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‘Among his fellows cast’: A histotaphonomic investigation into the impact of the Black Death in England

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ABSTRACT

The Black Death had a devastating impact on communities living in Europe during the mid-14th century. The devastation wreaked by the epidemic was thought to lead to the disruption of social norms, including those surrounding the burial of the dead. Some scholars have, however, suggested this was not always the case, in particular, for those communities living in rural settings (Kacki et al., 2011). Recent excavation at Thornton Abbey in Lincolnshire revealed two burial populations; one associated with the abbey's medieval hospital and the other a mass grave that was in use during the Black Death epidemic. Together with the mass grave and post-epidemic burials from East Smithfield, London these two populations presented an opportunity to explore the early taphonomic histories of the plague dead through the inspection of bone diagenesis associated with bacterial soft tissue decomposition. The histological analysis of 81 skeletons revealed striking differences in the post-mortem treatment of the plague dead in rural Lincolnshire compared to those buried in urban London, and in this paper, we explore the possible scenarios that may account for this variability. We also present three cases where the individuals' status in life may have led to attempts at inhibiting their corporeal decay.

KEYWORDS

Black Death, Histology, Bioerosion, Medieval, England, lime

1. INTRODUCTION

The Black Death epidemic (A.D 1347-1351), caused by the bacterium *Yersinia pestis*, is estimated to have killed between 30-60% of the population of Europe. In England, between 40-55% of the population had died from the epidemic by 1350 (Gottfried 1983: xiii; Horrox 1994: 3; Hufthammer and Walloe 2013). Historical accounts from the time – such as a letter from Wolstan de Bransford, Bishop of Worcester to the Dean of Worcester warning of the dangers to those visiting the town – have been used as evidence to suggest that death rates were so high in certain places that there were not enough people alive or well enough to bury the dead, and as a consequence, bodies were left decomposing in homes and on the streets (Horrox 1994: 268). It has been argued that the difficulties in coping with the sheer volume of the dead meant that in some cases there were significant delays between death and burial, and that normative funerary rites were abandoned, with both fresh and partially decomposed bodies being hastily disposed of in emergency mass graves (Daniell 2005: 189).

More recently, however, the idea that those who died of the Black Death were subject to notably different funerary rites in comparison to those who died before and after the outbreak have been challenged (e.g. Kacki et al., 2011). Indeed, there is a notable dearth of mass graves dating to the Black Death, and as such it is speculated that the majority of the plague dead were afforded normative treatment, such as burial in single graves in established cemeteries which were simply expanded to accommodate additional burials, even despite the rapid accumulation of dead bodies (Gilchrist and Sloane 2005: 74). If this were the case, many such individuals would remain archaeologically indistinguishable from those who died at other times. Moreover, the response to the epidemic may have varied according to the circumstances facing individual communities. For instance, the response in urban centres where there were more concentrated populations may have required a different approach to the one taken by rural or smaller communities where the numbers of dead were more manageable and whose burial could be dealt with more effectively, in some cases, perhaps even without the need for mass burial (Kacki et al., 2011: 586; Wilmott et al., 2020: 191).

There is also the issue of biased historical sources which may skew our perception of the epidemic and its impact on the survivors. For example, manorial records such as those from Halesowen in the west Midlands report that most deaths occurred amongst children and the elderly, with the majority of survivors aged between twenty and forty (Platt 1996: 10). In contrast, however, the demographic profile from the mass graves at East Smithfield in London suggest that mostly young and middle-aged adults died during the plague. Consequently, Gilchrist and Sloane (2005: 209) suggest that either the manorial records are inaccurate, or that the situation in large urban centres was indeed very different to that in rural communities. As such, determining the extent to which people who died during the Black Death were treated differently in death from those who died before and after the epidemic, and how this might have varied in different parts of England, becomes of particular importance for understanding communal responses to the crisis.

This paper assesses the histological preservation of human bones recovered from two medieval sites from England; Thornton Abbey in Lincolnshire and East Smithfield in London. Both sites present two distinct cemetery populations; one which represents those who died during the mid-14th century Black Death epidemic, and another which represents those who died either before and/or after the plague. The main aim of our study was to assess bone diagenesis, and bacterial bioerosion specifically, to investigate whether there was evidence for variation in the early post-mortem treatment of the remains during, as well as before and after, the Black Death epidemic. The East Smithfield and Thornton Abbey assemblages were chosen as they represent largely urban and rural communities respectively, thus allowing us to test whether urban and rural populations experienced different pressures which may have had an effect on how the dead were managed during the outbreak.

1.2 Histotaphonomy

Mineralised tissues are subject to a variety of physico-chemical changes after the death of an organism. Some of these occur before burial as a result of natural (e.g. bodily decomposition) and artificial (e.g. cremation) processes. Post-burial changes occur as a result of geochemical and biological interactions between the bone and its burial environment (Kendall et al., 2018). Microbial bioerosion is a principal form of alteration which affects archaeological mineralised tissues (Turner-Walker et al., 2002). Hackett (1981) categorised four distinct types of microbial tunnelling, known as micro-foci of destruction (MFD). Lamellate, budded and linear-longitudinal MFD are known as non-Wedl tunnelling and are generally thought to be produced by bacteria (Jackes et al., 2001; Kendall et al., 2018). The fourth category, Wedl tunnelling, has been associated with the activity of exogenous saprophytic fungi in terrestrial environments (Marchiafava et al., 1974; Fernandez-Jalvo et al., 2010, but see Kendall et al., 2018). In aquatic environments cyanobacteria produce transversely-oriented tunnels in bone, somewhat similar in form to Wedl tunnelling but with a larger diameter (Bell and Elkerton 2008; Turner-Walker and Jans 2008; Pesquero et al., 2010; Huisman et al., 2017; Brönnimann et al., 2018; Turner-Walker 2019).

Studies of bones from archaeological sites in temperate Europe have shown significant correlations between early taphonomy and the extent of bacterial bioerosion and, in aerobic burial environments at least, no relationship with burial environment (Jans et al., 2004; Nielsen-Marsh et al., 2007; White and Booth 2014; Booth 2016; Brönnimann et al., 2018). In particular, disarticulated (particularly butchered) bones tend to show little or no bacterial attack (Jans et al., 2004; Nielsen-Marsh et al., 2007; Brönnimann et al., 2018; Morales et al., 2018). In contrast, bones from bodies that were buried intact soon after death have usually been extensively bioeroded by bacteria (Jans et al., 2004; Nielsen-Marsh et al., 2007; Booth 2016; Booth and Madgwick 2016; Brönnimann et al., 2018; Papakonstantinou 2020). Bones from mummified bodies show little or no bacterial attack (Booth et al., 2015). These observations have been explained under a model where bacterial bioerosion is largely dictated by the extent to which the bone was exposed to bacterial soft tissue decomposition in the early post-mortem period (Bell et al., 1996; Jans et al., 2004; Booth 2016). For instance, butchered bones are stripped of soft tissue before soft tissue decomposition has begun thereby limiting exposure to soft tissue decomposition and any related bioerosion. Most methods of mummification involve the arrestation or inhibition of bacterial decomposition in order to preserve the soft tissues (Aufderheide 2003). By contrast, bones buried as part of intact bodies are exposed to extensive soft tissue decomposition. As such, taphonomic trajectories, including funerary treatments, which would have differentially affected the way in which bones had been exposed to soft tissue decomposition would leave characteristic signatures of bioerosion within the internal bone microstructures. For instance, bodies exposed on the ground surface are usually rapidly exposed by skeletonising insects, limiting bone exposure to soft tissue decomposition (Fernandez-Jalvo et al., 2010; White and Booth 2014; Kontopoulos et al., 2016). Mummification or desiccation of bodies involves the arrestation of decomposition, again limiting related osteolytic activity (Booth et al., 2015).

There is, however, ongoing debate around the origins of the bacteria responsible for bacterial bioerosion (see Kendall et al., 2018 and Booth 2017). Relationships between bacterial bioerosion and early taphonomy in archaeological remains and in some limited taphonomic experiments have been used to suggest that osteolytic bacteria are enteric to an organism and attack the bone after transmigrating out of key endogenous microbiomes such as the gut during bodily putrefaction (Bell et al., 1996; Jans et al., 2004; Nielsen-Marsh et al., 2007; White and Booth 2014; Booth 2016). This model is also supported by bones from similar aerobic depositional environments showing diverse patterns of bacterial attack related to early taphonomy, as well as findings that a substantial proportion of archaeological neonatal and perinatal skeletons remain free from bacterial attack, which is difficult to explain by anything other than those infants having lived for too short a period to have developed an osteolytic endogenous microbiome (Jans et al., 2004; Nielsen-Marsh et al., 2007; Booth 2016; Booth, Redfern and Gowland 2016; Brönnimann et al., 2018; Booth 2019).

