. All hypoplastic bands recorded in this study reflected regular patterns, with multiple simultaneously developing lines frequently displayed in both groups. This regularity is suggestive of prevailing physiological alterations (Goodman *et al.*, 1988; Hillson, 1992, 1996), but the data also indicates experiences of systemic stress (King *et al.*, 2005). One individual line could be inferred to have been associated with a single traumatic event, having no relationship with social status or continual stress (Malville, 1997).

Both groups were almost completely affected by LEH; however, the Cemetery individuals displayed significantly higher LEH frequencies, implying that their health was more heavily disrupted during childhood years. It is unlikely that individuals from the Priory

Table 2. Linear enamel hypoplasia descriptive statistics for Cemetery and Priory samples in individual teeth

Status	Jaw	Tooth	*n*	Min. LEH count	Max. LEH count	Mean LEH count	Standard Deviation
Cemetery	Maxillary	LC	22	0	6	2.95	1.86
		LI^2	17	0	5	1.88	1.65
		LI^1	11	0	9	3.00	2.72
		RI^1	12	0	9	2.83	2.85
		RI^2	12	0	5	2.00	1.65
		RC	20	0	5	2.70	1.87
	Mandibular	LC	26	0	6	2.69	2.18
		LI^2	23	0	5	1.70	1.57
		LI^1	20	0	5	1.65	1.84
		RI^1	20	0	5	1.70	1.83
		RI^2	24	0	6	1.67	1.68
		RC	26	0	6	2.69	2.13
Priory	Maxillary	LC	12	0	4	.83	1.40
		LI^2	8	0	2	.25	.707
		LI^1	12	0	4	1.58	1.62
		RI^1	7	0	4	2.00	2.00
		RI^2	8	0	3	.38	1.06
		RC	10	0	4	.90	1.28
	Mandibular	LC	16	0	5	1.56	1.67
		LI^2	14	0	3	.93	1.14
		LI^1	12	0	2	.75	.965
		RI^1	12	0	3	.83	1.11
		RI^2	14	0	3	.64	1.08
		RC	16	0	6	1.75	1.91

Table 3. Linear enamel hypoplasia total counts and formation age descriptive statistics for Cemetery and Priory individuals

Status	Sex	Variable	*n*	Min. data	Max. data	Mean data	Standard Deviation
Cemetery	♀	LEH Total Count	7	2	36	14.43	13.15
		LEH Age Mean	7	1.95	4.18	3.40	.72
	♂	LEH Total Count	23	0	53	18.52	14.97
		LEH Age Mean	23	.00	4.23	3.17	1.05
	Total	LEH Total Count	30	0	53	17.57	14.46
		LEH Age Mean	30	.00	4.23	3.22	.97
Priory	♀	LEH Total Count	6	3	15	7.67	4.54
		LEH Age Mean	6	1.98	4.00	2.99	.79
	♂	LEH Total Count	13	0	30	8.08	8.85
		LEH Age Mean	13	.00	4.55	2.25	1.71
	Total	LEH Total Count	19	0	30	7.95	7.61
		LEH Age Mean	19	.00	4.55	2.49	1.50

did not produce hypoplastic lines, because forming enamel is highly sensitive to many forms of stressors (May *et al.*, 1993; Goodman & Rose, 1990). In this study, Priory individuals can be inferred to have been exposed to a lesser extent of stress when compared to the Cemetery group. Thus, confirming that LEH affects the dentition of more privileged, as well as lower ranking human groups, in line with LEH presence outcomes reported in studies analyzing high status archaeological human samples (e.g. Cucina & Işcan, 1997; Palubeckaitė *et al.*, 2002; Mayes & Barber, 2008).

