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THE SUBTLETIES OF STRESS: A COMPARATIVE ANALYSIS OF SKELETAL LESIONS BETWEEN THE MEDIEVAL AND POST-MEDIEVAL BLACK FRIARS CEMETERY POPULATION (13TH TO 17TH CENTURIES)

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ABSTRACT

The study of stress from an osteological perspective is challenging as we use skeletal remains to explore the lived experience and patterns of health. As an intricate overlap of multiple biological processes, the stress response system guides our understanding of how and why stress manifests as it does. Using traditional osteological methods of stress analysis, specifically cribra orbitalia, porotic hyperostosis and enamel hypoplastic lesions, this study focuses on the relationship between these indicators to explore differences in stress manifestation in the medieval and post-medieval periods in Denmark. Using the Black Friars cemetery population (13^{th} – 17^{th} centuries), results show an increase in stress from the medieval into the post-medieval period likely dictated by the strains of urbanism on a predominantly poor population. Additionally, a younger mean age at death was noted when multiple mild-moderate indicators were present as compared to one severe indicator being present. A recognition of the intricacies of the stress response effectively aids in the exploration of stress manifestation and the relationship, if any, between these well-used skeletal indicators.

INTRODUCTION

The study of stress in osteological research is a challenge from both a methdological and theoretical perspective as we use evidence from skeletal remains to help decipher the lived experience of past peoples, including their overall health and well-being. Where 'stress' represents a biological fluctuation mediated by tangible factors (e.g. starvation, disease), 'health' is the embodiment and perception of these biological changes at both an individual and population level (see Temple and Goodman 2014). This study explores stress through commonly used osteological indicators in an attempt to better understand how stress manifests in different skeletal tissues, and how the interaction between these might contribute to our interpretations. More specifically, it explores differences in stress manifestation between the medieval and post-medieval periods in the Danish Black Friars cemetery population.

BACKGROUND

Stress and the Skeleton

Stress can be broadly defined as either an actual or perceived threat triggering a myriad of biological responses that promote organism survival and maintain biological homeostasis (Selye 1936; Selye 1973; Chrousos and Gold 1992; Habib et al. 2001; Charmandari et al. 2005; Chrousos 2009). While the stress response system is a complex series of biological mechanisms, from an osteological perspective stress can only be approached in a rudimentary way largely due to the limitations of working with skeletal remains (Goodman et al. 1988; Armelagos and VanGerven 2003; Steckel 2005). Some of these limitations have been minimized through a variety of studies that champion multiple methods of analysis (e.g. Ribot and Roberts 1996, Larsen 1997; Hoppa and FitzGerald 1999; Steckel and Rose 2002; Lewis 2007) with attention paid to mortality profiles (e.g. DeWitte 2014) and epigenetic considerations (Rodney and Mulligan 2014; Gowland 2015); the introduction of new technologies and cross-disciplinary applications (e.g. Klaus 2014; Scott and Hoppa 2015; Scott et al. 2016); and a re-evaluation of common assumptions regarding how we transform skeletal analyses into commentaries on etiology and overall heath (e.g. Temple and Goodman 2014; DeWitte and Stojanowski 2015). If we are "not measuring health outcomes but rather evaluating stress" (Temple and Goodman 2014:189), then explorations into the subtleties of the stress response and timelines of manifestation must be at the forefront of consideration, where hidden heterogeneity dictates how stress is internalized individually (Wood et al. 1992) and how it manifests in different skeletal tissues (Weinstein et al. 1998; Cooper 2004). As such, when an individual experiences stress they do not necessarily display the entire array of potential stress responses (see Miles and Bulman 1994; Ribot and Roberts 1996), and therefore there is an increasing need to highlight subtle biological shifts that may have had much larger health consequences.

Most often, stress is identified in osteological material by the presence of lesions – so called indicators of stress. However, the challenge lies in how we define the relationship between these lesions. These osteological indicators do not operate in isolation, therefore it is important to consider how the presence of one type of lesion may affect the manifestation of another, or if exposure to one type of stressor alters how the skeleton may respond to subsequent episodes of stress (Goodman et al. 1988; Klaus and Tam 2009). More specifically, at an individual level, stress manifests differently based on multiple factors including age, sex, genetic susceptibility, etc. (Goodman et al. 1988) which is further confounded by cellular variability where teeth for example, are more buffered than bones against different types of stress (Garn et al. 1965).