More recent studies have identified limited bacterial tunnelling in butchered faunal bone employed in real-time taphonomic experiments, as well as in archaeological ecofacts of antler and ivory, suggesting that osteolytic soil bacteria are also involved (Kendall et al., 2018; Turner-Walker 2019; Eriksen et al., 2020). These results are puzzling when considered alongside the strong relationship with early taphonomy, although this could be explained if soil bacteria were more capable of bioeroding bone which is surrounded by decomposing soft tissue, or if soil bacteria have a limited bioerosive impact compared to endogenous bacteria (Booth 2017). Regardless of where osteolytic bacteria primarily originate, the observed relationships between bacterial bioerosion and early taphonomy suggests that histo-taphonomic analysis of bacterial alteration in bone may be used to identify whether taphonomic histories of particular bones and bodies varied (Turner-Walker 2008; Fernandez-Jalvo et al., 2010; Hollund et al., 2012; Booth 2016; Booth and Madgwick 2016; Brönnimann et al., 2018; Hollund et al., 2018; Mandl et al., 2018; Papakonstantinou 2020).

Cyanobacterial tunnelling has been observed in bones from aquatic environments, but also in bones from terrestrial contexts where they have become submerged in standing water (Bell and Elkerton 2008; Turner-Walker and Jans 2008; Pesquero et al., 2010; Huisman et al., 2017; Brönnimann et al., 2018; Turner-Walker 2020). The aetiology and classification of Wedl tunnelling in bone is disputed to some extent (see Kendall et al., 2018), but several studies have found an association with delayed burial/sub-aerial exposure, presumably because this facilitates access to fungal spores in the air (Booth 2014; 2016; Booth and Madgwick 2016; Brönnimann et al., 2018).

A combination of histotaphonomic analyses with more traditional macroscopic osteological methods of taphonomic research (e.g. articulation, completeness, surface modification, fracture patterns etc) and broad models of bodily decomposition under different circumstances, can be used to interpret early post-mortem processes and possible funerary treatments responsible for such changes. There are, however, some factors which can confound the relationship between the bacterial bioerosion of bone and early taphonomy, particularly hydrology. Waterlogged and/or anoxic environments inhibit osteolytic bacterial activity, and bones from these contexts which were permanently anoxic or waterlogged show little or no bacterial attack (Turner-Walker and Jans 2008; Hollund et al., 2012; Booth 2016). Bacterial attack is therefore usually absent from bones deposited in aquatic contexts but variable in bones from environments that are episodically anoxic or waterlogged (Bell and Elkerton 2008; Turner-Walker and Jans 2008; Hollund et al., 2012). Bactericidal substances or other factors present in the soil which serve to inhibit microbial activity (e.g. heavy metals, lime (calcium oxide, CaCO), tannic acids) would also have an effect on microbial bioerosion of bone (Painter, 1995; Müller et al., 2011; Schotsmans et al., 2012; 2014a; 2014b; Booth et al., 2015; Mandl et al., 2018; Kendall et al., 2018). Early taphonomy and funerary treatment can only be robustly used in interpretations of bacterial bioerosion in bones which have been recovered from similar aerobic, free-draining environments.

2. CASE STUDIES

2.1 Thornton Abbey, Lincolnshire

Founded in 1139 by William le Gros 1st Earl of Albemarle, Thornton Abbey was an Augustinian house in North Lincolnshire (Fig. 1). It was built above a 3-4m deep deposit of slightly alkaline free-draining fluvio-glacial sand and gravel that extends across the entire site, and which overlies the Burnham Chalk Formation (Whitham 1991). The abbey consists of a rectangular monastic precinct that covers approximately 30 hectares that are circumvented by moats, banks, walls and a stream. By the later Middle Ages, the abbey prospered through its success in the wool trade, and became one of the wealthiest monastic houses in England. However, it was closed in 1539 during the Dissolution of the Monasteries, after which it became the private property of minor gentry families (Oswald et al., 2010).

Fig. 1 Map of mainland Britain illustrating the location of Thornton Abbey, Lincolnshire and East Smithfield, London.

Despite unpublished excavations at the abbey during the 1950s, no systematic excavation of the abbey's precinct was undertaken until 2011 when an extensive series of geophysical and topographical surveys and excavation was undertaken in order to characterize the precinct and explore the developments at the abbey during and after the Dissolution (Willmott et al., 2020). Excavation revealed two significant discoveries. Firstly, a series of earthworks were found which belonged to a substantial building with a single-celled chapel at one end. This is believed to be the monastery's hospital of St James whose chapel, according to the only written account about the hospital, was repaired in 1322. This hospital would have served the canons as well as members of the laity during its time of use, including before, during, and after the Black Death epidemic (Willmott et al., 2020: 193). Associated with the hospital was a cemetery comprising single interments and a series of multiple burials containing two or three individuals each, which dated to the later phase of cemetery use. Osteological analysis of the hospital population identified 175 skeletons, representing 99 adults (of both sexes) and 76 non-adults (<18 years of age at death) (Hook, 2021).

A second discovery was the excavation of a mound located near to the entrance of the abbey's outer precinct. This was the site of a mass burial containing the remains of 48 men, women and children (Willmott et al., 2020). The grave consisted of eight distinctive overlapping rows where the bodies were laid in close proximity to each other, often with the feet of one body placed between the heads of two other bodies in another row. Non-adults were placed in between the bodies of the adults, or sometimes between their legs. The absence of intercutting between the skeletons, as well as the close proximity between each body, suggests they were buried either at the same time, or within a narrow time frame once the grave was open. The absence of dress accessories and the position of the bodies within the mass grave suggest the dead were buried in shrouds (Willmott et al., 2020: 183). Subsequent aDNA analysis of the remains from the mass grave confirmed that those present died from the Black Death (Willmott et al., 2020: 188).

In total, 44 individuals were sampled for histological analysis from Thornton Abbey; 19 from the mass grave, and 25 from the hospital cemetery. Whilst most samples from the hospital came from single interments, five individuals from two multiple burials were sampled in order to explore any differences in the degree of bone diagenesis between those in multiple burials and those in single burials. Two individuals were also sampled due to their burial inside the hospital's chapel.

2.2 East Smithfield, London

The East Smithfield cemetery is located in the City of London (Fig. 1) to the north-east of the Tower of London, and lies beneath the buildings that once formed part of the Royal Mint. The human burials included in this study were uncovered between 1986-1988 when 1012 skeletons were excavated from the site by the Museum of London's Department of Greater London Archaeology (DGLA; Grainger et al., 2008). None of the human skeletons recovered from East Smithfield have been radiocarbon dated, but associated artefacts, styles of graves (particularly mass trench graves linked to the Black Death epidemic), and historical documents detailing cemetery boundaries were used to divide the skeletal assemblage into two phases (Grainger et al., 2008).

The earliest phase of burial was linked to a cemetery and associated chapel (Holy Trinity) that were founded to accommodate the bodies of local people, and perhaps those in outlying parishes, who died during the Black Death epidemic (Grainger et al., 2008: 10). This cemetery, from here on referred to as the Black Death (E.S) cemetery, consisted of organised rows of single graves and mass burial trenches divided into two distinct eastern and western groupings (Grainger et al., 2008). There was no stratigraphic relationship between the single graves and mass burial trenches, and therefore it was not clear whether the mass burial trenches were in use from the cemetery's inception or were initiated at a later stage of the epidemic when the volume of bodies began to increase (Grainger et al., 2008: 19). The ordered nature of the burials within the graves led the excavators to speculate that both single graves and mass burial trenches were dug at the same time (Grainger et al., 2008:19). The presence of soil slumped in the base of the trenches suggests they had been open for an extended period of time before they were filled (Grainger et al., 2008: 19). The mass burial trenches were densely packed with stacks of up to five bodies; the position of the skeletons suggest, however, that despite this volume of dead, the bodies had been carefully placed in an orderly fashion (Grainger et al., 2008: 19). For example, infant and juvenile bodies were placed between the adults, as observed at Thornton Abbey. The presence of corroded nails and organic stains within both single graves and the mass burial trenches suggest that some of the burials from the Black Death (E.S) cemetery were coffined, however, this was not the predominant rite. Rather, most individuals appear to have been buried either in clothing or shrouds (Grainger et al., 2008: 13).

A small number of the skeletons from the western Black Death (E.S) cemetery were found in various stages of articulation without signs of grave disturbance. These bodies must have partially decomposed before they were interred suggesting that there was a delay between death and their burial (Grainger et al., 2008). These burials may represent those who were not discovered until sometime after death, those transported to the cemetery from elsewhere, or those left to decompose in open graves (Grainger et al., 2008: 19). Strontium and oxygen stable isotope analysis by Kendall et al., (2013) identified individuals buried at East Smithfield who probably grew up in London's hinterlands. It is worth considering in cases like this where some plague-dead probably were being moved over quite large distances, that the strontium and oxygen data, reflecting childhood residence further afield, could be used to infer the post-mortem movement of the dead.

