The Effect of Sex on Risk of Mortality During the Black Death in London, A.D. 1349–1350

Sharon N. DeWitte*

Department of Anthropology, University at Albany, Albany, NY 12222

KEY WORDS selective mortality; paleodemography; sex differentials; Denmark; England

ABSTRACT The Black Death of 1347–1351 was one of the most devastating epidemics in human history, and though it is frequently assumed that the epidemic killed indiscriminately, recent research suggests that the disease was selective, at least with respect to frailty. The purpose of this study is to determine whether the Black Death was similarly selective with respect to biological sex—that is, did either sex face an elevated risk during the epidemic or were men and women at equal risk of dying? A sample of 298 victims of the Black Death, from the East Smithfield cemetery in London, is compared to a pre-Black Death normal mortality sample of 194 individuals from two Danish urban cemeteries, St Mikkel Church (Viborg) and St Albani Church (Odense). To assess the effect of sex on risk of death, sex is modeled as a covariate affecting the Gompertz–Makeham model of adult mortality. The results suggest that sex did not strongly affect risk of death in either the normal mortality or Black Death samples. These results are important for improving our understanding of Black Death mortality patterns. This is essential for understanding the effects the Black Death had on European populations, and the methods used here can potentially be informatively applied to investigations of other episodes of epidemic diseases in past populations. Am J Phys Anthropol 139:222–234, 2009. © 2009 Wiley-Liss, Inc.

The Black Death of A.D. 1347–1351 was one of the most devastating epidemics in human history, killing tens of millions of Europeans and initiating or enhancing social, demographic, and economic changes throughout the continent (Twigg, 1984; Cohn, 2002; Hinde, 2003). The Black Death was exceptionally virulent. It is estimated that the epidemic killed 30–50% of individuals within affected populations in Europe (Poos, 1991; Cohn, 2002; Wood et al., 2003) with some locales experiencing even higher mortality (Cohn and Weaver, 2006). According to some contemporary chroniclers of the Black Death, individuals of all ages, men and women, rich and poor, were victims of the epidemic (see Horrox, 1994; Scott and Duncan, 2001; Cohn, 2002). For example, Villani (1995), a Florentine chronicler, described the Black Death as "a pestilence among men of every condition, age and sex" (translation quoted in Cohn, 2002, p 126). According to the chronicler Michele da Piazza (originally written in 1336–1361), the mortality from the Black Death was "so heavy that sex and age made no difference, but everyone died alike" (translation from Horrox, 1994, p 41). Given these reports by contemporary chroniclers and the very devastating mortality associated with the Black Death, it is tempting to assume that the disease was an indiscriminant killer and that no one, regardless of age, sex, and health or socioeconomic status, was safe during the epidemic.

Because of the very high mortality and short time span of the Black Death, some researchers have suggested that Black Death burial grounds might provide true cross-sections of the original populations—that is, skeletal samples of Black Death victims might more closely reflect the true age- and sex distributions and frequencies of disease within the original living populations than is available from normal attritional cemetery samples (Conheeney, 1999; Margerison and Knüsel, 2002; Gowland and Chamberlain, 2005). However, some contemporary chroniclers believed that the epidemic was selective and, for example, killed more women than men (Cohn, 2002). Following the Black Death of 1347–1351, there were periodic outbreaks of plague in Europe until the eighteenth century; based on the epidemiological characteristics of these epidemics, they were probably caused by the same disease responsible for the fourteenth century Black Death (Scott and Duncan, 2001). Some contemporary reports of those subsequent plagues suggest that men were killed at a higher rate than were women (Cohn, 2002). In an outbreak of plague in 1361, referred to as the "Pestilence of Children," several chroniclers noted that this outbreak differentially affected young men and children (Holmes, 1971; Hatcher, 1977). If the Black Death or subsequent plagues were selective at all, burial grounds associated with the epidemics may not provide representative samples of the living populations.

Grant sponsor: National Science Foundation; Grant number: BCS-0406252; Grant sponsor: The Wenner–Gren Foundation for Anthropological Research; Grant number: 7142; Grant sponsors: The American–Scandinavian Foundation, The Pennsylvania State University's Research and Graduate Studies Office, University at Albany Center for Social and Demographic Analysis (CSDA), University at Albany Research Foundation.

*Correspondence to: Sharon N. DeWitte, Department of Anthropology, AS 237, University at Albany, Albany, NY 12222, USA. E-mail: sdewitte@albany.edu

Received 23 June 2008; accepted 14 October 2008

DOI 10.1002/ajpa.20974
Published online 12 January 2009 in Wiley InterScience (www.interscience.wiley.com).

DeWitte and Wood (2008) have shown that the Black Death was probably selective with respect to pre-existing health conditions, or frailty (which in the context of that study referred to an individual's age-adjusted relative risk of death during the normal, nonepidemic period just prior to the onset of the Black Death). That is, at least with respect to frailty, there is evidence that the Black Death was not an indiscriminate killer; individuals who were in poor health (or at least apparently poor skeletal health) before the epidemic were more likely to die during the Black Death than their healthier peers. Using a multistate model of morbidity and mortality and a sample of individuals who died during the Black Death (the East Smithfield cemetery sample described below), DeWitte and Wood analyzed the risk of death associated with certain nonspecific skeletal lesions or stress markers: linear enamel hypoplasia, porotic hyperostosis, cribra orbitalia, tibial periostitis, and short femur length (as a proxy for short adult stature). Periostitis can occur at any age as the result of trauma, hemorrhage, or infection (Larsen, 1997; Ortner, 2003). Porotic hyperostosis and cribra orbitalia are lesions on the cranial vault bones and orbital roofs, respectively, that occur as bone marrow expands (Mensforth et al., 1978; Ortner, 2003). Both porotic hyperostosis and cribra orbitalia are generally associated with anemia during childhood, but the lesions can be retained into adulthood. Linear enamel hypoplasia is a macroscopic tooth enamel defect caused by the disruption of enamel formation as a result of infection or nutritional deficiencies during childhood (Huss-Ashmore et al., 1982; Dahlberg, 1991; Roberts and Manchester, 2005). Adult stature reflects, among other things, exposure to chronic stress (e.g. malnutrition) during development; short adult stature, relative to other individuals within the population, may indicate poor health and poor nutrition during the developmental years (Haviland, 1967; Powell, 1988; Steckel, 1995; Roberts and Manchester, 2005). DeWitte and Wood (2008) analyzed these skeletal lesions or stress markers because they wanted to obtain a general measure of the health of individuals just before the Black Death. They found that, in general, individuals with nonspecific skeletal lesions were at a higher risk of mortality during the epidemic than their peers without such lesions. A comparison of the pattern in the Black Death sample with that in a pre-epidemic, normal mortality sample revealed that the Black Death, though selective with respect to frailty, was perhaps not as strongly selective as normal mortality, presumably because the epidemic killed otherwise healthy individuals who would have been unlikely to die under normal circumstances (DeWitte and Wood, 2008).

Given this evidence that the Black Death was selective with respect to frailty, it is important to determine whether other factors influenced risk of death during the epidemic. This paper addresses the question of whether biological sex had an effect on an individual's risk of death during the Black Death. That is, was either sex at higher risk, or were men and women at equal risk during the Black Death? There are many modern diseases that differentially affect one sex. Many studies that examine sex differences in infection have found that males are more susceptible than females to a wide range of diseases caused by viruses, bacteria, parasites, and fungi; the course of disease is often more severe in males, and they frequently face higher risks of mortality from parasitic and infectious diseases (Hoff et al., 1979; Oliviera et al., 1981; Kirkwood et al., 1983; Brabin and Brabin, 1992; Acuna-Soto et al., 2000; Klein, 2000; Noymer and Garenne, 2000; Wells, 2000; Blessmann et al., 2002; Owens, 2002; Leone et al., 2004; Jansen et al., 2007). For example, some important bacterial infections, such as *Staphylococcus aureus*, are more common in males (Laupland et al., 2003), and males are more susceptible to most types of respiratory tract infections, are more likely to suffer from severe symptoms, and are at higher risk of mortality from such infections than females at all ages (Falagas et al., 2008). Such sex differences are not limited to humans, as in many mammal and bird species the incidence and severity of parasite infections are higher in males (May, 2007). However, males are not always at a disadvantage with respect to diseases. Malaria, for example, more severely affects women, particularly pregnant women, even though the incidence of the disease appears similar in both sexes (Roberts et al., 2001). Studies using mouse models have revealed several other diseases that disproportionately affect females (Alexander, 1988; Roberts et al., 1995; Pasche et al., 2005).

In modern cases of bubonic plague, the disease that many argue was the cause of the Black Death (e.g. Yersin, 1894), infection is often, but not always, more common in men. In cases of plague in the United States between 1975–1988, men made up a higher proportion of those infected and killed by the disease (Butler, 1989; Poland, 1989); this difference occurs, in part, because some of the risk factors for acquiring plague in the United States, such as hunting and ranch work, are more commonly engaged in by men (Cleri et al., 1997; Perry and Fetherston, 1997). Men are also more frequently affected by plague in Madagascar (Blanchy et al., 1993; Boisier et al., 1997, 2002; Chanteau et al., 2000; Migliani et al., 2006), Kazakhstan (Aikimbajev et al., 2003), and some areas of China (Pollitzer, 1954); and a seroepidemiological study suggests that Malagasy men are more susceptible to the disease than are women (Ratsitorahina et al., 2000). This pattern is not universal; in an outbreak in Hainan, China, men and women were equally affected (Pollitzer, 1954), and the incidence of plague is higher among females in India (Pollitzer, 1954), Tanzania (Davis et al., 2006; Kamugisha et al., 2007), Kenya, and Mozambique (Tikhomirov, 1999). Researchers have suggested that the higher incidence of bubonic plague in females in Tanzania might be the result of different sleeping arrangements (men sleep in beds and women sleep on the floor) or differences in outdoor activities that increase the risk of exposure for women (Davis et al., 2006; Kamugisha et al., 2007).