From a methodological perspective, studies of lesions are our best guide in determining whether or not stress has occurred. However, there are distinct limitations associated with their static nature and the type of data that can be observed (Lewis and Roberts 1997; Lewis 2007). While there are methods to determine age at onset for some of these indicators, they are limited by a short period of formation or the challenges of bone remodelling (Dreizen et al. 1964; Parfitt 1977; 1994; Goodman and Song 1999; Lewis 2000). Further, studies of stress are generally approached from either adult or subadult perspectives with each age cohort suited to different research objectives. However, by assessing the continuum of stress, through examinations of morbidity and mortality profiles, we are able to identify long term health outcomes beyond the period of onset (see Meindl and Swedlund 1977; White 1978; Cook and Buikstra 1979; Rose et al. 1978; Hummert and VanGerven 1983; Porter and Pavitt 1987; Miles and Bulman 1994; Ribot and Roberts 1996; Steckel 2005; Klaus and Tam 2009). While some lesion-based methods can better inform our understanding of causative factors (e.g. Walker et al. 2009), others provide information regarding the age-at-onset (e.g. Newman and Gowland 2015). No one method provides a complete snapshot of the stress response and resultant hard tissue changes influencing the data produced. Further, while these skeletal disruptions represent an activation of the stress response system under the broadest definition, it cannot be assumed that overall health or well-being is equally impacted. How these physical manifestations translate into perceptions of health is far more complicated within a bioarchaeological context (Temple and Goodman 2014). It is with these considerations in mind, that this study explores the stress response within and between skeletal indicators, in an attempt to better understand the lived experience in Denmark during the Middle Ages.

Black Friars Monastery and Cemetery

Established in the first half of the 13th century, the Black Friars Monastery and associated cemetery was established on the island of Fyn in Odense, Denmark (Møntegården Odense bys Museer 2010). Located in the northwestern corner of the city, the Black Friars monastery expanded rapidly with the construction of a second church and quickly became a prominent landmark in the city (Christensen 1988). The religious reach of this order was also extensive when in AD 1316 the friars were allowed to receive confessions at St. Knud's Church (Christensen 1988), giving them further responsibility to their parishioners within the city. After Reformation, which saw the destruction of the Black Friars monastery (Christensen 1988; Becher 1999; Boldsen and Mollerup 2006), the cemetery remained in use until AD 1607 (Christensen 1988). The cemetery had two distinct phases of interment: the medieval or monastic phase (AD 1240 – 1536) and the post-medieval or public phase (AD 1536 – 1607) (Figure 1) (Mollerup and Boldsen 2010). During the medieval period the cemetery was likely reserved for middle class and monastic burials as those who were financially able could pay for their soul to be closer to God after death (i.e., buried in close proximity to the Church) (Jakobsen 2008). Whereas the burials dating to the post-medieval period were likely a mixture of both middle and lower class individuals as the cemetery became publically run after AD 1551 (Becher 1999) and accommodated the closure of three other cemeteries post-Reformation (Mollerup and Boldsen 2010). It is likely that the large density of individuals in this expanding urban environment created a fluid cemetery composition that catered to both personal burial preference but also to the needs of the most impoverished. Nearly 800 square meters of the Black Friars cemetery was excavated beginning in 1972 to facilitate new construction and development in the city center (Nielsen 1982a; 1982b; Becher 1999). Estimates vary as to how many individuals were interred in the cemetery, but likely between 660 and 710 individuals were interred at the site with well over half belonging to the post-medieval period (Mollerup and Boldsen 2010).