Soon after the Black Death began to subside around A.D 1350, Edward III founded the Abbey of Saint Mary Graces on the site of the East Smithfield cemeteries (Grainger et al., 2008; Grainger and Phillpotts 2011). The foundation's Cistercian community first used the existing Holy Trinity chapel until A.D. 1353 when it was incorporated into the Abbey of Saint Mary Graces (Grainger et al., 2008; Grainger and Phillpotts 2011). A new church was built around

A.D. 1361 and a churchyard was located to the east of the earlier, western Black Death (E.S) cemetery (Grainger et al., 2008: 29-31). Four-hundred-and-forty single articulated skeletons were recovered from this later phase cemetery, referred to herein as St Mary Graces (E.S). Burial continued here until the Dissolution in the mid-16th century A.D. (Grainger and Phillpotts 2011).

Some of the graves from the Black Death (E.S) cemetery and St Mary Graces (E.S) had been partially filled with charcoal (Grainger et al., 2008; Grainger and Phillpotts 2011). It was unclear whether these deposits represented the remains of planks, charring of a coffin, or deliberate deposition of charcoal itself (Grainger et al., 2008: 20). In one case, the charcoal included some domestic waste which suggested that it had been deposited directly from a domestic hearth (Grainger et al., 2008: 20). Grainger et al., (2008: 21) hypothesised that charcoal and ash may have been used to absorb fluids from decomposing bodies, perhaps in order to slow the decomposition of those individuals that had been transported long distances. However, some of the charcoal burials came from areas of the cemetery that were not associated with the plague and, unfortunately, the presence and absence of charcoal was not recorded for each specific grave in the site reports (Grainger and Phillpotts 2011: 104).

The burial sediments at East Smithfield uniformly comprised aerobic, slightly acidic sandy loams. The water table in the area is quite high, but there was no evidence that any of the graves had experienced sustained episodes of waterlogging (Grainger et al., 2008; Grainger and Phillpotts 2011). In a study of 301 human bones from varied locations and time periods, Booth (2016) found that bacterial bioerosion was significantly more varied and lower on average in bone samples from the East Smithfield Black Death cemetery than in their sample as a whole, particularly when compared to other articulated burials from historical cemeteries.

However, these results were not discussed in detail. Mass grave trenches such as those excavated at East Smithfield and Thornton Abbey do not represent conventional funerary practice in medieval Britain, and as such, combining the analysis of these two cemeteries' remains presented an opportunity to better understand society's response to the plague at that time.

3. METHODS

We examined bone diagenesis and bioerosion in human remains from East Smithfield and Thornton Abbey using transmitted light microscopy applied to histological bone thin sections. Scanning Electron Microscopy (SEM) is a higher-resolution tool for inspecting diagenetic features in bone, and there are cases where diagenetic features that are ambiguous under transmitted light microscopy can be more reliably identified using SEM. However, these sorts of cases occur infrequently. We had no trouble identifying diagenetic features in any of the human bone thin sections from East Smithfield or Thornton Abbey using transmitted light microscopy. Most data on bone bioerosion have been generated using transmitted light microscopy, and so employing this technique in our own study ensures that our data are directly comparable. Light microscopy is cheap and accessible, meaning that a higher number of samples could be analysed. We were therefore able to accumulate a higher number of samples that allowed for more robust statistical testing than would have been possible using SEM.

A diamond coated rotary blade was used to cut samples measuring approximately 1x1cm from the diaphysis of the lower long bones; most samples were taken from a femur due to the robusticity of the bone, and to allow for comparability with published studies (e.g. Nielsen-Marsh and Hedges 2000; Jans et al., 2004; Hollund et al., 2012; Booth 2016). The extracted bone samples were embedded in LR White Acrylic resin (Agar Scientific) in preparation for thin sectioning. Thin sections approximately 70-100μm thick were cut from sampled bone using a Leica 1600 diamond-saw microtome, after which each section was mounted on a glass slide using Entellan (Merck Chemicals). The thin sections from East Smithfield had been prepared by Trylzelaar (2003). The sections were analysed under normal and polarized light using a Leica DM 2700 P microscope fitted with polarizing filters at 20Å~, 40Å~ and 100Å~ magnification. Images were acquired using a Leica MC170 HD microscope-incorporated camera.

Each sample was assessed macroscopically to identify the presence/absence and degree of bioerosion using the Oxford Histological Index (OHI; Hedges et al., 1995; Millard 2001). We distinguished between non-Wedl, Wedl, and cyanobacterial tunnelling (Fig. 2). Variable orientations of lamellar bone means that it appears birefringent when examined under a polarising light filter. Degradation of bone collagen affects this structure, and reduces birefringence. Reduction or absence of birefringence, recorded here using the Birefringence Index (BI), is therefore indicative of collagen loss, whether that is microbially or chemically mediated (Jans et al., 2002). Statistical analysis of the data was undertaken using IBM SPSS software and R Studio (RStudio Team 2020).

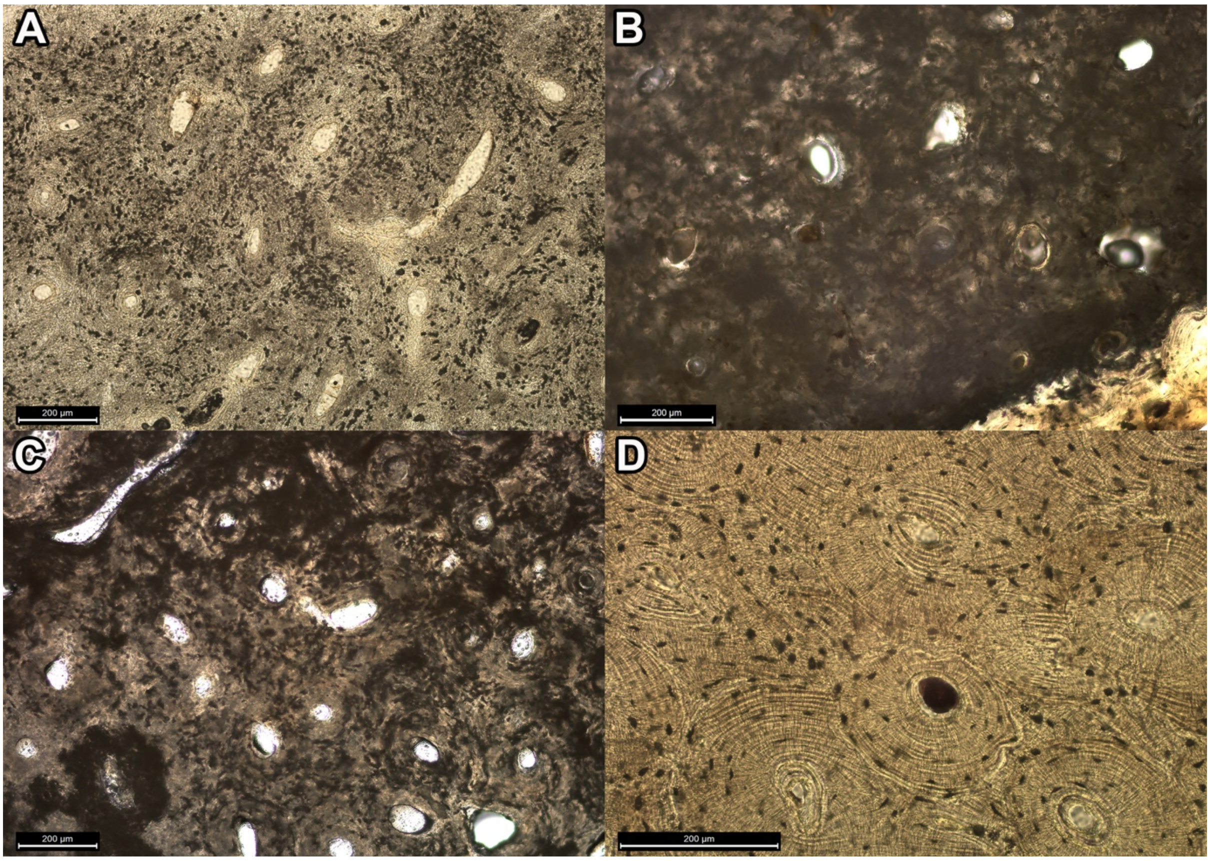

Fig. 2 Transmitted light micrographs showing the extent of bacterial bioerosion in femoral thin sections sampled from skeletons buried at Thornton Abbey, Lincolnshire: A) Sample from SK 19 with an OHI score of 2; B) Sample from SK 34 with an OHI score of 0; C) Sample from SK 51 with an OHI score of 1; D) Sample from SK 53 with an OHI score of 5.

4. RESULTS AND DISCUSSION

Our original intention was to record the extent of Wedl and non-Wedl MFD using the OHI. However, in samples where Wedl tunnelling only ever accounted for a small proportion of the overall levels of bioerosion, it was so small that it would not have registered on the OHI scale. Therefore, we only recorded presence/absence data for Wedl tunnelling. We did the same for cyanobacterial tunnelling, which was entirely absent from all of our bone thin sections.