From this brief overview, it is clear that there are important sex-mediated differences in susceptibility to or severity of many diseases. According to Brabin and Brabin (1992), differences between males and females in the patterns and results of infection with parasitic diseases can result, among other things, from differences in exposure to infective vectors as a consequence of behavior and work patterns and differences in immunity and response to treatment. Differences between men and women with respect to activity patterns may explain some sex differences in modern human diseases, such as bubonic plague as described above. Sex hormones play an important role in the immune system and account for some of the observed sex differences in disease patterns—in general (though there are several important exceptions), estrogens seem to enhance both cellular and humoral immunity, whereas androgens reduce immunocompetence (Grossman, 1985; Ansar Ahmed et al., 1999; Klein, 2000; Roberts et al., 2001; Janele et al., 2006). This has been demonstrated in animal models; for example, ovarectomized female mice have been found to be less resistant to bacterial infection compared to control females (Leone et al., 2004), and gonadectomized male mice display higher immune response and resistance to disease compared to control males (Klein, 2000). There are some cases in which estrogen reduces immune function; for example, estrogen appears to downregulate gamma interferon production, which is probably necessary for resistance to some pathogens (Pasche et al., 2005). Sex hormones also affect behaviors, such as aggression and dispersal, that can play a role in risk of exposure to and spread of disease (Klein, 2000). Sexual dimorphism may also play a role in sex differences in disease patterns, as the larger sex potentially provides more resources or larger "targets" for parasites (May, 2007).

With respect to some modern diseases, men and women face different risks of morbidity and mortality, but can differentials associated with infectious disease be detected in samples from past populations? Physical anthropologists have investigated this question using skeletal material. For example, Ortner (1998) and Larsen (1998) reported higher frequencies of periostitis in men compared to women in prehistoric Native American samples; as mentioned above, periostitis can be caused by infectious disease, so such results might indicate higher morbidity from infectious disease among men in those populations (Ortner, 1998). Cassidy (1984) also reported higher frequencies of periostitis among men in a Mississippian site, although the sex difference was not statistically significant. Larsen (1997) reports several studies that found a higher frequency or greater severity of periostitis among females compared to males in prehistoric Southwestern US samples. Šlaus (2000) found that the frequency of periostitis in women was double that in men in a late medieval skeletal sample from Croatia, although the results were not statistically significant. However, in an early medieval skeletal sample from Croatia, a significant sex difference was found in the frequency of periostitis, with the male frequency almost twice that of females (Šlaus, 2008). Roberts et al. (1998) investigated sex differences in maxillary sinusitis in medieval English cemeteries; results varied, but the only significant difference was a higher frequency among females at the rural site of Wharram Percy. More recent data on maxillary sinusitis from North American, English, and Nubian cemetery samples yielded a consistent pattern of higher frequencies in women compared to men (Roberts, 2007). Grauer et al. (1998) found in a sample from a nineteenth century Chicago poorhouse that frequencies of periostitis, linear enamel hypoplasia, and other lesions potentially indicative of infectious diseases did not differ significantly between the sexes. Buikstra and Cook (1981) and Powell (1988) failed to find a sex difference in the frequency of tuberculosis in some Middle and Late Woodland and Mississippian sites; however, Powell (1991) found that the frequency for females was higher than that of males at Irene Mound.

The focus of the current study, the medieval Black Death, does not lend itself to the same kind of analysis conducted in the studies described above; the Black Death killed much too quickly to leave any visible signs on the victims' bones (Scott and Duncan, 2001; Cohn, 2002); so, one cannot compare the frequency of lesions in men and women to investigate sex patterns of Black Death morbidity and mortality. As mentioned above, sex differences in mortality are noted by chroniclers of the epidemic, but there is not sufficient evidence in existing written records to provide a clear understanding of the sex pattern of Black Death mortality. Researchers have inferred the *age* pattern of Black Death mortality from documentary evidence. Russell (1948) examined the *inquisitions post mortem*, English royal inquisitions into the cause of death of people (mostly men) who held land directly from the king, and produced life-table estimates of age-specific mortality among high-status individuals during the Black Death in England. Further, using manorial court records from the English village of Halesowen, Razi (1980) estimated ages at death among the peasantry during the epidemic. Unfortunately, it is not possible to analyze the sex pattern of mortality from such documents given that most provide information only about males (Russell, 1948; Razi, 1980), and documentary evidence may not be completely accurate. Fortunately, existing skeletal samples of Black Death victims can potentially provide information about the sex pattern and other demographic patterns of Black Death mortality that is unavailable from surviving historical documents. Such skeletal samples can also potentially yield pathogen DNA, which can be used to identify and characterize the cause of the epidemic (Drancourt et al., 1998, 2007; Raoult et al., 2000; Drancourt and Raoult, 2002; Gilbert et al., 2004; Wiechmann and Grupe, 2005).

During the Black Death, it was necessary to establish mass burial grounds throughout Europe because existing cemeteries were not sufficient to accommodate all of the victims of the epidemic. One such burial ground is the East Smithfield cemetery in London, an exclusively Black Death cemetery that is, to date, one of only a few excavated cemeteries with clear documentary and archeological evidence linking it to the medieval epidemic. The East Smithfield cemetery was established in late 1348 or early 1349 to accommodate the overwhelming number of people killed during the Black Death in London; in 1348, there were apparently over one hundred parish cemeteries in the city of London and the surrounding suburbs, yet the East Smithfield cemetery was necessary to supplement or perhaps temporarily replace existing cemeteries (Hawkins, 1990). East Smithfield was used until the Black Death ended in London in 1350. The cemetery was excavated by the Museum of London Department of Greater London Archaeology (now the Museum of London Archaeology Service: http://www.molas.org.uk) from 1986 to 1988 as part of the larger Royal Mint site located in northeast London near the Tower of London. The Royal Mint site includes the East Smithfield Black Death cemetery, the Cistercian Abbey of St Mary Graces (in use between 1350 and 1538), and a victualling yard for the Royal Navy (in use between 1560 and 1785); the Royal Mint was moved to the site from the Tower of London in the early nineteenth century, and it remained there until the late 1960s (Grainger and Hawkins, 1988). Excavation of the East Smithfield cemetery revealed several hundred skeletons, some of which were too degraded to be recovered from the burial ground. Ultimately, ~600 Black Death skeletons were recovered and are currently curated at the Museum of London; researchers at the Museum's Centre for Human Bioarchaeology previously analyzed the East Smithfield cemetery, and summaries of their findings can be found at http://www.museumoflondon.org.uk/English/Collections/OnlineResources/CHB/. The East Smithfield cemetery provides a rare opportunity to examine the mortality patterns of the Black Death, as most, if not all, individuals interred there were victims of the epidemic in London.

Several researchers have analyzed the East Smithfield Black Death cemetery to determine the age pattern of Black Death mortality. Waldron (2001) compared the East Smithfield cemetery to a post-Black Death normal (i.e. nonepidemic) mortality sample from the St Mary Graces cemetery in London. Waldron estimated age at death using standard methods based on age-related changes of such skeletal features as the pubic symphysis and cranial sutures. Many of the adult skeletons in each sample were too poorly preserved to allow for age or sex estimation; furthermore, sex differences in skeletal morphology generally do not appear until after puberty; so, sex is frequently not estimated for juveniles in paleodemographic studies. Waldron assigned sex or age to juvenile and poorly preserved adult skeletons by making two assumptions. First, he assumed that the sex ratio of children was the same as that of the adults in each assemblage, and thereby assigned sex to juveniles. Waldron also assumed that the adults of unknown age were distributed evenly among each of the adult age categories. Using these assumptions, he found that there were no systematic differences between the mortality profiles of the two cemeteries, and inferred that no particular age was disproportionately affected during the Black Death.

Margerison and Knüsel (2002) compared the age-at-death distribution of the East Smithfield burials to that of St Helen-on-the-Walls in York, northern England, a normal cemetery in use from the late twelfth century to 1550. Margerison and Knüsel used the East Smithfield data of Waldron (2001), though they excluded from their analysis those individuals who could not be assigned an age or sex. For St Helen-on-the-Walls, adult ages were estimated using standard methods based on age-related changes of the dentition, pubic symphysis, iliac auricular surface, and sternal rib-ends. Both the East Smithfield and St Helen-on-the-Walls distributions were compared to a model life table that was assumed to be representative of the age distribution of a poor medieval urban population. The East Smithfield mortality profile was significantly different from that of the nonepidemic cemetery. There were fewer infants and more juveniles in East Smithfield than expected from a living medieval population, but in general the epidemic age-at-death distribution resembled the age distribution of a living population as might be expected of a catastrophic cemetery. Similarly, researchers at the Museum of London Centre for Human Bioarchaeology found that the majority of adults in East Smithfield died in early adulthood, and they concluded that the cemetery resembles a living population age structure more than a typical nonepidemic mortality sample (Kausmally, 2007).

Gowland and Chamberlain (2005) compared East Smithfield to a sample from Blackgate cemetery in Newcastle, north-east England. Unlike Waldron (2001) and Margerison and Knüsel (2002), who used traditional age-estimation methods, Gowland and Chamberlain used Bayesian inversion to estimate individual adult ages at death. They scored age-related changes of the pubic symphysis and iliac auricular surface according to the protocols established by Brooks and Suchey (1990) and Lovejoy et al. (1985), respectively. Using known-age reference samples, Gowland and Chamberlain estimated the likelihoods of displaying particular skeletal age indicator stages given known age. These likelihoods were combined with informative prior distributions of age-at-death (from model life tables) in Bayes' theorem to obtain estimates of individual age (a similar approach was used in the current study, and is described below in Materials and Methods). The Blackgate age-at-death distribution was similar to the normal mortality profile from a model life table, and the East Smithfield distribution was found to resemble a living population age distribution, suggesting that all age groups were equally affected by the Black Death.