MATERIALS AND METHODS

Two hundred and three individuals were used in this analysis; 152 adults and 51 subadults (<18 years of age). Selection of these individuals was based primarily on preservation of the cranium (i.e., orbits, posterior vault, and dentition). Temporal classification was assigned to each individual based on arm position (see Kieffer-Olsen 1993; Jantzen et al. 1994) and cemetery location (see Nielsen 1982a; 1982b) with 61 medieval individuals (52 adults, 9 subadults) and 142 post-medieval individuals (100 adults, 42 subadults). For all adult individuals sex was determined using a suite of standard pelvic and cranial traits (Table 1) (Genovés 1959; Phenice 1969; St. Hoyme and İşcan 1989; Buikstra and Ubelaker 1994; Milner 1992; Bruzek 2002; Walker 2005). Adult age estimation was assessed using the pubic symphyses (Todd 1921; Brooks and Suchey 1990) and the auricular surface (Lovejoy et al. 1985; Meindl and Lovejoy 1989). Additionally, due to limitations with these methods for aging older adult individuals, fovea capitis lipping and spicule formation along the greater trochanter and neck of the femur were also used (Milner and Boldsen 2012). Age estimation for the subadults was based on dental formation, eruption and epiphyseal closure (Moorrees et al. 1963a; 1963b; Ubelaker 1989; Schaefer et al. 2009) (Table 2).

For all individuals, cribra orbitalia (CO), porotic hyperostosis (PH) and enamel hypoplastic lesions (EHL) were assessed. Based on gross observation, supplemented by photographs, CO and PH were scored following Stuart-Macadam (1982) and Ribot and Roberts (1996) as: absent – no evidence of lesions; mild – slight pitting, no expansion of bone, scattered foramina; moderate – scattered large and small foramina, some coalescence of foramina, no expansion of bone; advanced – foramina have linked to trabecular structure, substantial coalescence, some expansion of bone; and severe – severe pitting, gross expansion of bone, trabecular exposure, substantial coalescence of foramina, deformation of normal contour (Figure 2). All adults were assessed for CO and PH; however, only 38 subadults could be assessed due to missing cranial elements.

For EHL, a standard dental inventory was completed for all individuals with enamel defects only counted if they were visible to the naked eye. Counts were grouped into categories to minimize potential intra-observer error as follows: absent - no evidence of defects; mild - maximum of one defect present; moderate - two to three defects present; severe - more than three defects present (Scott 2015). To avoid counting the same stress event multiple times (see Boldsen 2007), only one tooth with a complete crown was used from each individual for analysis. For subadults that meant excluding those under 6 years of age. While all teeth may show evidence of EHL, anterior teeth are most susceptible to these defects (Cutress and Suckling 1982; Goodman and Rose 1990); therefore, the left mandibular canine was preferentially chosen for this analysis (right side when absent) as it was the most abundant tooth within the sample and has the longest period of enamel formation between 1.4 – 6.2 years (Reid et al. 2002; Reid and Dean 2006; Reid and Ferrell 2006). When absent, the maxillary central incisors were used followed by the maxillary canines which capture a similar developmental period between 1.1 – 5.0 years and 1.7 – 5.3 years, respectively (Reid and Dean 2006:343). Six adults and 20 subadults could not be assessed due to absent or incomplete permanent dentition. For EHL, intra-observer error was assessed using 21 adults and 17 subadults. The same 21 adults were used for CO and PH re-checks but only 5 subadults due to the relative ease of CO and PH classification.

A weighted quadratic kappa reliability test (κ_w) was used to test intra-observer error with all kappa values falling within acceptable limits (Table 3).

RESULTS

Loglinear analysis, used to explore the interactions between categorical variables, showed no significant partial correlations or interaction effects between CO, PH and EHL in either the adults or subadults (Table 4). As a result, subsequent analysis focused on age, sex and temporal comparisons. For the subadults, a Fisher's exact test was used to compare the frequency of lesions across time periods with no significant differences for any indicator. However, the level of manifestation for PH and EHL was increased in the post-medieval period, but not significantly. When comparing indicators between age groups, only EHL prevalence was significantly different (p=0.007) with those in the oldest subadult age group (> 10 years) showing an increased frequency (Table 5). This was not unexpected as older individuals would have more years of life at risk. In general, PH and EHL were more prevalent in the older subadult group, whereas CO was more common in the youngest subadult age group (<10 years).

For the adults, chi-square tests demonstrated no significant differences in frequency between indicators for sex or time period. However, there was a significant difference in PH frequency between age categories (χ^2=14.753; df=6; p=0.012). In the oldest adult age group (45 - 60 years) the majority of individuals did not have evidence of PH or when present it was classified as mild; however, in the younger adult age groups (18 - 29 years and 30 - 44 years) PH presented as moderate or severe. Further, in the youngest adult age group individuals were distributed fairly equally across all four manifestation categories (Table 6).