4.1 Thornton Abbey, Lincolnshire

Histological examination of 44 samples from Thornton Abbey was undertaken by KH and CR; 25 samples from the hospital cemetery and 19 samples from the mass grave (Table 1). All but two samples exhibited non-Wedl tunnelling consistent with bacterial bioerosion. Wedl tunnels were not observed in any of the Thornton Abbey samples.

The Thornton Abbey mass grave samples had OHI scores between 0 and 2, with the majority (42%) of the samples having an OHI score of 0. In all cases, variation in OHI was attributable to bacterial bioerosion. The majority of the hospital samples (72%) also had OHI scores of 0 and 1, however, there were also a few samples with OHI scores of 2 and 3 (Fig. 3). Amongst the later multiple burials from the hospital cemetery, there was no difference between their OHI scores and those from the single interments; all but one sample had OHI scores of 1. A Mann-Whitney U-test of the total Thornton Abbey population revealed there was no significant difference between the OHI scores of the mass grave and hospital cemetery samples (U=195,500, p=.290).

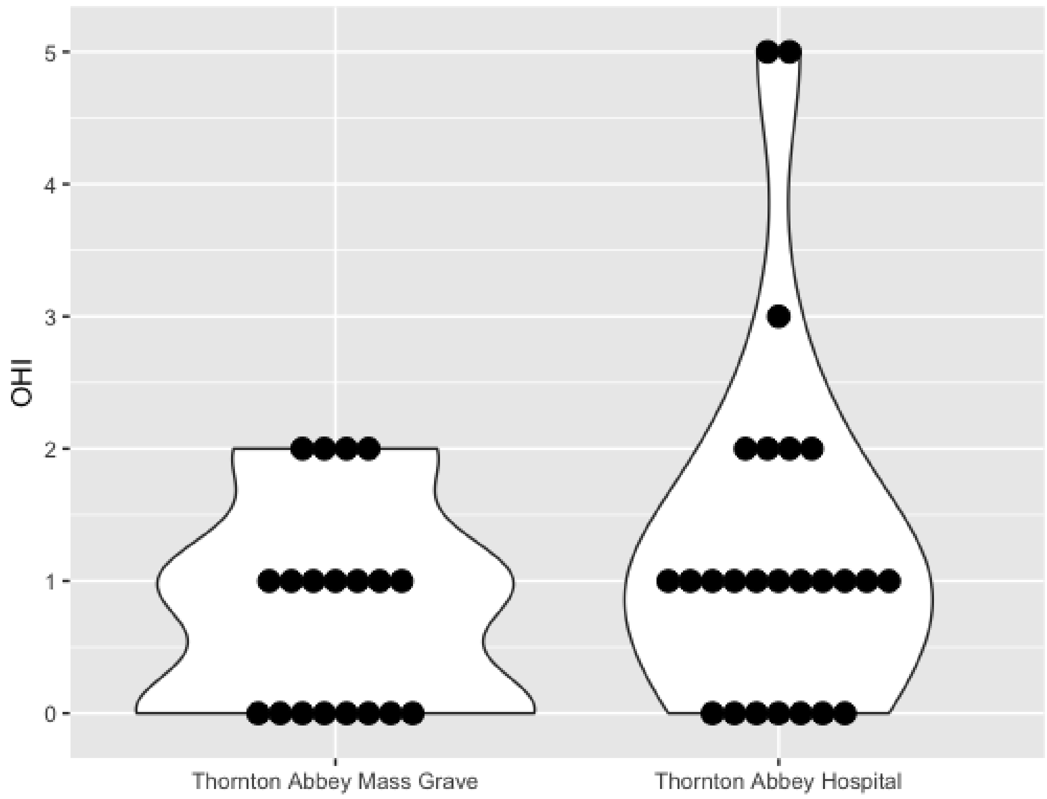

Fig. 3 Vase plot showing the distribution of OHI scores at Thornton Abbey, representing samples analysed from the mass grave (Black Death population) and the hospital cemetery (non-Black Death population). Note the similarly high density of lower OHI scores in both populations (RStudio Team 2020; Wickham 2016).

Two samples from the hospital cemetery were outliers, both having OHI scores of 5 reflecting the complete absence of bacterial tunnelling and a well-preserved microstructure. Using cross-polarised light, both samples were allocated a Birefringence Index of 1 which indicates no loss of collagen (Fig. 4). In all other samples, Birefringence Index varied with the degree of bacterial bioerosion. The absence of bacterial bioerosion within the samples from these two skeletons (SK 53, SK 54) suggest a divergent taphonomic history with very little soft tissue decomposition and rapid skeletonisation.

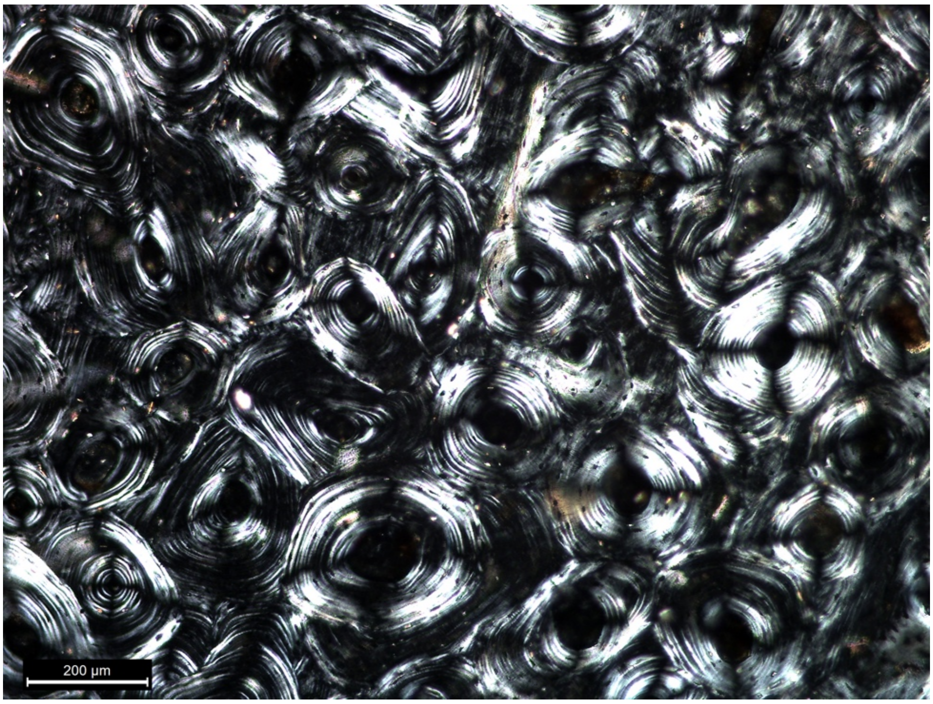

Fig. 4 Transverse femoral thin section from SK 54 (Thornton Abbey, hospital cemetery) viewed under cross-polarized light, 10x magnification. The micrograph shows the absence of bacterial attack and well-preserved internal microstructure. The sample was given an OHI score of 5 and a Birefringence Index of 1.

4.2 East Smithfield, London

Thin sections cut from femora of thirty-seven individuals buried at East Smithfield were examined histologically by Tryzelaar (2003) and Booth (2014; 2016); 26 samples came from the Black Death (E.S) cemetery, whilst 11 samples came from the later phase of burial at St Mary Graces (E.S) (Table 1). Twenty-four out of thirty-seven (64%) showed extensive bacterial tunnelling (OHI <3), ten (27%) showed more minor bacterial attack (OHI=3), and 3 (8%) were entirely free from bioerosion (OHI=5). However, while samples from both the Black Death (E.S) cemetery and St Mary Graces (E.S) tended to show extensive bacterial bioerosion, OHI scores in bones from the Black Death (E.S) cemetery were noticeably more variable and higher on average than OHI scores from St Mary Graces (E.S) (Fig. 5). Booth (2016: Table 1) found that OHI scores in bones from the Black Death (E.S) cemetery were significantly different from those in samples from articulated skeletons recovered from other historical cemetery sites around Britain, with a higher proportion (14/26, 53%) of Black Death (E.S) samples showing intermediate OHI scores of 2-3, and 2/26 (8%) showing no bioerosion at all (OHI=5; Booth 2016). The distribution of OHI scores amongst the samples from the cemetery at St Mary Graces (E.S) was consistent with what has been observed in articulated burials from other historic period cemeteries, with one notable outlier which was entirely free from bioerosion (OHI=5). The location of the burial within the East Smithfield cemetery (Eastern group, Western group, or St. Mary Graces) showed no significant relationship with OHI scores (Kruskal-Wallis chi-squared = 1.9353, df = 2, p = 0.38). Minor Wedl tunnelling was observed in 8/37 (22%) of the samples from East Smithfield; two came from the Black Death (E.S) graves, while six came from St. Mary Graces (E.S). Birefringence Index scores were directly related to the extent of bioerosion.