Waldron (2001) explicitly addressed the question of sex differences in Black Death mortality in addition to reconstructing the age pattern of mortality. Waldron found that males outnumbered females in both of his samples. Though the age distributions for males and females were similar in the normal mortality sample, in the Black Death sample, female mortality peaked in the mid-twenties, whereas mortality was more uniform across adult ages among males. The higher male-to-female ratio in the normal mortality sample compared to the Black Death sample (1.88:1 *vs.* 1.33:1) suggested to Waldron that males were not at higher risk than females during the epidemic relative to conditions of normal mortality. Waldron concluded that the skeletal evidence does not support the idea that any particular age or sex was at an elevated risk of dying during the Black Death relative to normal mortality, and that the East Smithfield cemetery probably does not provide a representative sample of the population of London.

It is possible that the male/female ratio observed in the East Smithfield cemetery is not representative of the true sex-pattern of Black Death mortality. As mentioned above, Waldron (2001) assigned sex to juveniles and poorly preserved adults by assuming a uniform sex ratio across all ages. However, differences in the sex ratios of adults and juvenile within a population may arise because of secular trends in sex ratios (Allan et al., 1997; Garenne, 2002; Ulizzi and Zonta, 2002; Catalano and Bruckner, 2006), or because of sex differences in age-specific mortality. Therefore, the sex ratios of adults in the East Smithfield and St Mary Graces cemeteries may very well have differed from those of the children. Even if individuals of indeterminate sex are eliminated from the analysis of mortality patterns, there remains the problem of potentially biased skeletal samples. In the case of East Smithfield, for example, according to the archeologists who excavated the cemetery, up to 2,400 people were originally buried in the cemetery during the epidemic in London, but only ~600 skeletons were ultimately recovered during excavation (Hawkins, 1990). Furthermore, corrosive metals from the minting process at the Royal Mint (which was located on the site from 1806 to 1975) leached through the soil at the Royal Mint site and damaged or destroyed many skeletons in the East Smithfield cemetery (Grainger and Hawkins, 1988; Gilchrist and Sloane, 2005). It is possible, given the vagaries of burial, preservation, and incomplete excavation, that the observed sex ratios provide imperfect representations of those who actually died during the Black Death. Given the potential problems with using raw frequencies to infer mortality patterns, the current study was undertaken to verify Waldron's finding using an appropriate hazards model to evaluate the difference in risk of death between males and females during the epidemic. Unlike Waldron's previous study, no attempt is made here to determine sex in juveniles; so, this analysis is limited to the mortality pattern of adults.

MATERIALS AND METHODS

Skeletal samples

East Smithfield Black Death cemetery. As mentioned above, the East Smithfield cemetery in London is one of the few excavated, exclusively Black Death cemeteries in Europe. The purpose, location, and size of the East Smithfield cemetery are carefully noted in contemporary records, and there is archeological evidence to further link the cemetery to the time of the Black Death (Grainger and Hawkins, 1988; Hawkins, 1990). There is no evidence that the Black Death cemetery was used for burials after the fourteenth century epidemic (Hawkins, 1990); so, the individuals interred there died while the Black Death devastated London, and most, if not all, were victims of the epidemic.

For this study, a sample of 298 adults was selected from the East Smithfield cemetery and analyzed by the author at the Museum of London Centre for Human Bioarchaeology. This sample comprises all of the excavated adults from East Smithfield that were preserved well enough to provide sufficient data on age and sex.

Medieval Danish cemeteries: St Mikkel Church and St Albani Church. To fully understand Black Death mortality patterns, the East Smithfield sample must be compared to a normal (i.e. nonepidemic) mortality sample that approximates conditions in the affected population just before the epidemic. The ideal comparison sample for East Smithfield would be made up of individuals from an urban community as similar as possible to London and dated to just before the epidemic, so that any observed differences between the two cemeteries could be attributed with confidence to the effects of the Black Death. Post-Black Death cemeteries should be avoided given that the epidemic caused dramatic demographic changes throughout Europe (Bowsky, 1971; Hatcher, 1977; Gottfried, 1983; Herlihy, 1997; Cohn, 2002); and the selective mortality associated with the epidemic would have created a post-Black Death population that was probably different from the original pre-Black Death population (DeWitte and Wood, 2008). According to Paine (2000), episodes of catastrophic mortality (of which the Black Death is an example) can have effects on the age-at-death distribution that are evident for decades.

For this study, a sample was selected from the medieval Danish urban parish cemeteries of St Albani Church, Odense, and St Mikkel Church, Viborg, both of which form part of the current Anthropological Database at Odense University, Denmark (ADBOU) collection. Both the St Albani Church and St Mikkel Church cemeteries were used from the 1100s until the Protestant Reformation in the mid-1500s, and they therefore potentially contain individuals who died during the Black Death, which reached Denmark in 1348 or 1349, and certainly contain those who died after the epidemic ended in Denmark in 1350 (Benedictow, 2004). However, medieval and early modern Danish burials, up to the time of the Reformation, can be dated accurately using the arm positions of the interred individuals (Kieffer-Olsen, 1993; Jantzen et al., 1994). Kieffer-Olsen (1993) found that the dates obtained using arm position have a narrower margin of error than those provided by radiocarbon dating. For this study, only individuals interred in the St Albani Church and St Mikkel cemeteries with arm positions used exclusively or predominantly before 1350 were selected for the control sample. The control sample is therefore composed mostly, if not exclusively, of individuals who died shortly before the Black Death reached Denmark. For this study, a combined sample of 194 adults was selected from St Mikkel Church and St Albani Church; this comprises all of the individuals from these cemeteries who died before the Black Death and were preserved well enough to yield data on age and sex.

There were several advantages to using the Danish sample as a comparison for East Smithfield. It is sufficiently large to allow for the estimation of the parameters of the model used in this study. The Danish skeletons are well-preserved, thereby providing adequate data on age and sex. Arm position data allowed for the selection of a predominantly if not exclusively pre-Black Death sample. Further, although the samples in this study are from two different geographic regions, Denmark and Southern England, the populations from which they were drawn were probably similar economically, socially, and demographically (Benedictow, 1993; Sawyer and Sawyer, 1993; Poulsen, 1997; Widgren, 1997; Roesdahl, 1999). According to Benedictow (1993), England and southern Scandinavia had much in common culturally and climatically during the Middle Ages. Sufficient historical records that would allow for an exhaustive comparison of the demographic patterns of medieval Denmark and southern England do not exist, but the evidence that does exist reveals similarities between the two regions. For example, estimates for mean life expectancy at birth, based on historical documents and skeletal data, are the same for England and Scandinavia circa 1300 (22–28 years) (Benedictow, 1993). During the middle ages, English and Danish societies were based primarily on lords and peasants (Poulsen, 1997); in both southern England and Denmark, the open field system of crop cultivation dominated, and peasants in those regions cultivated extensive fields of cereal crops (Sawyer and Sawyer, 1993; Poulsen, 1997; Widgren, 1997). The East Smithfield and Danish cemeteries are all from urban areas. Even though the Danish cities were certainly not as large as London, Viborg and Odense were major centers for politics, religion, and trade during the Middle Ages. There were probably genetic similarities between the English and Danish populations, given the history of pre-Conquest Norse settlement of England. Genetic similarities between the populations of England and Denmark resulting from Norse settlement of England persist today; for example, a recent study of Y chromosome haplotypes in Britain by Capelli et al. (2003) revealed a German/Danish influence in all modern English samples (the researchers found no significant differences between modern Danish and northern German samples with respect to this haplotype). Comparing two populations with genetic similarities might reduce the potential that observed differences in mortality patterns between the two samples arise because of underlying genetic differences. It cannot be stated with certainty that the two populations were so similar that any observed differences between the samples only reflect differences in Black Death *versus* normal mortality. London was a very large city in the fourteenth century, and no other contemporaneous European city is likely to provide a perfect match in terms of such things as population size, the extent of trade, and the interaction of people from different areas of the world. Therefore, if mortality patterns differ between the East

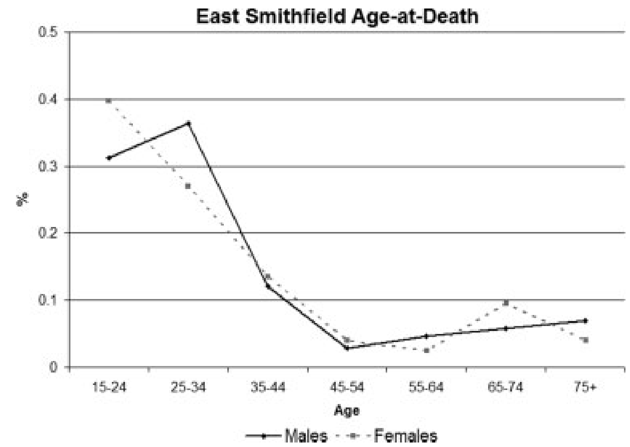

Fig. 1. Comparison of age-at-death distributions for adult males and females within the East Smithfield Black Death cemetery; data from current study.