Fisher's exact tests suggested a significant difference in the level of stress manifestation between males and females in the medieval period for PH (χ^2=11.543; p=0.002) and EHL (χ^2=11.548; p=0.008). For both EHL and PH, more females occupied the mild and moderate manifestation categories whereas a greater number of males consistently showed either severe evidence of these lesions or none at all (Table 7). There were no differences in the level of manifestation between sexes in the post-medieval group. Looking at age groups within each time period, there were no significant differences in the level of manifestation in the medieval group; however, in the post-medieval group the manifestation of EHL was significantly different by age (χ^2=12.339; p=0.029). The youngest and oldest age groups (18 - 29 years and 45 - 60 years) showed the highest severity of manifestation, whereas the 30 - 44 year age group showed the most individuals classified with mild or moderate lesions.

Lastly, and perhaps most interesting despite small sample sizes and overlapping confidence intervals in age estimations, is the observation that individuals who exhibited two or more mild-moderate manifestations of stress, showed a reduced mean age at death (32.97 years) as compared to those with a single but severe indicator (36.5 years). This is suggestive that a portion at least of those with multiple stress indicators across different tissue types were not surviving as compared to others. This speaks in part to considerations of Wood et al.'s concerns of hidden heterogeneity of risks and reflects the subtle nature of how stress spreads across different tissues with differing effects.

DISCUSSION

The variability in how stress was internalized across this population was no doubt influenced by the severity of the stress and differential tissue responses. The relationship between CO and PH has been well-explored in the literature (e.g. Oxenham and Cavill 2010) with arguments that both indicators share a similar dietary etiology that is likely multifactorial in nature (Wapler et al. 2004; Thillaud 2008; Walker et al. 2009). However, these indicators do not always manifest in tandem (Stuart-Macadam 1989) and as such may represent a different threshold to stress influenced by the differences in trabecular and cortical thickness of the orbital roof and posterior cranial vault (Caffey 1937; Stuart-Macadam 1989; Wiggins 1991).

In the subadults CO was more prevalent than PH and despite no interaction effects between these two indicators, PH was not present in any individuals without CO. Because CO and PH lead to a thinning of the cortical bone with eventual macroscopic porosity (Wapler et al. 2004), it is possible that orbital changes may reflect more mild/moderate stressors compared to PH, as the highly vascularized nature of the eye orbit makes the surrounding skeletal tissues more vulnerable to the effects of stress, specifically glucocorticoid oversaturation. An increase in glucocorticoids can reduce blood flow to skeletal tissues (Goans et al. 1995; Drescher et al. 2000; Weinstein 2010) and because these pathways deliver osteoblast cells to bone, when they are reduced remodelling disruptions can occur that decrease overall bone strength (Weinstein 2010). As is typical of CO and PH, when the diplöe expands the cortical bone naturally thins creating these lesions (Stuart-Macadam 1985). Due to the less vascularized nature of the posterior parietals, it is possible that the PH visible in this subadult group results from more severe stress than what prompted the formation of CO. Comparatively, in the adult group there was a reduced prevalence of CO but an increased level of PH likely reflecting selective mortality, as the subadults (i.e., non-survivors) who had increased CO early in life were less likely to survive into adulthood.