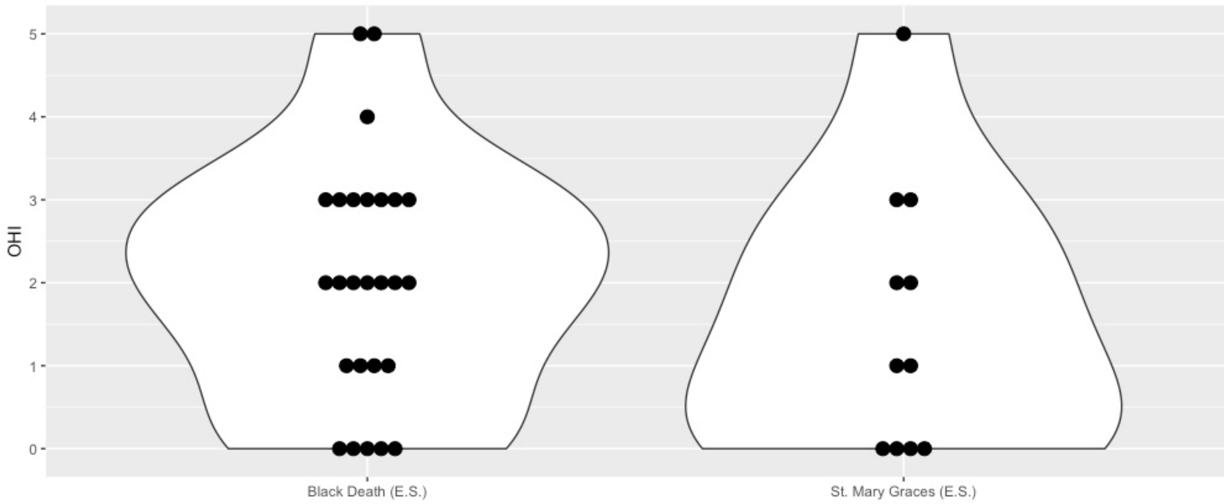

Fig. 5 Vase plot showing the distributions of OHI scores at East Smithfield according to those burials from the Black Death cemetery, and those burials from the post-Black Death cemetery of St Mary Graces. The plot shows a greater density of higher OHI scores in the Black Death sample (RStudio Team 2020; Wickham 2016).

< Insert Table 1 here >

4.3 Influence of Sex and Age-at-Death

There are broad average differences in the micro-organisation of bones in males, females, and in individuals of different ages, due to variation in the rate of bone remodelling caused by sex-specific hormones and the cumulative effects of remodelling through time (Khosla et al., 2006; Turner-Walker 2012). In order to rule out the influence of such characteristics on the degree of bacterial bioerosion observed, we combined OHI scores of samples from Thornton Abbey and East Smithfield to test whether there was any relationship with biological sex and age-at-death estimates obtained from the osteological analysis of the skeletal remains. There were no significant differences in OHI scores between skeletons that were confidently estimated as male or female (Wilcoxon rank sum test, $W = 334$, $p = 0.369$), or between skeletons of people who had died at different ages (Kruskal-Wallis chi-squared = 5.8482, df = 6, $p = 0.4404$).

4.4 Comparing Thornton Abbey and East Smithfield

The datasets from Thornton Abbey and East Smithfield were combined in order to compare them directly. The distribution of OHI scores were similar between all the samples from Thornton Abbey and those from St Mary Graces (E.S), which post-dated the Black Death epidemic; a Wilcox rank sum test confirmed that there was no significant difference between the two groups ($W=278$, $p=0.4323$). In contrast, the distribution of OHI scores from the Black Death (E.S) cemetery at East Smithfield was significantly different from the Thornton Abbey and St Mary Graces (E.S) samples combined (Wilcoxon rank sum, $W=984$, $p=0.005$; Fig. 6).

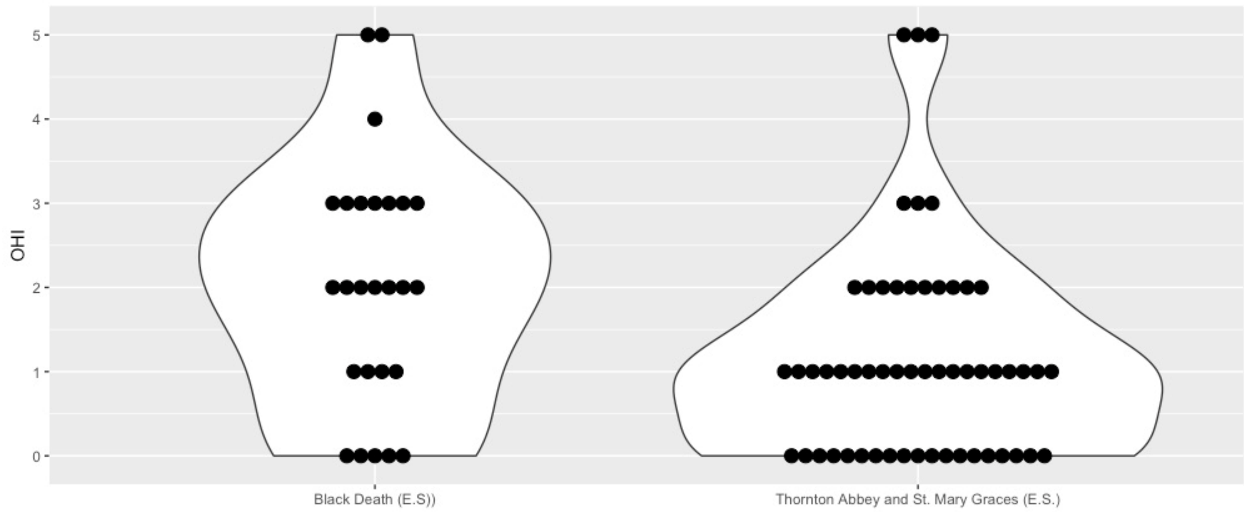

Fig. 6 Vase plot illustrating distributions of OHI scores from the Black Death (E.S) cemetery compared to the distribution of OHI scores from all burials at Thornton Abbey and St Mary Graces (E.S) combined (RStudio Team 2020; Wickham 2016). The OHI scores of the Thornton Abbey and St. Mary Graces (E.S) samples are distributed towards lower OHI scores similar to scores for other burials from historic cemeteries (see Booth 2016). The distribution of OHI scores from the Black Death (E.S) cemetery are significantly elevated in comparison.

The less variable and generally lower levels of bacterial bioerosion in the bones from the Black Death (E.S) cemetery suggest that, on the whole, this subset of samples had followed slightly different taphonomic trajectories from the bones from St. Mary Graces (E.S) and Thornton Abbey. All of the Black Death (E.S) burials were excavated from similar aerobic, free-draining burial environments, with proximate burials sometimes showing highly variable levels of bacterial attack. It is difficult to explain the variable patterns of bacterial attack by differences in environmental conditions that would have affected local soil microbiomes given the consistencies in the nature of the burial environment, and particularly the lack of evidence for anoxic or waterlogged burial contexts. Therefore, the best current explanation for variation in bacterial attack detected in the Black Death (E.S) burials is that those individuals were subject to different early post-mortem treatments which influenced the extent to which the bones were exposed to bacterial soft tissue decomposition.

The distribution of OHI scores from the Black Death (E.S) burials are similar to those observed in bones of bodies deposited in caves, and bodies that were left to decompose in storage pits on the Danebury Iron Age hillfort in Hampshire (Booth 2014; Booth and Madgwick 2016). Therefore, speculative scenarios which could reasonably be responsible for these variable patterns of bacterial bioerosion amongst the Black Death (E.S) burials include the discovery of bodies a while after death, delays between death and burial, attempts to preserve bodies before transportation (using charcoal, for instance), and/or decomposition of bodies in open, sheltered, or poorly-covered graves. Delays in burial would have ensured that some soft tissue loss would have been rapidly promoted by invertebrates thereby reducing the level of bacterial decomposition in the bone. The extent to which this treatment affected bodily decomposition and related bone bioerosion would be dependent on other factors affecting decomposition, such as temperature and humidity (Campobasso et al., 2001). These results are consistent with observations that some of the skeletons recovered from the Black Death (E.S) graves were found in partial articulation, suggesting the bodies had partially decomposed before they were buried. Alternatively, attempts to preserve bodies usually involve some arrestation of bacterial soft tissue decomposition, and the presence of charcoal in some of the graves has previously been interpreted as representing attempts to preserve bodies. Finally, the histological evidence may tally with evidence for silting in the mass grave trenches which has been used to suggest that the graves were left open for some time.

Burials from St Mary Graces (E.S) which post-dated the epidemic showed extensive patterns of bacterial attack consistent with burial of intact bodies soon after death, as would be expected for people subject to normative burial rites at this time. The contrast between the Black Death (E.S) cemetery and later burials at St Mary Graces (E.S) in East Smithfield support a scenario whereby communities in London were struggling to cope with the number of dead accumulating in and around the urban centre during the plague, which for some resulted in substantial delays between death and burial.