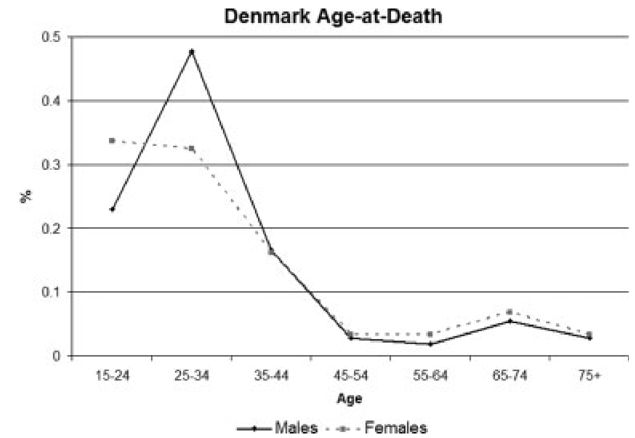

Fig. 2. Comparison of age-at-death distributions for adult males and females within the Danish normal mortality samples; data from current study.

Smithfield and Danish cemeteries, potential population differences must be considered.

Age and sex estimation

Age estimation. Ages were estimated using the method of transition analysis described by Boldsen et al. (2002). The transition analysis method of age estimation, just like traditional methods, uses skeletal traits that change with age, specifically features of the pubic symphysis, iliac auricular surface, and cranial sutures. In transition analysis, data from a known-age reference collection are used to obtain the conditional probability that a skeleton will exhibit a particular age indicator stage or suite of age indicator stages given the individual's known age. Using Bayes' theorem, this conditional probability is then combined with either a prior distribution of ages at death based on documentary information or a uniform prior to determine the posterior probability that a skeleton died at a certain age given that it displays particular age indicator stages. This age-estimation method avoids the problem of age mimicry associated with traditional methods whereby estimated ages are biased toward the age distribution of the known-age reference sample that is used as a standard (Bocquet-Appel and Masset, 1982; Boldsen et al., 2002). For this study, transition analysis was applied to skeletal age indicators on the pubic symphysis and the iliac auricular surface and to cranial suture closure as described by Boldsen et al. (2002), and the ADBOU (Anthropological Database, Odense University) Age Estimation software was used to determine individual ages-at-death. The ADBOU program uses data from seventeenth century Danish rural parish records for an informative prior distribution of ages at death (the Gompertz–Makeham parameter estimates for this prior are: $\alpha_1 = 0.01273$, $\alpha_2 = 0.00002478$, and $\beta = 0.01618$). The program uses a conditional probability estimated from the Smithsonian Institution's Terry Collection that an individual with certain age indicators will be a given age; by combining the informative prior and the conditional probability, the program uses Bayes' theorem to obtain the highest posterior point estimate of age for each skeleton.

Sex determination. Sex was determined from features of the skull and pelvis using the standards described in Buikstra and Ubelaker (1994).

Gompertz–Makeham model

Because only adults were included in this analysis, mortality was modeled using the three-parameter Gompertz–Makeham mortality function, which fits the general human pattern of relatively low mortality during the young adult ages and an increasing risk of death with senescence (Wood et al., 2002). To determine the sex-pattern of Black Death mortality, sex was modeled as a covariate acting upon the parameters of the Gompertz–Makeham model; the effect of the covariate was modeled using a proportional hazard specification (because it is based on the Gompertz–Makeham model, this model is fully parametric):

$$h_i(t_i|x_i\theta) = h(t_i)e^{(x_i\rho)}$$

where the baseline hazard $h(t_i) = \alpha_1 + \alpha_2 e^{\beta t}$, t_i is the age of the ith skeleton in years, x_i is the sex covariate, and ρ is the parameter representing the effect of the covariate on the baseline hazard.

In this analysis, females were coded as 0, and males were coded as 1. Parameters were estimated using maximum likelihood analysis with Holman's program *mle* (Holman, 2002, available at http://faculty.washington.edu/djholman/mle/); multiple start values were used in model estimation to avoid local maxima. The model was fit separately to the data from the East Smithfield and Danish samples. A significant positive or negative estimate for the parameter representing the effect of the covariate on the hazard would suggest men were at an increased or decreased risk of death, respectively, compared to women. A likelihood ratio test (LRT) was used to assess the fit of the full model compared to the baseline model, which did not include sex as a covariate; that is, the LRT tests the null hypothesis that sex had no effect on risk of death (H_0: effect of sex covariate = 0). The LRT was computed as follows: LRT $= -2[\ln(L_{sex}) - \ln(L_{baseline})]$, where LRT approximates a χ^2 distribution with $df = 1$ if there is no effect of sex.

RESULTS

Figures 1 and 2 show the age-at-death distributions by sex for the East Smithfield and Danish samples, respectively. In the East Smithfield sample, there is a higher

TABLE 1. Numbers of adult males and females

	Males	Females
East Smithfield (n = 298)	173	125
Denmark (n = 194)	108	86

TABLE 2. Maximum likelihood estimates of the effect of the sex covariate and likelihood ratio tests of H_0

East Smithfield		Denmark	
Sex (s.e)	LRT	Sex (s.e.)	LRT
−0.09 (0.1)	2.93	0.07 (0.1)	0.27

Effect of sex covariate = 0.

proportion of females compared to males at the earliest adult ages, 15–24 years, but a lower proportion of females between ages 25 and 34 years; there are only slight, varying differences in the proportions of males and females at older ages. In the Danish sample, there is also a higher proportion of females between 15 and 24 years, but a lower proportion of females between the ages of 25 and 35 years; as in East Smithfield, there are minor differences in the proportions of males and females at the older adult ages. Within each sample, the male and female age-at-death distributions do not significantly differ from one another based on results of the Kolmogorov–Smirnov test (East Smithfield: $D_{m,n}$ = 0.08, $P > 0.05$; Denmark: $D_{m,n}$ = 0.11, $P > 0.05$).

Table 1 summarizes the number of adult males and females in the East Smithfield and Danish samples. In both cemetery samples, there are more males than females; the ratio of males to females in East Smithfield is 1.38:1, and in the Danish sample, the ratio is 1.26:1.

The numbers of adult males and females within each cemetery might suggest that males were actually at a higher risk of death than were females both during the Black Death and under conditions of normal mortality, as males outnumber females in both samples; however, the analysis of the effect of sex on risk of death (Table 2) reveals that there was little, if any, difference in risk of death for males and females during the Black Death *and* during times of normal mortality.

The estimated value of the parameter representing the effect of the sex covariate within the Danish sample suggests that under conditions of normal mortality, males were at a slightly higher risk of mortality than adult females. This is consistent with the general pattern of higher male mortality observed in many studies (e.g. see Owens, 2002; May, 2007). However, the standard error for this estimate is quite large, and is probably underestimated. To estimate the parameters of the model used in this study, the highest posterior point estimate of each individual's age was used. Although the transition analysis method yields age estimates that are expected to be unbiased, they still have large estimation errors associated with them. The errors associated with ages were not incorporated when the model was fit; so, the reported standard error might be underestimated to an unknown degree; readers should therefore view the standard error estimates with caution. The estimated value of the parameter representing the effect of the covariate is not significantly different from zero; so, these results do not indicate a substantial difference in risk of death between men and women in the normal mortality sample. The result of the likelihood ratio test further indicates that sex had no significant effect on risk of death; though including the sex covariate does improve the fit of the model very slightly, this result is not statistically significant (χ^2 = 0.27, P = 0.61).

The low and negative estimated value of the parameter representing the effect of the sex covariate for the East Smithfield sample suggests that men were at a slightly lower risk of death during the Black Death compared to women. However, as is the case for the Danish normal mortality sample, the standard error is quite large (and is also probably underestimated, for the same reason as above). Given that the estimated value of the parameter representing the effect of the covariate is not significantly different from zero, these results suggest that men and women were not at a significantly different risk of death during the epidemic. As was the case for the normal mortality sample, according to the likelihood ratio tests, including sex as a covariate improves the fit of the model for the East Smithfield sample, although the result of the LRT is not statistically significant (χ^2 = 2.93, P = 0.09).

DISCUSSION

Comparison of age-at-death distributions

As detailed above, the current study is not the first investigation of the mortality patterns within the East Smithfield Black Death cemetery. Figures 3–6 compare the age-at-death distributions for East Smithfield obtained by this and several previous studies of the Black Death cemetery (Waldron, 2001; Margerison and Knüsel, 2002; Gowland and Chamberlain, 2005; Kausmally, 2007). As mentioned above, Margerison and Knüsel used data for East Smithfield obtained by Waldron, though they excluded the individuals of unknown age or sex used in Waldron's study. Unsurprisingly, the age-at-death distributions of Margerison and Knüsel (2002) and Waldron (2001) do not differ significantly. Their distributions are therefore combined in all figures for ease of comparison with other studies. Differences among the age-at-death distributions were tested using the Kolmogorov–Smirnov test (results shown in Table 3).

The male age-at-death distribution (see Fig. 3) from the current study does not differ significantly from that obtained by the Museum of London Centre for Human Bioarchaeology (hereafter referred to as MoL), and both differ significantly from those obtained by Margerison and Knüsel (2002) and Waldron (2001). The female age-at-death distribution from the current study differs significantly from all others in Figure 4; the distributions from the MoL, Margerison and Knüsel (2002), and Waldron (2001) do not differ significantly from one another. Figure 5 shows the age-at-death distributions for both sexes combined, and includes the results from Gowland and Chamberlain (they did not present separate results for males and females and thus are not included in Figs. 3 and 4). The distribution from the current study differs significantly from the distributions obtained in all other studies; the MoL distribution also differs significantly from all others. The Margerison and Knüsel (2002) and Waldron (2001) distributions do not differ significantly from that obtained by Gowland and Chamberlain (2005). Figure 6 compares the age-at-death distributions from the current study and from Gowland and Chamberlain (2005) (the other studies are excluded as they do not report age estimates beyond the 45+ terminal age inter-

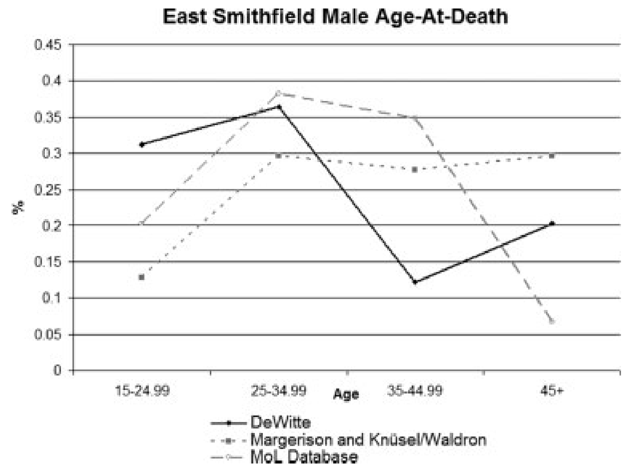

Fig. 3. Comparison of male age-at-death distribution within East Smithfield from the current study, Margerison and Knüsel (2002), Waldron (2001), and the Museum of London Centre for Human Bioarchaeology (Kausmally, 2007).