Nearly 70 percent of all adult and subadult individuals showed evidence of EHL. While the association between EHL and increased mortality has been well explored in the literature (e.g. Rose et al. 1978; Cook and Buikstra 1979; Amoroso et al. 2014; for a review see Armelagos et al. 2009), a dissimilar pattern emerges in the Black Friars population. For example, at the Danish medieval site of Tirup, Boldsen (2007) demonstrated an increase in adult mortality when EHL were present, particularly in males where those with EHL had a mean age at death of 37.6 years and those without had a mean age at death of 49.3 years. However, for the Black Friars sample, adult males with and without EHL had a mean age at death of 34.8 years and 33.2 years, respectively. As Boldsen argues (2007), stress may manifest in the skeleton from one of two circumstances: 1) heterogeneity in an individual's immune system or 2) the activation of other pre-existing variables that lead to frailty. Because frailty is not fixed, there is a need to consider the impact of prevalence on these age at death estimates. For the Black Friars males with evidence of EHL, they also showed a higher prevalence of other lesions being present compared to the males without EHL. While no interaction effects were present, there was a trend in the data to suggest that those with multiple indicators with mild-moderate manifestation could be more detrimental than a single severe indicator which may perhaps be driving the EHL results of this study. Additionally, early life stress events have been closely linked with increased stress sensitivity in adulthood (Cameron and Demerath 2002; Boldsen 2007; DeWitte and Wood 2008; Miller et al. 2011; Fagundes et al. 2013) where the earlier the onset of initial stress, the more sensitive an individual will become in later years (Armelagos et al. 2009; Fagundes et al. 2013) which may further explain why those with EHL plus other indicators formed in childhood have a reduced age at death than those with EHL alone.

While both the medieval and post-medieval periods were fraught with factors affecting overall levels of stress, the increase observed in the post-medieval period is likely reflective of both cemetery inclusion and factors associated with urbanism. While the Black Friars cemetery was opened in AD 1240, only about 10 percent is made up of individuals before AD 1400 (Mollerup and Boldsen 2010); therefore, the majority of medieval burials represent those who lived during the post-plague years which saw economic success through cattle production and the rebound of essential resources. The decreased population and resultant land desertion in the mid-14th century after the Black Death led to a shift in the economic livelihood of Denmark where cattle production became the primary economic export to European markets (Hybel and Poulsen 2007).

After the Protestant Reformation in AD 1536, the post-medieval period ushered in urban expansion with population rebound, increased demand for a limited food supply and political unrest (Randsborg 2009). Despite stable weather patterns and agricultural success, outbreaks of the cattle plague in AD 1518 and 1559 challenged the new found economic success of Denmark. Additionally, constant lands feuds with Sweden led to the loss of vital agricultural land during this post-medieval period resulting in food shortages and crises within these urban settlements (Hybel and Poulsen 2007; Randsborg 2009). Despite the introduction of new products such as tomatoes and potatoes from the New World after AD 1520, Denmark was not immune to food supply disruptions as widespread famine swept through Europe between AD 1594 and 1597 (Fagan 2000; Hybel and Poulsen 2007). Additionally, economic shifts that saw an increase in fish transport from North America disrupted the Danish markets and their strong-hold on cod (Barrett et al. 2011). In this expanding urban environment more individuals were living in over-crowded spaces with poor sanitation and an abundance of infective agents (Mollat 1986; Hybel and Poulsen 2007) further devastating the predominantly poor population of urban Denmark (Anderson 2011).

CONCLUSION

From an analysis of the Danish Black Friars cemetery sample it appears that stress increased into the post-medieval period likely due to the rise of urbanism. Stress was more detrimental (i.e., resulted in a younger age at death) when spread across multiple indicators than the different manifestations *within* each indicator. Perhaps then, the various levels of manifestation for each indicator are more reflective of differential frailty and tissue susceptibility to the effects of stress (Laan et al. 1993). While no interaction effects were observed between CO, PH and EHL in this study, an increased focus in how stress differentially effects skeletal tissues and their relationship to one another allows us to better explore the complexities of stress in the past.

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CONFLICT OF INTEREST STATEMENT

Neither authors have any conflict of interest to declare in regards to this manuscript.

CONTRIBUTION DETAILS

Scott completed primary data collection and analysis for this manuscript and wrote approximately 80 percent of the content. Hoppa provided supervision during project development and facilitated research access. Funding support for data collection and analysis was also contributed by Hoppa. Preliminary data analysis was supplemented by Hoppa in addition to manuscript writing (approximately 20 percent).