In contrast to the evidence from the Black Death (E.S) cemetery at East Smithfield, the comparably high levels of bacterial attack found in the burials from both the mass grave and hospital cemetery at Thornton Abbey indicate there was no substantial difference between how the dead were treated based on whether they died during or before/after the Black Death epidemic. The extensive patterns of bacterial bioerosion in these bones are consistent with the majority of remains having been buried intact soon after death. These patterns of bacterial attack were comparable with those from the later burials at St Mary Graces (E.S) as well as other complete articulated burials recovered from other cemeteries dating to historic periods (Booth 2016).

The absence of cyanobacterial tunnelling from both assemblages we studied is unsurprising given neither was from an aquatic context, and that it is unlikely they were submerged in standing water for substantial periods of time given they were all eventually buried in well-drained soils (Brönnimann et al., 20180. The absence of Wedl tunnelling from the Thornton Abbey sample is consistent with these bodies having been rapidly buried intact soon after death thereby preventing access to airborne fungal spores. The distribution of Wedl tunnelling among the East Smithfield assemblage is more difficult to explain. Its presence in some of the samples from the Black Death (E.S) graves makes sense if there was a substantial delay between death and burial, or if bodies lay in open or poorly-covered graves for a time (Booth 2016; Booth and Madgwick 2016; Brönnimann et al., 2018). However, most samples showing Wedl tunnelling were associated with the burials at St. Mary Graces (E.S) and presumably came from bodies that were rapidly buried soon after death. One of these samples was entirely free from bacterial bioerosion, and there is further evidence (presented below) that it came from a body that had been intentionally preserved and possibly displayed. The presence of Wedl tunnelling in other burials from St. Mary Graces (E.S) may suggest that similar practices were afforded to other burials from this phase, but with a much more limited effect on bacterial bone bioerosion. However, the range of processes and contexts which drive Wedl tunnelling are still unclear and it is possible some other factor may be responsible (Kendall et al., 2018).

4.5 Results in their historical context

This study aimed to identify whether the Black Death had an impact on the way in which the dead were treated during the epidemic, since such events are often said to lead to the abandonment of normative behaviour and a change in practice, particularly due to the volume of dead needing burial. The evidence presented here from Thornton Abbey and East Smithfield has shed considerable light on how two communities in two different regions of England shared a similar situation and adapted to it at a local level. The following discussion will explore some of the patterns observed in the data and how they might be explained within the wider context of the archaeological and historical record.

4.5.1 Coping in a catastrophe

Whilst some inmates of the hospital at Thornton Abbey may well have died during the plague and were perhaps buried before the creation of the mass grave, there is nothing to suggest from the sample analysed that they were treated any differently to those buried either before or after the epidemic. The extent of bacterial bioerosion observed in the plague-dead suggests they were not exposed to the activity of skeletonizing insects for an extended period of time, or preserved, as might have happened if the dead were transported from far away, as proposed for some of those in East Smithfield. We know the population at Thornton Abbey was not exclusively from the monastic household since the demographic profile of the mass grave represents a mixed population of both sexes and age groups, and therefore it seems likely that most individuals lived near to the abbey or were already present at the abbey when they died. It also seems that strategies were in place for the burial of those who died from the plague. For example, the absence of dress accessories or personal effects amongst the bodies in the mass grave indicates that the deceased were prepared for burial, including the removal of their clothes and personal possessions, and subsequently their bodies were wrapped in shrouds. The compression of the shoulders and minimal exposure to skeletonizing insects – as indicated by the extensive bone bioerosion linked to bacterial soft tissue decomposition – suggest this was the case (Willmott et al., 2020: 183). It seems, therefore, that attempts were made to ensure that the mass grave dead were prepared for burial in a similar way to those who died and were buried under 'normal' circumstances at the hospital's cemetery.

Willmott et al. (2020) suggest that subtle differences in the levels between the rows of bodies in the mass grave indicates that it was backfilled over a short period of time, perhaps even partially backfilled after each row of dead were interred. This would have made the burial of the dead more manageable, whilst early burial would have also facilitated extensive bacterial soft tissue decomposition as reflected by the OHI scores. In contrast to the mass grave sample from Thornton Abbey, the Black Death (E.S) burials from East Smithfield show more variable levels of bacterial bioerosion (Fig. 6). While a good proportion of these burials showed extensive patterns of bacterial attack consistent with intact burial, a substantial number experienced early taphonomic histories which had variably limited the extent to which the bones were exposed to bacterial soft tissue decomposition.

The variability in the OHI scores for the Black Death (E.S) burials at East Smithfield suggest the situation in London was very different to that in Lincolnshire. The numbers of dead in Lincolnshire may have been more manageable than presented to those in London; this certainly seems to be the case given the greater number of mass burials in the urban centre, and the greater number of dead excavated from those mass graves. It may have been that fewer people died amongst Thornton Abbey's surrounding rural communities, or that initially, many of the laity were buried in the nearby parish church of St Lawrence in Thornton Curtis, and are therefore not accounted for. Those primarily responsible for burial may also explain the divergent patterns observed between the histotaphonomic profiles of the mass grave dead at Thornton Abbey and those at East Smithfield.

Monastic houses and their hospitals, as at Thornton Abbey, were accustomed to providing services and care for many sectors of society, particularly the poor, the sick, and the dying (Willmott et al., 2020: 192; Gilchrist 1995: 8-14). Accommodating large numbers of dead was not unexpected nor beyond the capabilities of these communities. For example, excavation at other monastic houses both in Britain (e.g. St Mary Spital, London) and in northern Europe (e.g. Heiligen-Geist hospital, Lübeck, Germany), have revealed a number of other mass graves suggesting that the religious communities based at such institutions were both familiar with, and capable of, dealing with large numbers of dead including those who died during famine – such as the widespread famine of the early-14th century – and epidemics such as the Black Death (Lucas 1930: 366; Lügert et al., 2002: 160; Connell et al., 2010: 217; Willmott et al., 2020: 192). This certainly seems the case at Thornton Abbey where the plague-dead were interred with considerable care and placed in organised, overlapping rows. There is no evidence to suggest that burial was in any way hurried or disorganised, nor were the bodies thrown into the grave without due care and attention (Willmott et al., 2020: 183). Time was taken to populate the mass grave, suggesting those responsible had some expectation or knowledge that a number of individuals would need to be buried.

Advance preparations may have been in place due to the time delay between the arrival of the plague in England and the first reported cases in Lincolnshire. The Black Death arrived in England via the port of Melcombe Regis in Dorset and subsequently spread rapidly, reaching London by late September of 1348 (Grainger et al., 2008: 9-10). In contrast, it was not until the late Spring or early Summer of the following year that the plague was first reported in north Lincolnshire, almost six months after it had ravaged London (Willmott et al., 2020: 188). The delay to its arrival may therefore have allowed those rural villages, as well as the monastic community at Thornton Abbey to prepare for the worst possible scenario including plans for a mass grave within the abbey's outer precinct.

At Thornton Abbey, it is likely that the burial of the plague-dead (like those at the hospital) was overseen by the abbey's inmates, including its canons. Central to their dealing with the dying, and the dead, may have been the desire to adhere to the appropriate processes befitting a medieval 'good death' which dictated that preparations be put in place for the individual's soul, including the performance of the last rites to assist the soul's passage through purgatory, defined in the late 13th century as a liminal space for the purification of the soul in preparation for heaven (Gilchrist and Sloane 2005: 6, 19, 22). Such beliefs were central to the Christian psyche at this time that it is possible to appreciate why the abbey's inmates would want to facilitate the appropriate funerary processes.

In London, the Black Death cemeteries at East Smithfield were planned, organised and managed by the Crown as part of Edward III's response to the disease after he was informed of the plague's presence in France in the Spring of 1348 (Grainger et al., 2008: 28). The land used for the East Smithfield cemeteries was purchased prior to the plague by the king's agent, John Corey, and it is likely that he was instructed to make the land available for its use as an emergency burial site during the epidemic (in addition to West Smithfield) (Grainger et al., 2008: 28). Grainger et al. (2008: 28) posit that the 'atypical' level of organisation at the site may indicate that the Crown's agents oversaw the day-to-day use of the burial space and determined their layout, order of burial, and perhaps even who was permitted for burial. Unlike at Thornton Abbey, finds from East Smithfield indicate that some of the dead were buried in clothing, or at least some of the fastenings, such as copper alloy buckles, were used to keep the body within an item of dress (Grainger et al., 2008: 21-22). The preparation of these bodies may well have varied according to individual circumstances; perhaps for some during the early stages of the epidemic, the dead were prepared at home before transfer to the burial site, in keeping with secular funerary preparations at this time (Gilchrist and Sloane 2005: 23, 227). For others, however, and perhaps as the epidemic progressed and the numbers of dead increased, fewer attempts were made to prepare the dead in the same way, perhaps out of fear, or simply there were fewer surviving relatives to do so, and instead, the dead were buried in their clothing by those tasked with filling the mass grave trenches.