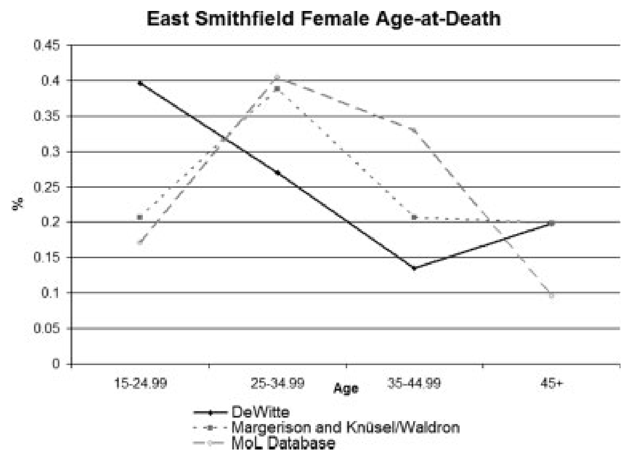

Fig. 4. Comparison of female age-at-death distribution within East Smithfield from the current study, Margerison and Knüsel (2002), Waldron (2001), and the Museum of London Centre for Human Bioarchaeology (Kausmally, 2007).

val). Though both studies yield an age-at-death distribution for East Smithfield that shows a general decline in frequency with increasing age, the two distributions are significantly different.

The variation in age-at-death patterns obtained by different studies of East Smithfield is not surprising given that different age-estimation methods were used by the researchers. Because of the variation in age estimates, previous researchers have come to very different conclusions about East Smithfield; that is, Gowland and Chamberlain (2005) and Margerison and Knüsel (2002) concluded that the cemetery is more representative of a living population than is a normal mortality sample, whereas Waldron concluded that it is not. Even though the age-at-death patterns from the current study differ from those obtained by Waldron (2001), the analysis of the effect of sex on risk of death yielded results consistent with Waldron's ultimate conclusion that the Black Death did not differ from normal mortality in terms of sex differentials.

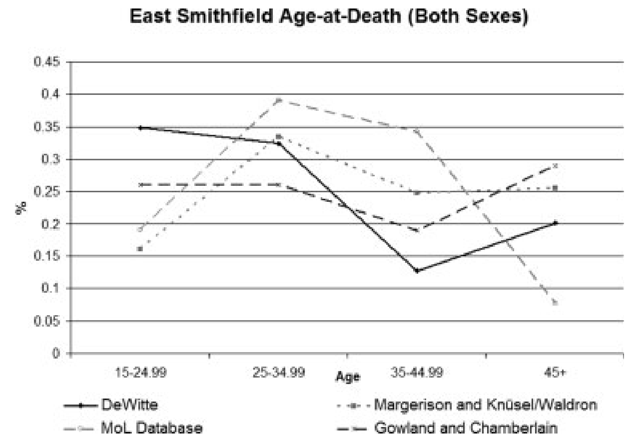

Fig. 5. Comparison of adult age-at-death distribution within East Smithfield from the current study, Gowland and Chamberlain (2005), Margerison and Knüsel (2002), Waldron (2001), and the Museum of London Centre for Human Bioarchaeology (Kausmally, 2007).

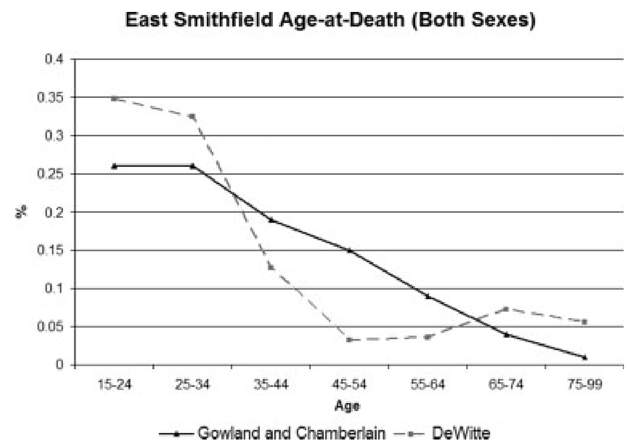

Fig. 6. Comparison of adult age-at-death distribution within East Smithfield from the current study and Gowland and Chamberlain (2005).

Effect of sex on risk of death

A previous study using the East Smithfield Black Death cemetery found that mortality associated with the medieval epidemic was selective with respect to frailty (DeWitte and Wood, 2008); individuals who were in relatively poor health before the Black Death were more likely to die during the epidemic than their peers who were in good health right before the epidemic. Black Death mortality was therefore similar to normal normality as it disproportionately killed the weakest members of the population. The current analysis yields evidence that Black Death mortality was apparently not selective with respect to sex among adults. As with the previous study of selectivity with respect to frailty, a similarity is seen here between the Black Death mortality pattern and that of the normal mortality sample—in both cases, sex did not significantly affect risk of death in adults. In this study, the estimated values of the parameters representing the effects of the sex covariate differ between the two samples; if taken at face value, the results indicate that under conditions of normal mortality, men

TABLE 3. Results of Kolmogorov–Smirnov tests comparing age-at-death distributions

Age-at-death: All adults	DeWitte	Margerison and Knüsel	Waldron	Museum of London	Gowland and Chamberlain
DeWitte	–	$D_{m,n}$ = 0.19*	$D_{m,n}$ = 0.18*	$D_{m,n}$ = 0.16*	$D_{m,n}$ = 0.15*
Margerison and Knüsel		–	$D_{m,n}$ = 0.03	$D_{m,n}$ = 0.18*	$D_{m,n}$ = 0.10
Waldron			–	$D_{m,n}$ = 0.18*	$D_{m,n}$ = 0.07
Museum of London				–	$D_{m,n}$ = 0.18*
Gowland and Chamberlain					–

Age-at-death: Males	DeWitte	Margerison and Knüsel	Waldron	Museum of London
DeWitte	–	$D_{m,n}$ = 0.25*	$D_{m,n}$ = 0.22*	$D_{m,n}$ = 0.13
Margerison and Knüsel		–	$D_{m,n}$ = 0.03	$D_{m,n}$ = 0.23*
Waldron			–	$D_{m,n}$ = 0.22*
Museum of London				–

Age-at-death: Females	DeWitte	Margerison and Knüsel	Waldron	Museum of London
DeWitte	–	$D_{m,n}$ = 0.19*	$D_{m,n}$ = 0.18*	$D_{m,n}$ = 0.23*
Margerison and Knüsel		–	$D_{m,n}$ = 0.04	$D_{m,n}$ = 0.10
Waldron			–	$D_{m,n}$ = 0.12
Museum of London				–

* Distributions that are significantly different at $\alpha = 0.05$.

faced a slightly higher risk of dying than women, but during the Black Death, men were at a lower risk of death. However, given the error associated with those estimates, these results suggest that sex did not have a significant effect on the risk of death under either conditions of normal or catastrophic Black Death mortality. This study has demonstrated that although the epidemic was apparently selective with respect to some factors (i.e. traits associated with frailty), it might have been less discriminating with respect to other characteristics.

As described above, for the current study, an attempt was made to select a normal mortality comparison sample from a population that was similar to the pre-Black Death London population. The Danish sample used here was drawn from urban parish cemeteries and does provide a good comparison sample, but there might have been differences between the English and Danish populations. For this particular study, however, potential population differences are not a serious concern given the similar lack of a significant effect of sex on risk of mortality in both samples as shown above.

It should be noted that in this analysis, sex was modeled as a covariate affecting the entire Gompertz–Makeham model; that is, sex was modeled as proportional to the entire hazard, independent of age. It is possible that differences in risk of death existed between men and women at different adult ages. Perhaps pregnancy influenced female risk of death during the epidemic; in modern cases of malaria, for example, pregnant women, particularly those who are having their first offspring, suffer from more severe symptoms and are more likely to die than men and nonpregnant women (Kochar et al., 1999; Roberts et al., 2001; Menendez, 2006). Such age patterns are not captured using the proportional hazards assumption. Further analyses of the sex-pattern of Black Death mortality might reveal whether the effect of the sex covariate did, in fact, vary with age.