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LIST OF FIGURES

Figure 1

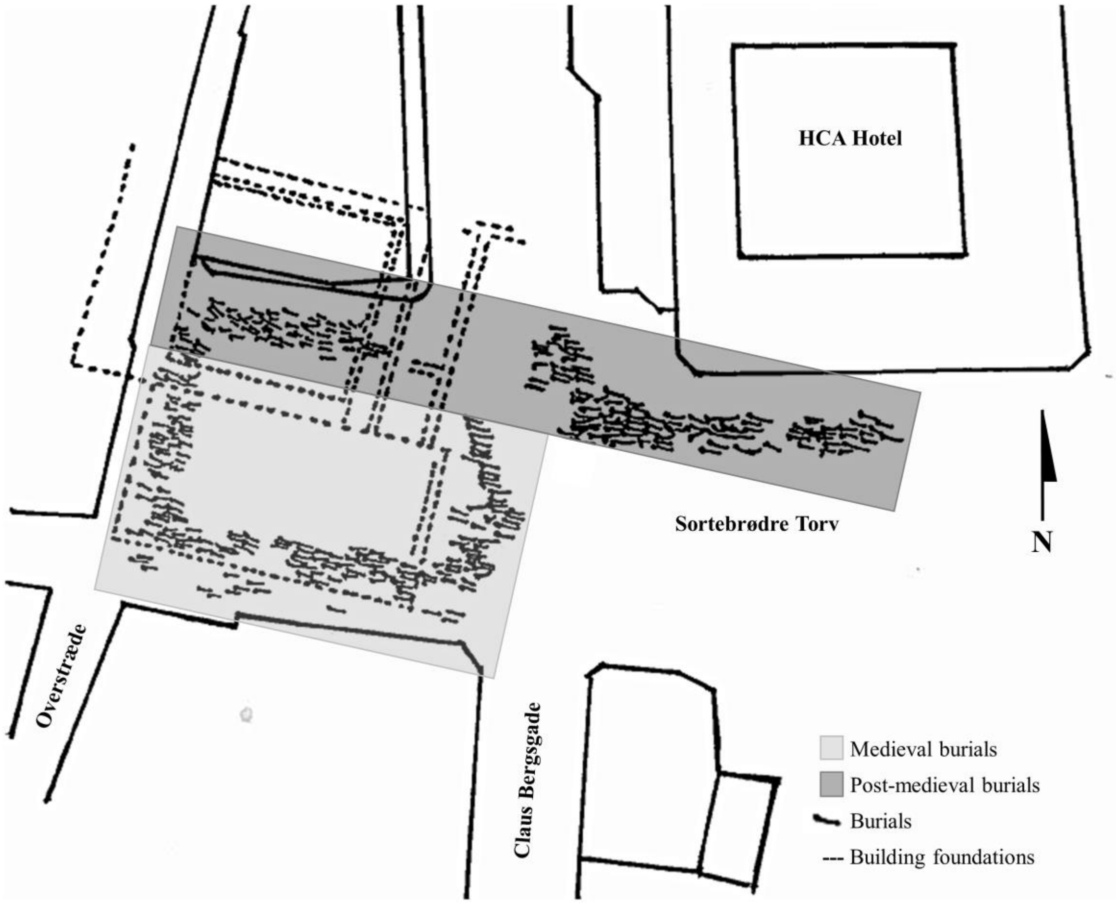
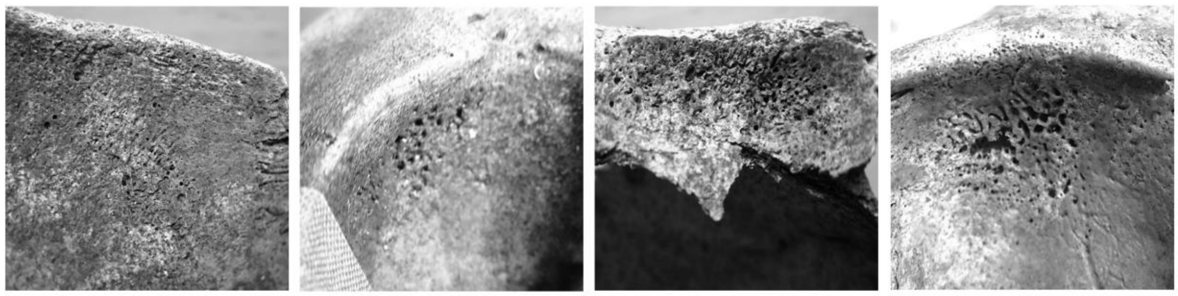
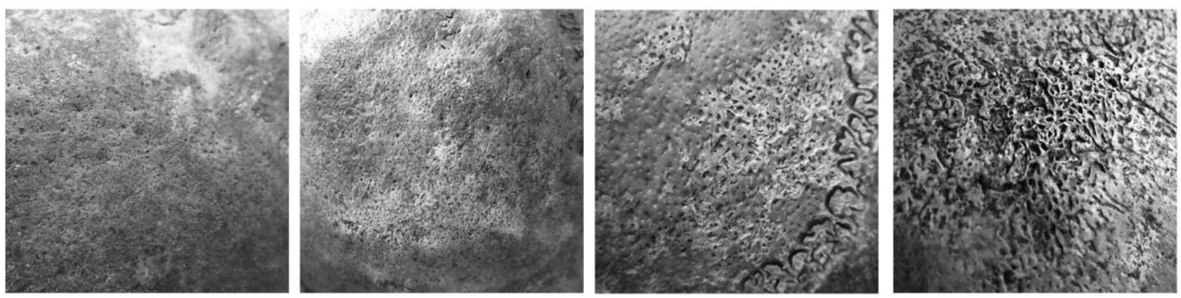