Despite the epidemic, these plague cemeteries were nonetheless consecrated spaces (Gilchrist and Sloane 2005: 74), meaning those buried within the mass graves were not to be treated or perceived differently from other members of society who died under 'normal' circumstances. The orderly lay out of the plague graves at East Smithfield and Thornton Abbey demonstrate that the plague dead were treated and buried in a way that was deemed acceptable for members of a Christian community, but within the limits of what could reasonably be undertaken in each region and under the particular circumstances. In the case of East Smithfield, this was determined by the volume of the dead, the extent of the area from where the dead were gathered, and perhaps even the state of decomposition that some of the deceased were found in prior to burial.

4.5.2 The incorruptible dead

At both Thornton Abbey and St Mary Graces (E.S), we found evidence for the divergent post-mortem treatment of possible high-status individuals. Three samples, one from a burial found beneath St. Mary Graces (E.S), and two from burials within the hospital chapel at Thornton Abbey, presented no evidence of bacterial bioerosion suggesting some disruption to bacterial soft tissue decomposition in the immediate post-mortem interlude.

The un-bioeroded sample from St Mary Graces (E.S) came from one of two burials recovered from beneath the abbey; one of these burials (SK 13530) belonged to an adult male, aged 36-45, who was buried supine in a timber coffin packed with crushed lime. Unfortunately, it was not possible to sample the second burial, which belonged to an older male (≥46) who was interred in a small timber coffin containing a layer of lime/crushed chalk which was placed within a chalk-walled vault beneath the foundations of the presbytery (Grainger and Phillpotts 2011: 47). The nature and location of these two burials led Grainger and Phillpotts (2011: 104) to suggest that quicklime was applied to their burials in an attempt to preserve the bodies of two high-status individuals, perhaps even temporarily for display prior to burial.

The application of lime or its liquid form (quicklime) to cadavers is often thought to aid in reducing the smell of bodily decay and quicken the rate of decomposition due to its alkalinity and bactericidal properties (Aufderheide 2003; Kim et al., 2008; Schotsmans et al., 2015: 466). Studies have found, however, that the presence of lime in the burial environment can in fact reduce the rate of decomposition resulting in a better-preserved corpse (Forbes, Stuart and Dent 2005: 27; Schotsmans et al., 2012: 50, 58). Lime can also retard bodily decomposition within the first six months through desiccation of the soft tissues (Aufderheide 2003: 56; Kim et al., 2008; Schotsmans et al., 2012; 2013; 2020). An early study by Bell et al. (1996) found evidence of minimal bacterial degradation in a skeleton that had been buried for seventy years in a coffin underneath unslaked lime. More recently, histological analysis on the remains of pigs confirmed that those buried in lime exhibited better preservation and less bacteria in the sampled tissues (Schotsmans et al., 2012; 2014a; 2014b).

The two outliers from Thornton Abbey who were buried at the eastern end of the hospital's chapel were also free from bacterial bioerosion and therefore distinct from other burials surrounding the hospital. One of these individuals (SK 53) was a man aged 35-45 years at death, who received an inscribed limestone grave cover, which recorded his name as Richard de W'Peton, abbreviated from 'Wispeton', referring to the modern town of Wispington, nearly 40 miles from Thornton Abbey. He died on 13th April 1317 during the Great Famine (1315-1317). An effigy depicting a man with tonsured hair wearing clerical robes and holding a chalice was also incised on the grave cover (Willmott and Townend 2017) (Fig. 7). Within the grave, his body was placed in a wooden coffin, alongside a pewter chalice, which at this time was a marker of priestly status (Gilchrist and Sloane 2005: 160). The prominent burial of Richard de W'Peton within the hospital's chapel, and the proximity to the burial of a second adult of indeterminate sex/age (SK 54), suggests they were both held in high regard within this monastic community. Given the striking similarities between the OHI scores of the aforementioned lime burial from St Mary Graces (E.S) and the two individuals from Thornton Abbey, X-ray diffraction (XRD) analysis and inductively coupled plasma-optical emission spectroscopy (ICP-OES) was performed on soil samples taken from within the graves of SK 53 and SK 54 (buried inside the hospital's chapel), and compared to soil from the graves of SK 36 and SK 51 who were buried in the hospital cemetery surrounding the chapel. Calcite is an abundant mineral that often occurs in soils of different kinds. However, the results of the XRD analysis and ICP-OES suggest there were traces of calcite within the burials of SK 53 and SK 54 above the expected levels for the fluvio-glacial sand and gravel soils (see Appendix A - Supplementary Resource 1). Levels of calcite were notably higher in the grave soils from SK 53 and SK 54 compared to the soil from SK 36 and SK 51. Given that SK 53 and SK 54 are entirely free from bacterial attack compared to all the others who were buried in exactly the same deposit of sandy gravel soil and who *did* display bacterial bioerosion, it may indicate that the use of lime was part of the funerary rites afforded to the two individuals buried inside the hospital's chapel.

Fig. 7 Incised grave cover of Richard de W'Peton who was buried within the chapel of St James' Hospital at Thornton Abbey, Lincolnshire.

Alternatively, whilst liming may have been one way in which the religious communities at Thornton Abbey and St Mary Graces (E.S) attempted to preserve these bodies, it is also possible that multiple complementary methods were involved for which there is no surviving evidence. For some senior members of secular and religious society, alternative post-mortem treatments for preserving the soft tissues included embalming, evisceration and excarnation (Camporesi 1983; Brown, 1981; Weiss-Krejci, 2008; Weiss-Krejci 2010; Schotsmans et al., 2015). Evisceration and/or embalming, namely the removal of the internal organs and the treatment of the corpse with preservatives such as aromatics or salts, was adopted in England in the late 12th century (Brown, 1981: 228; Westerhof 2008: 79; Weiss-Krejci 2010: 133). Evisceration and the division of the body was costly, and a distinct symbol of high status most often afforded to kings and queens, but occasionally to other well-regarded individuals including clerics. For example, in 1240, Edmund of Abingdon, the exiled Archbishop of Canterbury died in France. His body was buried in the Cistercian monastery of Potigny, whilst his heart and entrails were buried at the Church of St Jacques in Provins where he spent his final days (Brown, 1981: 229). In addition to being a marker of status, such methods may have offered a sense of permanence akin to that of paradise where there was no place for bodily corruption (Camporesi 1983: 25, 75-77). Those whose lives were virtuous and free from sin were thus those whose bodies were free from decay (Camporesi 1983: 25). According to Duch (2016: 73), the process of evisceration and embalming – and perhaps even the application of lime – provided those who wanted it with the means to demonstrate their virtuosity, since incorruptibility symbolised the departure of the soul to heaven. Whether through the use of lime or some other method, the two burials from the hospital chapel at Thornton Abbey and the burial from St Mary Graces (E.S) represent a clear attempt to preserve these individuals through the inhibition of (bacterial) soft tissue decomposition, and as such, may explain why their bone samples were free from any bacterial attack.

5. CONCLUSIONS

This study sought to investigate how two different medieval communities in England – one rural, the other urban – managed the challenges presented by increased numbers of dead arising from the Black Death epidemic of the mid-14th century. Evidence for bone diagenesis and bacterial bioerosion from the histological analysis of femoral thin sections revealed significant variation in the early post-mortem treatment of those who died during the epidemic in urban London, in comparison to those who died in rural Lincolnshire. We propose that the data for London reflects a community under pressure from significant numbers of dead, including those from the wider surrounding area who experienced delays between death and burial. In contrast, there was no substantial difference between how the dead were treated at Thornton Abbey regardless of whether or not they died during or before/after the plague. Here it seems that not only were the numbers of dead more manageable, the burial process itself may have been facilitated by the involvement of the abbey's inmates. This study highlights the need to consider the unique circumstances facing individual communities affected by the Black Death, and whilst the epidemic may have disrupted many aspects of everyday life, where circumstances allowed, attempts were made to perform appropriate rites. Our analysis also revealed instances in both London and Lincolnshire of individuals' whose early post-mortem treatment diverged significantly from the remainder of the population. In drawing upon contextual evidence from the burials and the historical record, we have explored the possible reasons for this variability, including attempts to preserve those afforded a particular status in life.

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APPENDIX CAPTION

APPENDIX A - SUPPLEMENTARY RESOURCE 1: Supplementary Resource 1 provides details and results of the X-ray diffraction (XRD) analysis and inductively coupled plasma-optical emission spectroscopy (ICP-OES) undertaken on soil samples collected from inside the graves of SK 53 and SK 54 who were buried within the hospital's chapel, and SK 36 and SK 51 who were buried in the cemetery surrounding the hospital's chapel, at Thornton Abbey in Lincolnshire.