The possibility of sampling or preservation bias is a concern for any paleodemographic study. For the current study, the possibility exists that differences in the numbers and age-at-death patterns of males and females might be caused by differential preservation or biases in sex estimation. In many paleodemographic samples, males outnumber females. It has been suggested that this sex bias might be at least partly the result of more rapid disintegration of lightly built female skeletons (Bennike, 1985), although studies of differentials in preservation have failed to find a difference between adult males and females (Weiss, 1972; Walker et al., 1988; Bello et al., 2006). Using a known-age/sex sample from Christ Church, Spitalfields, London, Bello et al. (2006) found that among subadults, male preservation was better than that of females; however, a similar pattern was not demonstrated for adults. Potential sex differentials in preservation are of particular concern in this study because individuals were included in the samples only if they were sufficiently preserved to allow for estimation of age and sex. Examination of Figures 1 and 2 suggests that differential preservation does not, by itself, account for the observed differences between males and females. Within both the East Smithfield and Danish samples, the largest proportional differences between males and females occur at the younger adult ages, and there are only slight differences above the age of 35 years (Figs. 1 and 2). It is unclear how differential preservation could create such an excess of males between ages of 25 and 35 years, but not at other ages. It is unlikely that females preserve as well as or better than males between the ages of 15 and 25 years and after the age of 35 years, but preserve less well just between the ages of 25 and 35 years.

Errors in sex estimation in favor of males may explain an observed excess of males. According to Weiss (1972), errors in sex estimation result in 12% too many males, on average, in skeletal samples, because there is a tendency to categorize skeletons of intermediate size or rugosity as male rather than female. Meindl et al. (1985) found in a study of known-sex adults that males are more often misclassified than are females, and that the sex ratios from skeletal samples might actually underestimate the excess of males. Meindl et al. further suggest that the sex bias might be partly the result of reliance upon cranial features for sex estimation, as older skulls of both sexes tend to look increasingly masculine. However, this trend does not explain the sex ratio observed in the current study given that both pelvic and cranial features were used to determine sex. As with differential preservation, it is unlikely that biases in sex estimation would create an excess of males just in the 25- to 35-year interval and not at other ages.

The observed sex ratio among adults might also be affected by temporal fluctuations in the sex ratio at birth; in modern human populations, variation in sex ratios at birth can occur at random or in responses to stressors such as natural and human-made disasters (Garenne, 2002; Ulizzi and Zonta, 2002; Catalano and Bruckner, 2006). However, such fluctuations in sex ratios are unlikely sufficient to explain the excess of males' ages of 25–35 years in both the East Smithfield and Danish samples. In modern populations, disasters such as major earthquakes or terrorist attacks tend to result in a *reduction* of the number of males born, and observed random fluctuations in modern populations have not resulted in sex ratios as high as those observed in the current study (Garenne, 2002; Catalano and Bruckner, 2006).

Perhaps the excess of males in both samples at least partly reflects a real imbalance in the sex ratio within the living medieval populations. Both the East Smithfield and Danish samples are from urban cemeteries, and there might have been more men than women in the living populations because of migration into the respective cities by men seeking work. Forbes (1971) analyzed burial records from London *circa* 1593, and found that for both plague and nonplague deaths, there were many more males than females between the ages of 20 and 49 years; he suggests that this pattern might indicate more males than females in the original living population. Alternatively, Russell (1985) suggests female infanticide in medieval England as potential source of sex bias in adults.

It is important to consider the effect that a biased sex ratio might have on the estimate of the effect of sex on risk of death. One might expect that an excess of males caused by preservation bias or errors in sex estimation might lead to an overestimate of the effect of the sex covariate as modeled here. In the current study, there are more males than females in both samples, and the estimate of the effect of the sex covariate is positive in Denmark but negative in East Smithfield (although neither estimate was significantly different from zero). This suggests that if the excess of males in each sample is an artifact of preservation bias or errors in sex estimation, at least the estimate of the effect of the sex covariate is not consequently biased in any particular direction.

Comparison with modern bubonic plague

Studies of Black Death mortality patterns often raise questions about the cause of the medieval epidemic. Many researchers have argued, since Alexander Yersin first identified *Yersinia pestis* as the causative agent of modern bubonic plague (Yersin, 1894), that the Black Death was an outbreak of bubonic plague. Some of the symptoms of the fourteenth century epidemic, as described in contemporary chronicles, were broadly similar to those of modern plague. In particular, both modern plague and the Black Death are characterized by the development of huge swellings, or buboes, in the armpit, groin, or neck. However, many researchers remain unconvinced that the Black Death was bubonic plague, or they argue that it existed in a very different form nearly 700 years ago given the many important differences between the medieval and modern diseases (e.g. differences in mortality, transmission, and symptoms) (Twigg, 1984; Scott and Duncan, 2001; Cohn, 2002; Wood and DeWitte-Avina, 2003; Wood et al., 2003). Unfortunately, the results of the current study are not informative about the cause of the Black Death. As described above, neither sex is consistently disproportionately affected in modern cases of bubonic plague. Every pattern has been observed in cases of bubonic plague: there are cases of modern bubonic plague in which men are disproportionately infected and killed by plague, cases in which women are more frequently affected, and cases in which both sexes appear equally affected (Pollitzer, 1954; Blanchy et al., 1993; Boisier et al., 1997, 2002; Tikhomirov, 1999; Chanteau et al., 2000; Ratsitorahina et al., 2000; Aikimbajev et al., 2003; Migliani et al., 2006; Kamugisha et al., 2007). The results from the current study are not inconsistent with some cases of bubonic plague, but clearly the observed variation in modern plague sex differentials make it impossible to infer anything about the cause of the Black Death from an examination of sex patterns alone.

CONCLUSION

The results shown here suggest that neither sex was disproportionately affected during the Black Death. These results, produced using different methods from those of Waldron (2001), support his conclusion that men were not at a significantly higher risk of dying than women during the Black Death compared to times of normal mortality. By combining the results of this study with a previous analysis (DeWitte and Wood, 2008) of selectivity of the Black Death, which suggested that frail individuals were more likely than healthy people to die during the epidemic, a clearer understanding of Black Death mortality patterns emerge. The combined results suggest that Black Death mortality, although clearly much more devastating than normal mortality, had similar patterns of selectivity.

Given the observed variation in patterns of sex differentials associated with modern outbreaks of bubonic plague, the results from the current study neither confirm nor refute the commonly held belief that the Black Death was a medieval epidemic of bubonic plague. Analysis of pathogen DNA from known Black Death victims, using methods that yield sequences that can be compared to those of modern pathogens, probably provides the only means of resolving questions about differences between the medieval and modern pathogens.

The results from this study might be somewhat surprising given modern patterns of sex differentials in morbidity and mortality. However, perhaps the method used here is insufficient to capture the true pattern of sex differences in mortality under conditions of either Black Death or normal medieval mortality. As mentioned above, in this study, sex was modeled as proportional to the entire adult mortality hazard, independent of age. It is possible that differences in risk of death existed between men and women at different adult ages or age intervals. Further study will be undertaken to help resolve the age pattern of the effect of the sex covariate.

ACKNOWLEDGMENTS

I would like to thank Christopher Ruff, the Associate Editor, two anonymous reviewers, James Wood, Eric Jones, and Holly Dunsworth for their very helpful and insightful comments on an earlier version of this manuscript. I am very grateful to Bill White and his associates at the Museum of London Centre for Human Bioarchaeology for providing access to the East Smithfield skeletons, and to Jesper Boldsen for providing access to the Danish skeletal collection at the Anthropological Database, Odense University, Denmark, and for his help with the ADBOU age estimation program. I also thank both Drs. White and Boldsen for generously providing the physical facilities for this work. Darryl Holman and Bethany Usher provided analytical and computational advice, without which this work would not have been possible.

LITERATURE CITED

Acuna-Soto R, Maguire JH, Wirth DF. 2000. Gender distribution in asymptomatic and invasive amebiasis. Am J Gastroenterol 95:1277–1283.

Aikimbajev A, Meka-Mechenko T, Temiralieva G, Bekenov J, Sagiyev Z, Kaljan K, Mukhambetova AK. 2003. Plague in Kazakhstan at the present time. Przegl Epidemiol 57:593–598.

Alexander J. 1988. Sex differences and cross-immunity in DBA/2 mice infected with *L. mexicana* and *L. major*. Parasitology 96(Pt 2):297–302.

Allan B, R Brandt, JE Seidel, Jarrell J. 1997. Declining sex ratios in Canada. Can Med Assoc J 156:37–41.

Ansar Ahmed SA, Hissong BD, Verthelyi D, Donner K, Becker K, Karpuzoglu-Sahin E. 1999. Gender and risk of autoimmune diseases: possible role of estrogenic compounds. Environ Health Perspect 107(Suppl 5):681–686.

Bello SM, Thomann A, Signoli M, Dutour O, Andrews P. 2006. Age and sex bias in the reconstruction of past population structures. Am J Phys Anthropol 129:24–38.

Benedictow OJ. 1993. Plague in the late medieval Nordic countries: epidemiological studies. Oslo: Middelalderforlaget. 329p.

Benedictow OJ. 2004. The Black Death, 1346–1353: the complete history. Woodbridge, UK: Boydell Press.

Bennike P. 1985. Paleopathology of Danish skeletons: a comparative study of demography, disease and injury. Copenhagen: Akademisk Forlag.

Blanchy S, Ranaivoson G, Rakotojanabelo A. 1993. Clinical epidemiology of plague in Madagascar (current data). Arch Inst Pasteur Madagascar 60(1/2):27–34.

Blessmann J, Van Linh P, Nu PA, Thi HD, Muller-Myhsok B, Buss H, Tannich E. 2002. Epidemiology of amebiasis in a region of high incidence of amebic liver abscess in central Vietnam. Am J Trop Med Hyg 66:578–583.

Bocquet-Appel JP, Masset C. 1982. Farewell to paleodemography. J Hum Evol 11:321–333.

Boisier P, Rahalison L, Rasolomaharo M, Ratsitorahina M, Mahafaly M, Razafimahefa M, Duplantier JM, Ratsifasoamanana L, Chanteau S. 2002. Epidemiologic features of four successive annual outbreaks of bubonic plague in Mahajanga, Madagascar. Emerg Infect Dis 8:311–316.