HCA Hotel
Sortebrødre Torv
N
Overstræde
Claus Bergsgade
Medieval burials
Post-medieval burials
Burials
--- Building foundations

Figure 2



CO Category 1 (mild) CO Category 2 (moderate) CO Category 3 (advanced) CO Category 4 (severe)



PH Category 1 (mild) PH Category 2 (moderate) PH Category 3 (advanced) PH Category 4 (severe)

LIST OF TABLES

Table 1 Distribution of sexes between time periods

Time Period	Female	Male	Total
Medieval	23	29	52
Post-medieval	55	45	100
Total	78	74	152

Table 2 Distribution of age between time periods

Age (years)	Medieval	Post-medieval	Total
0-18	9	42	51
19-29	15	31	46
30-44	33	63	96
45-59	4	5	9
60+	0	1	1
Total	61	142	203

Table 3 Intra-observer recheck values using a weighted quadratic Kappa test (κ_w)

Indicator	Kappa value	Standard error	95% confidence interval
CO	0.860	0.116	0.632 to 1.088
PH	0.909	0.094	0.724 to 1.094
EHL	0.679	0.201	0.285 to 1.072

0.00 = poor agreement; 1.00 = almost perfect agreement (Landis and Koch 1977:165)

Table 4 Parameter estimates for loglinear analysis and interaction effects between CO, PH, and EHL

	Effect	Estimate	Std. Error	Z	Sig.	95% Confidence Interval	
						Lower	Upper
ADULTS	CO*PH*EHL	0.007	0.101	0.074	0.941	-0.191	0.206
	CO*PH	-0.001	0.101	-0.009	0.993	-0.200	0.198
	CO*EHL	-0.076	0.101	-0.750	0.454	-0.275	0.123
	PH*EHL	0.027	0.101	0.267	0.789	-0.172	0.226
SUBADULTS	CO*PH*EHL	0.031	0.294	0.107	0.915	-0.545	0.608
	CO*PH	0.434	0.294	1.474	0.141	-0.143	1.011
	CO*EHL	-0.116	0.294	-0.393	0.695	-0.692	0.461
	PH*EHL	-0.337	0.294	-1.146	0.252	-0.914	0.239

Table 5 Percentage of subadult individuals with CO, PH, and EHL divided by age group

Indicator	**CO**	**PH**	**EHL**
<10 years	76%	17%	33%
>10 years	58%	22%	84%

Table 6 Adult distribution of PH across manifestation categories divided by age

Age (years)	**Absent**	**Mild**	**Moderate**	**Advanced**	**Severe**	**Total**
18-29	21	12	10	3	0	46
30-44	55	31	9	0	0	95
45-60	10	1	0	0	0	11
Total	86	44	19	3	0	152

Table 7 Adult distribution of PH and EHL across manifestation categories in the medieval group divided by sex

	Sex	**Absent**	**Mild**	**Moderate**	**Advanced**	**Severe**	**Total**
PH	Female	16	3	2	1	1	23
	Male	26	1	2	0	0	29
	Total	42	4	4	1	1	51
EHL	Female	3	7	11		2	23
	Male	9	4	5		11	29
	Total	12	11	16		13	51