Site	Skeleton	Element	Sex	Age	Context	Grave type	Location	OHI	BI	Non-Wedl MFD	Wedl MFD	Cyanobacterial tunnelling
East Smithfield, London	5728	Femur	M	35-45	Black Death	Single	Eastern	1	0.5	Present	Absent	Absent
East Smithfield, London	9849	Femur	M	35-45	Black Death	Single	Western	1	0.5	Present	Absent	Absent
East Smithfield, London	11117	Femur	F	25-35	Black Death	Trench	Western	2	0.5	Present	Absent	Absent
East Smithfield, London	9517	Femur	M	35-45	Black Death	Trench	Western	2	0.5	Present	Absent	Absent
East Smithfield, London	12884	Femur	M	35-45	Black Death	Single	Western	2	0.5	Present	Absent	Absent
East Smithfield, London	5265	Femur	M	25-35	Black Death	Single	Western	0	0.5	Present	Present	Absent
East Smithfield, London	6388	Femur	F	Adult	Black Death	Trench	Eastern	5	1	Absent	Absent	Absent
East Smithfield, London	6398	Femur	F	25-35	Black Death	Single	Western	4	0.5	Present	Absent	Absent
East Smithfield, London	6509	Femur	M	35-45	Black Death	Single	Eastern	2	0.5	Present	Absent	Absent
East Smithfield, London	6602	Femur	M	15-25	Black Death	Single	Eastern	3	0.5	Present	Absent	Absent
East Smithfield, London	7163	Femur	F	35-45	Black Death	Single	Western	3	0.5	Present	Absent	Absent
East Smithfield, London	8099	Femur	M	35-45	Black Death	Single	Western	0	0.5	Present	Absent	Absent
East Smithfield, London	13774	Femur	M	Adult	Black Death	Single	Western	3	0.5	Present	Absent	Absent
East Smithfield, London	13747	Femur	M	Adult	post-Black Death	Single	St Mary Graces	2	0.5	Present	Absent	Absent
East Smithfield, London	13530	Femur	M	Adult	post-Black Death	Single	St Mary Graces	5	0.5	Absent	Present	Absent
East Smithfield, London	13666	Femur	M	35-45	post-Black Death	Single	St Mary Graces	2	0.5	Present	Present	Absent
East Smithfield, London	16122	Femur	F	45+	post-Black Death	Single	St Mary Graces	3	0.5	Present	Present	Absent
East Smithfield, London	10348	Femur	M	45+	post-Black Death	Single	St Mary Graces	0	0.5	Present	Absent	Absent
East Smithfield, London	10070	Femur	M	45+	post-Black Death	Single	St Mary Graces	0	0.5	Present	Absent	Absent
East Smithfield, London	8126	Femur	U	Adult	Black Death	Single	Western	5	0.5	Absent	Absent	Absent
East Smithfield, London	5859	Femur	F	35-45	Black Death	Trench	Eastern	2	0.5	Present	Absent	Absent
East Smithfield, London	8210	Femur	F	45+	Black Death	Single	Western	0	0.5	Present	Absent	Absent
East Smithfield, London	6545	Femur	M	Adult	Black Death	Single	Eastern	3	0.5	Present	Absent	Absent
East Smithfield, London	12774	Femur	F	45+	Black Death	Trench	Western	3	0.5	Present	Absent	Absent
East Smithfield, London	12691	Femur	F	35-45	Black Death	Trench	Western	3	0.5	Present	Absent	Absent

East Smithfield, London	6383	Femur	F	35-45	Black Death	Single	Western	0	0.5	Present	Absent	Absent
East Smithfield, London	8414	Femur	F	25-35	Black Death	Trench	Western	2	0.5	Present	Absent	Absent
East Smithfield, London	8217	Femur	F	35-45	Black Death	Single	Western	2	0.5	Present	Absent	Absent
East Smithfield, London	12897	Femur	M	35-45	Black Death	Single	Western	3	0.5	Present	Absent	Absent
East Smithfield, London	11606	Femur	M	35-45	Black Death	Trench	Western	0	0.5	Present	Absent	Absent
East Smithfield, London	10213	Femur	U	Adult	Black Death	Trench	Western	1	0.5	Present	Absent	Absent
East Smithfield, London	10635	Femur	F	45+	post-Black Death	Single	St Mary Graces	0	0.5	Present	Present	Absent
East Smithfield, London	11997	Femur	U	Adult	Black Death	Single	Western	1	0.5	Present	Present	Absent
East Smithfield, London	10250	Femur	NA	5-15	post-Black Death	Single	St Mary Graces	0	0.5	Present	Present	Absent
East Smithfield, London	10240	Femur	F	Adult	post-Black Death	Single	St Mary Graces	1	0.5	Present	Absent	Absent
East Smithfield, London	14421	Femur	F	15-25	post-Black Death	Single	St Mary Graces	1	0.5	Present	Absent	Absent
East Smithfield, London	10801	Femur	M	35-45	post-Black Death	Single	St Mary Graces	3	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 5	Femur	NA	6-11	non-Black Death	Single	St James's hospital	0	0.5	Present	Present	Absent
Thornton Abbey, Lincolnshire	SK 20	Femur	M	36-45	non-Black Death	Single	St James's hospital	0	0	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 26	Femur	F	45+	non-Black Death	Single	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 30	Femur	NA	6-11	non-Black Death	Single	St James's hospital	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 34	Femur	M	45+	non-Black Death	Single	St James's hospital	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 36	Femur	M	26-35	non-Black Death	Single	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 48	Femur	M	26-35	non-Black Death	Single	St James's hospital	2	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 51	Femur	NA	6-11	non-Black Death	Single	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 53	Femur	M	36-45	non-Black Death	Single	St James's hospital	5	1	Absent	Absent	Absent
Thornton Abbey, Lincolnshire	SK 54	Femur	M	26-35	non-Black Death	Single	St James's hospital	5	1	Absent	Absent	Absent
Thornton Abbey, Lincolnshire	SK 62	Femur	M	36-45	non-Black Death	Single	St James's hospital	0	0	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 66	Femur	NA	11-13	non-Black Death	Single	St James's hospital	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 72	Femur	M	36-45	non-Black Death	Single	St James's hospital	2	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 73	Femur	NA	6-11	non-Black Death	Single	St James's hospital	3	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 85	Femur	M	36-45	non-Black Death	Single	St James's hospital	1	0.5	Present	Absent	Absent

Thornton Abbey, Lincolnshire	SK 92	Femur	M	45+	non-Black Death	Single	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 109	Femur	NA	6-11	non-Black Death	Single	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 132	Femur	F	36-45	non-Black Death	Single	St James's hospital	2	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 137	Femur	M	26-35	non-Black Death	Double burial	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 138	Femur	NA	6-11	non-Black Death	Double burial	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 150	Femur	M	36-45	non-Black Death	Triple burial	St James's hospital	2	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 157	Femur	NA	1-5	non-Black Death	Triple burial	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 158	Femur	M	36-45	non-Black Death	Triple burial	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 58	Femur	NA	6-11	non-Black Death	Single	St James's hospital	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 153	Femur	M	18-25	non-Black Death	Single	St James's hospital	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 2	Femur	M	25-35	Black Death	Mass grave	Mass grave	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 3	Femur	M	45+	Black Death	Mass grave	Mass grave	2	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 4	Femur	F	30-40	Black Death	Mass grave	Mass grave	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 6	Femur	F	45+	Black Death	Mass grave	Mass grave	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 8	Femur	M	35-45	Black Death	Mass grave	Mass grave	0	0	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 9	Femur	F	26-30	Black Death	Mass grave	Mass grave	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 14	Femur	M	25-35	Black Death	Mass grave	Mass grave	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 15	Femur	?M	45+	Black Death	Mass grave	Mass grave	2	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 17	Femur	NA	6-11	Black Death	Mass grave	Mass grave	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 19	Femur	?F	35-50	Black Death	Mass grave	Mass grave	2	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 21	Femur	NA	5-9	Black Death	Mass grave	Mass grave	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 28	Femur	NA	13-15	Black Death	Mass grave	Mass grave	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 31	Femur	?M	45+	Black Death	Mass grave	Mass grave	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 33	Femur	NA	9-12	Black Death	Mass grave	Mass grave	2	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 39	Femur	NA	5-6	Black Death	Mass grave	Mass grave	0	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 41	Femur	?M	45+	Black Death	Mass grave	Mass grave	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 49	Femur	F	25-35	Black Death	Mass grave	Mass grave	1	0.5	Present	Absent	Absent
Thornton Abbey, Lincolnshire	SK 50	Femur	?M	18-25	Black Death	Mass grave	Mass grave	1	0.5	Present	Absent	Absent

Thornton Abbey, Lincolnshire	SK 61	Femur	M	35-45	Black Death	Mass grave	Mass grave	0	0.5	Present	Absent	Absent

Table 1. Details of the human remains sampled for thin section analysis from Thornton Abbey, Lincolnshire and East Smithfield, London. Sex categories are: M = male, ?M = possible male, F=female, ?F = possible female, NA = not applicable, U=undetermined. 'OHI' refers to Oxford Histological Index and 'BI' refers to Birefringence Index (BI).