The Priory individuals had a mean hypoplasia formation age of 2.49 years – a much earlier result than in the Cemetery (3.22 years). It could be tempting to propose that dietary implications of weaning and post-weaning periods which often lead to nutritional imbalances in the early years of childhood (Goodman & Rose, 1990; Blakey *et al.*, 1994; Kennedy, 2005) could have contributed to the formation of LEH in this group, because (on average) human juveniles undergo this event around 2.5 years of age (Kennedy, 2005). It is stressed that in this article, 'weaning' is defined as the cessation of breast-feeding and inclusion of solid non-maternal food soources into juvenile diet (World Health Organization Website, 2002; Griffiths *et al.*, 2007). Although the age at which non-maternal food sources are introduced to weaned children is highly variable amongst human societies (e.g. Stewart-Macadam & Dettwyler, 1995; Griffiths *et al.*, 2007), many osteoarchaeologists assign weaning related significance to 'peak' LEH records (e.g. Lanphear, 1990; Iregren, 1992; Ubelaker, 1992; Moggi-Cecchi *et al.*, 1994; Wright, 1997). On the other hand, some studies have shown that such a link is weak or possibly non-existent (e.g. Blakey *et al.*, 1994; Corruccini *et al.*, 1985; Santos & Coimbra, 1999; Saunders & Keenleyside, 1999; Wood, 1996). Thus, the most suitable interpretation of the above result would be achieved if data informative of the weaning age for this population from Canterbury was available. Unfortunately, no such background information can be found in the literature. Therefore, the reported differences in LEH formation ages remain attributed to non-specific physiological disruptions specific to social status.

To further support the link between health and social status, this project predicted that age-at-death estimates would differ significantly between the medieval Cemetery and Priory. The results imply that longevity records in this sample were in line with the documented differences in status. Mean age-at-death estimates for the former and the latter were 39.8 and 44.1 years, respectively, still falling within the 'middle adult' age category (35–50 years) (Buikstra & Ubelaker, 1994), but were evidently significantly different between each other. Perhaps, more pronounced results would have been obtained had sub-adult and juvenile burials been considered in the analysis. It is potentially a future step for studies exploring the health of this medieval population. Nevertheless, the results do reflect outcomes from other studies that addressed the relationship between childhood stress and longevity (e.g. Šlaus *et al.*, 2002; Palubeckaitė *et al.*, 2002; Steckel, 2005; Boldsen, 2007). Additionally, the present study further adds to Armelagos and colleagues' (2009) bioarchaeological support for the Barker hypothesis, which proposes that pathological events occurring early in life make a negative impact on the adult health (Paneth *et al.*, 1996).

The aetiology of LEH and definition of stress in a bioarchaeological context are of a multi-facetted nature (Goodman & Armelagos, 1988; Neiburger, 1990; Ribot & Roberts, 1996). Researchers have argued that hypoplastic lines are not necessarily valid indicators of physiological (particularly malnutrition) stress (e.g. Neiburger, 1990). Several types of causation of enamel defects have been proposed, including genetic predisposition for defective enamel; single traumatic events; poisoning with chemical or other harmful substances; even cultural modification of teeth (Neiburger, 1990). These are all valid points; however, the degree to which such aspects would influence population-based health profiles is relatively low, as high frequency and severity of LEH would still reflect a continuum of stressful events in a child's life.

Finally, this study finds that hypoplastic defects are valid indicators of stress, especially in the context of age-at-death, when analyzed from a social status hierarchy perspective. However, a purely macroscopic approach to LEH examination could be under-estimating pathological structure of enamel in affected dentition (Hassett, 2011); hence, careful inferences are made about this ancient population. Here, differences in the examined variables indicate exposure to uncertain conditions and suggest continuous physiological disruptions faced during childhood in the Cemetery individuals. Teeth remain the most useful ancient skeletal specimens for detecting markers of stress, as other bone pathologies acquired during childhood are generally difficult to diagnose in adult samples, due to bone modelling and remodelling and thus the disappearance of lesions during bone growth (McHenry & Schulz, 1976; Roberts & Manchester, 2005). The enamel's ability to register disruptive events was useful in researching childhood stress in this sample, particularly as it reflected textually documented social status divide of this population.

Conclusions

The results indicate that childhood stress may reflect adult mortality in this sample, and that the wellbeing of individuals from diverse social backgrounds can be successfully examined via carefully controlled LEH studies. Frequent stress can be assumed for Cemetery individuals, as inferred from the presence of multiple and regular LEH lines. Both groups display LEH; however, significantly lower frequencies in the Priory sample suggest stress of a lesser extent. The mean age-at-death estimates fell within the 'middle adult' category (35–50 years) (Buikstra & Ubelaker, 1994). Perhaps, biological significance of social status would be more pronounced if juvenile burial frequencies were considered. This study provides quantitative data that supports the social status divide of this British medieval population.

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