Boisier P, Rasolomaharo M, Ranaivoson G, Rasoamanana B, Rakoto L, Andrianirina Z, Andriamahefazafy B, Chanteau S. 1997. Urban epidemic of bubonic plague in Majunga, Madagascar: epidemiological aspects. Trop Med Int Health 2:422–427.

Boldsen JL, Milner GR, Konigsberg LW, Wood JW. 2002. Transition analysis: a new method for estimating age from skeletons. In: Hoppa RD, Vaupel JW, editors. Paleodemography: age distributions from skeletal samples. Cambridge: Cambridge University Press. p 73–106.

Bowsky WM. 1971. The Black Death: a turning point in history? New York: Holt, Rinehart & Winston.

Brabin L, Brabin BJ. 1992. Parasitic infections in women and their consequences. Adv Parasitol 31:1–60.

Brooks S, Suchey J. 1990. Skeletal age determination based on the os pubis: a comparison of the Ascadi–Nemeskéri and Suchey–Brooks methods. J Hum Evol 5:227–238.

Buikstra JE, Cook DC. 1981. Pre-Columbian tuberculosis in West-Central Illinois: prehistoric disease in biocultural perspective. Northwestern University Archaeological Program Scientific Papers No. 5. In: Buikstra JE, editor. Prehistoric tuberculosis in the Americas. Evanston, IL: Northwestern University Archaeological Program. p 115–139.

Buikstra JE, Ubelaker DH, editors. 1994. Standards for data collection from human skeletal remains: proceedings of a seminar at the Field Museum of Natural History (Arkansas archaeology research series 44). Fayetteville, AR: Arkansas Archeological Survey Press.

Butler T. 1989. The Black Death past and present. 1. Plague in the 1980s. Trans R Soc Trop Med Hyg 83:458–460.

Capelli C, Redhead N, Abernethy JK, Gratrix F, Wilson JF, Moen T, Hervig T, Richards M, Stumpf MP, Underhill PA, Bradshaw P, Shaha A, Thomas MG, Bradman N, Goldstein DB. 2003. A Y chromosome census of the British Isles. Curr Biol 13:979–984.

Cassidy CM. 1984. Skeletal evidence for prehistoric subsistence adaptation in the Central Ohio River Valley. In: Cohen MN, Armelagos GJ, editors. Paleopathology at the origins of agriculture. New York: Academic Press. p 307–345.

Catalano R, Bruckner T. 2006. Secondary sex ratios and male lifespan: damaged or culled cohorts. Proc Natl Acad Sci USA 103:1639–1643.

Chanteau S, Ratsitorahina M, Rahalison L, Rasoamanana B, Chan F, Boisier P, Rabeson D, Roux J. 2000. Current epidemiology of human plague in Madagascar. Microbes Infect 2:25–31.

Cleri DJ, Vernaleo JR, Lombardi LJ, Rabbat MS, Mathew A, Marton R, Reyelt MC. 1997. Plague pneumonia disease caused by *Yersinia pestis*. Semin Respir Infect 12:12–23.

Cohn SK Jr. 2002. The Black Death transformed: disease and culture in early Renaissance Europe. London: Arnold.

Cohn SK Jr, Weaver LT. 2006. The Black Death and AIDS: CCR5-Delta32 in genetics and history. QJM 99:497–503.

Conheeney J. 1999. Reconstructing the demography of medieval London from studies on human skeletal material: problems and potential. Trans Lond Middlesex Archaeol Soc 50:78–86.

Dahlberg AA. 1991. Interpretations of general problems in amelogenesis. In: Ortner DJ, Aufderheide AC, editors. Human paleopathology: current syntheses and future options. Washington, DC: Smithsonian Institution Press. p 269–272.

Davis S, Makundi RH, Machang'u RS, Leirs H. 2006. Demographic and spatio-temporal variation in human plague at a persistent focus in Tanzania. Acta Trop 100(1/2):133–141.

DeWitte SN, Wood JW. 2008. Selectivity of the Black Death with respect to preexisting health. Proc Natl Acad Sci USA 105:1436–1441.

Drancourt M, Aboudharam G, Signoli M, Dutour O, Raoult D. 1998. Detection of 400-year-old *Yersinia pestis* DNA in human dental pulp: an approach to the diagnosis of ancient septicemia. Proc Natl Acad Sci USA 95:12637–12640.

Drancourt M, Raoult D. 2002. Molecular insights into the history of plague. Microbes Infect 4:105–109.

Drancourt M, Signoli M, Dang LV, Bizot B, Roux V, Tzortzis S, Raoult D. 2007. *Yersinia pestis Orientalis* in remains of ancient plague patients. Emerg Infect Dis 13:332–333.

Falagas ME, Vardakas KZ, Mourtzoukou EG. 2008. Sex differences in the incidence and severity of respiratory tract infections. Respir Med 102:627.

Forbes TR. 1971. Chronicle from Aldgate: life and death in Shakespeare's London. New Haven: Yale University Press.

Garenne M. 2002. Sex ratios at birth in African populations: a review of survey data. Hum Biol 74:889–900.

Gilbert MT, Cuccui J, White W, Lynnerup N, Titball RW, Cooper A, Prentice MB. 2004. Absence of *Yersinia pestis*-specific DNA in human teeth from five European excavations of putative plague victims. Microbiology 150(Pt 2):341–354.

Gilchrist R, Sloane B. 2005. Requiem: the Medieval Monastic Cemetery in Britain. London: Museum of London Archaeology Service.

Gottfried RS. 1983. The Black Death: natural and human disaster in medieval Europe. New York: Free Press.

Gowland RL, Chamberlain AT. 2005. Detecting plague: palaeodemographic characterisation of a catastrophic death assemblage. Antiquity 79:146–157.

Grainger I, Hawkins D. 1988. Excavations at the Royal Mint site 1986–1988. Lond Archaeol 5:429–436.

Grauer AL, McNamara EM, Houdek DV. 1998. A history of their own: patterns of death in a nineteenth-century poorhouse. In: Grauer AL, Stuart-Macadam P, editors. Sex and gender in paleopathological perspective. Cambridge: Cambridge University Press. p 149–164.

Grossman CJ. 1985. Interactions between the gonadal steroids and the immune system. Science 227:257–261.

Hatcher J. 1977. Plague, population, and the English economy, 1348–1530. London: Macmillan.

Haviland WA. 1967. Stature at Tikal, Guatemala: implications for ancient Maya demography and social organization. Am Antiq 32:316–325.

Hawkins D. 1990. Black Death and the new London cemeteries of 1348. Antiquity 64:637–642.

Herlihy D. 1997. The Black Death and the transformation of the West. Cambridge, MA: Harvard University Press.

Hinde A. 2003. England's population: a history since the domesday survey. London: Hodder & Arnold.

Hoff R, Mott KE, Silva JF, Menezes V, Hoff JN, Barrett TV, Sherlock I. 1979. Prevalence of parasitaemia and seroreactivity to *Trypanosoma cruzi* in a rural population of northeast Brazil. Am J Trop Med Hyg 28:461–466.

Holman DJ. 2002. mle: a programming language for building likelihood models. Version 2.0. Seattle, WA: Department of Anthropology, Center for Studies in Demography and Ecology, Center for Statistics and the Social Sciences, University of Washington.

Holmes GA. 1971. England: a decisive turning point. In: Bowsky WM, editor. The Black Death: a turning point in history? New York: Holt, Rhinehart & Winston. p 91–99.

Horrox R. 1994. The Black Death. Manchester: Manchester University Press.

Huss-Ashmore R, Goodman AH, Armelagos GJ. 1982. Nutritional inference from paleopathology. In: Schiffer M, editor. Advances in archaeological method and theory, Vol. 5. New York: Academic Press. p 395–473.

Janele D, Lang T, Capellino S, Cutolo M, Da Silva JA, Straub RH. 2006. Effects of testosterone, 17beta-estradiol, and downstream estrogens on cytokine secretion from human leukocytes in the presence and absence of cortisol. Ann N Y Acad Sci 1069:168–182.

Jansen A, Stark K, Schneider T, Schoneberg I. 2007. Sex differences in clinical leptospirosis in Germany: 1997–2005. Clin Infect Dis 44:e69–e72.

Jantzen C, Kieffer-Olsen J, and Madsen PK. 1994. De sma brodres hus i Ribe. In: Gelius W, Guldberg M, Stoumann I, editors. Mark og Montre Årbog for kunst- og kulturhistorie 30. Ribe: Ribe Amts Museumsråd. p 26–36.

Kamugisha ML, Gesase S, Minja D, Mgema S, Mlwilo TD, Mayala BK, Msingwa S, Massaga JJ, Lemnge MM. 2007. Pattern and spatial distribution of plague in Lushoto, north-eastern Tanzania. Tanzan Health Res Bull 9:12–18.

Kausmally T. 2007. East Smithfield Black Death cemetery. London: Museum of London Centre for Human Bioarchaeology. Available at http://www.museumoflondon.org.uk/English/Collections/OnlineResources/CHB/Database/Medieval+cemeteries/ESmithfieldBlackDeath.htm. Accessed August 21, 2008.

Kieffer-Olsen J. 1993. Grav og gravskike i det middelalderlige Danmark. Aarhus, Denmark: Aarhus University.

Kirkwood B, Smith P, Marshall T, Prost A. 1983. Relationships between mortality, visual acuity and microfilarial load in the area of the Onchocerciasis Control Programme. Trans R Soc Trop Med Hyg 77:862–868.

Klein SL. 2000. The effects of hormones on sex differences in infection: from genes to behavior. Neurosci Biobehav Rev 24:627–638.

Kochar DK, Thanvi I, Joshi A, Shubhakaran, Agarwal N, Jain N. 1999. Mortality trends in falciparum malaria—effect of gender difference and pregnancy. J Assoc Physicians India 47:774–778.

Larsen CS. 1997. Bioarchaeology: interpreting behavior from the human skeleton. New York: Cambridge University Press.

Larsen CS. 1998. Gender, health, and activity in foragers and farmers in the American southeast: implications for social organization in the Georgia Bight. In: Grauer AL, Stuart-Macadam P, editors. Sex and gender in paleopathological perspective. Cambridge: Cambridge University Press. p 165–187.

Laupland KB, Church DL, Mucenski M, Sutherland LR, Davies HD. 2003. Population-based study of the epidemiology of and the risk factors for invasive *Staphylococcus aureus* infections. J Infect Dis 187:1452–1459.

Leone M, Honstettre A, Lepidi H, Capo C, Bayard F, Raoult D, Mege JL. 2004. Effect of sex on *Coxiella burnetii* infection: protective role of 17beta-estradiol. J Infect Dis 189:339–345.

Lovejoy CO, Meindl RS, Mensforth RP, Barton TJ. 1985. Multifactorial determination of skeletal age at death: a method and blind tests of its accuracy. Am J Phys Anthropol 68:1–14.

Margerison BJ, Knüsel CJ. 2002. Paleodemographic comparison of a catastrophic and an attritional death assemblage. Am J Phys Anthropol 119:134–143.

May RC. 2007. Gender, immunity and the regulation of longevity. Bioessays 29:795–802.

Meindl RS, Lovejoy CO, Mensforth RP, Don Carlos L. 1985. Accuracy and direction of error in the sexing of the skeleton: implications for paleodemography. Am J Phys Anthropol 68:79–85.

Menendez C. 2006. Malaria during pregnancy. Curr Mol Med 6:269–273.

Mensforth RP, Lovejoy CO, Lallo JW, Armelagos GJ. 1978. The role of constitutional factors, diet, and infectious disease in the etiology of porotic hyperostosis and periosteal reactions in prehistoric infants and children. Med Anthropol 2:1–58.

Migliani R, Chanteau S, Rahalison L, Ratsitorahina M, Boutin JP, Ratsifasoamanana L, Roux J. 2006. Epidemiological trends for human plague in Madagascar during the second half of the 20th century: a survey of 20,900 notified cases. Trop Med Int Health 11:1228–1237.

Noymer A, Garenne M. 2000. The 1918 influenza epidemic's effects on sex differentials in mortality in the United States. Popul Dev Rev 26:565–581.

Oliviera JSM, Mello de Oliveira JA, Frederiques U Jr, Lima Filho EC. 1981. Apical aneurism of Chagas' heart disease. Br Heart J 46:432–437.

Ortner DJ. 1998. Male–female immune reactivity and its implications for interpreting evidence in human skeletal paleopathology. In: Grauer AL, Stuart-Macadam P, editors. Sex and gender in paleopathological perspective. Cambridge: Cambridge University Press. p 79–92.

Ortner DJ. 2003. Identification of pathological conditions in human skeletal remains. Amsterdam: Academic Press.

Owens IP. 2002. Ecology and evolution. Sex differences in mortality rate. Science 297:2008–2009.

Paine RR. 2000. If a population crashes in prehistory, and there is no paleodemographer there to hear it, does it make a sound? Am J Phys Anthropol 112:181–190.

Pasche B, Kalaydjiev S, Franz TJ, Kremmer E, Gailus-Durner V, Fuchs H, Hrabe de Angelis M, Lengeling A, Busch DH. 2005. Sex-dependent susceptibility to *Listeria monocytogenes* infection is mediated by differential interleukin-10 production. Infect Immun 73:5952–5960.

Perry RD, Fetherston JD. 1997. *Yersinia pestis*—etiologic agent of plague. Clin Microbiol Rev 10:35–66.

Poland JD. 1989. Plague. In: Hoeprich PD, Jordan MC, editors. Infectious diseases: a modern treatise of infectious processes, 4th ed. Philadelphia: J.B. Lippincott. p 1296–1306.

Pollitzer R. 1954. Plague. World Health Organization monograph series no. 22. Geneva: World Health Organization.

Poos LR. 1991. A rural society after the Black Death: Essex, 1350–1525. Cambridge: Cambridge University Press.

Poulsen B. 1997. Agricultural technology in medieval Denmark. In: Astill GG, Langdon J, editors. Medieval farming and technology: the impact of agricultural change in northwest Europe. Leiden: Brill. p 115–146.

Powell ML. 1988. Status and health in prehistory: a case study of the Moundville Chiefdom. Washington: Smithsonian Institution Press.
Powell ML. 1991. Endemic treponematosis and tuberculosis in the prehistoric southeastern United States: biological costs of chronic endemic disease. In: Ortner DJ, Aufderheide AC, editors. Human paleopathology: current syntheses and future options. Washington: Smithsonian Institution Press. p 173–180.
Raoult D, Aboudharam G, Crubezy E, Larrouy G, Ludes B, Drancourt M. 2000. Molecular identification by "suicide PCR" of *Yersinia pestis* as the agent of medieval black death. Proc Natl Acad Sci USA 97:12800–12803.
Ratsitorahina M, Rabarijaona L, Chanteau S, Boisier P. 2000. Seroepidemiology of human plague in the Madagascar highlands. Trop Med Int Health 5:94–98.
Razi Z. 1980. Life, marriage, and death in a medieval parish: economy, society, and demography in Halesowen, 1270–1400. Cambridge: Cambridge University Press.
Roberts CA. 2007. A bioarcheological study of maxillary sinusitis. Am J Phys Anthropol 133:792–807.
Roberts CA, Lewis ME, Boocock P. 1998. Infectious disease, sex, and gender: the complexity of it all. In: Grauer AL, Stuart-Macadam P, editors. Sex and gender in paleopathological perspective. Cambridge: Cambridge University Press. p 93–113.
Roberts CA, Manchester K. 2005. The archaeology of disease. Ithaca, NY: Cornell University Press.
Roberts CW, Cruickshank SM, Alexander J. 1995. Sex-determined resistance to *Toxoplasma gondii* is associated with temporal differences in cytokine production. Infect Immun 63:2549–2555.
Roberts CW, Walker W, Alexander J. 2001. Sex-associated hormones and immunity to protozoan parasites. Clin Microbiol Rev 14:476–488.
Roesdahl E, editor. 1999. Dagligliv i Danmarks middelalder: En arkæologisk kulturhistorie. Copenhagen: Nordisk Forlag.
Russell JC. 1948. British medieval population. Albuquerque: University of New Mexico.
Russell JC. 1985. The control of Late Ancient and Medieval population. Philadelphia: The American Philosophical Society.
Sawyer B, Sawyer PH. 1993. Medieval Scandinavia: from conversion to Reformation, circa 800–1500. Minneapolis: University of Minnesota Press.
Scott S, Duncan CJ. 2001. Biology of plagues: evidence from historical populations. Cambridge: Cambridge University Press.
Šlaus M. 2000. Biocultural analysis of sex differences in mortality profiles and stress levels in the Late Medieval population from Nova Rača. Croatia. Am J Phys Anthropol 111:193–209.
Šlaus M. 2008. Osteological and dental markers of health in the transition from the Late Antique to the Early Medieval period in Croatia. Am J Phys Anthropol 136:455–469.
Steckel RH. 1995. Stature and the standard of living. J Econ Lit 33:1903–1940.
Tikhomirov E. 1999. Epidemiology and distribution of plague. In: Plague manual: epidemiology, distribution, surveillance and control. Geneva: World Health Organization. p 11–41.
Twigg G. 1984. The Black Death: a biological reappraisal. London: Batsford Academic and Educational.
Ulizzi L, Zonta LA. 2002. Sex differential patterns in perinatal deaths in Italy. Hum Biol 74:879–888.
Villani M. 1995. In: Porta G, editor. Cronica con la continuazione di Filippo Villani, I. Parma: Fondazione Pietro Bembo/Ugo Guanda.
Waldron HA. 2001. Are plague pits of particular use to palaeoepidemiologists? Int J Epidemiol 30:104–108.
Walker PL, Johnson JR, Lambert PM. 1988. Age and sex biases in the preservation of human skeletal remains. Am J Phys Anthropol 76:183–188.
Weiss KM. 1972. On the systematic bias in skeletal sexing. Am J Phys Anthropol 37:239–249.
Wells JC. 2000. Natural selection and sex differences in morbidity and mortality in early life. J Theor Biol 202:65–76.
Widgren M. 1997. Fields and field systems in Scandinavia during the middle ages. In: Astill GG, Langdon J, editors. Medieval farming and technology: the impact of agricultural change in northwest Europe. Leiden: Brill. p 173–192.
Wiechmann I, Grupe G. 2005. Detection of *Yersinia pestis* DNA in two early medieval skeletal finds from Aschheim (Upper Bavaria, 6th century A.D.). Am J Phys Anthropol 126:48–55.
Wood JW, DeWitte-Avina SN. 2003. Was the Black Death yersinial plague? Lancet Infect Dis 3:327–328.
Wood JW, Ferrell RJ, DeWitte-Avina SN. 2003. The temporal dynamics of the fourteenth-century Black Death: new evidence from English ecclesiastical records. Hum Biol 75:427–448.
Wood JW, Holman DJ, O'Connor KA, Ferrell RJ. 2002. Mortality models for paleodemography. In: Hoppa RD, Vaupel JW, editors. Paleodemography: age distributions from skeletal samples. Cambridge: Cambridge University Press. p 129–168.
Yersin A. 1894. La peste bubonique a Hong-Kong. Ann Inst Pasteur (Paris) 8:662–667.