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Population Dynamics in Predynastic Upper Egypt: Paleodemography of Cemetery HK43 at Hierakonpolis

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
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By

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Abstract

The site of Hierakonpolis is considered to have played an important role in the development of the Egyptian state, which formed at end of the fourth millennium BC. Archaeological evidence suggests that, for the Middle and Late Predynastic periods (ca. 3900–3200 BC), Hierakonpolis may be characterized as having experienced the following: a growth in both settlement and population size, an increased reliance on cereal agriculture, development of craft specialization, and the presence of a social hierarchy as interpreted from an observed increase in the differentiation of mortuary behavior. Historical data suggest that these social and economic changes would have affected (and been affected by) the demographic properties of the population there. This dissertation reports the results of a paleodemographic analysis of the human skeletal assemblage recovered from cemetery HK43, which represents a nonelite population from the Predynastic period at the site of Hierakonpolis.

In an effort to reassess previous studies of the age-at-death distribution for HK43, this study begins with an evaluation of the use of dental attrition in estimating age-at-death for a subset of the HK43 sample. Age-at-death estimates using dental attrition are heavily influenced by the particular method used to calculate the yearly attrition rate for each tooth. Similar to results reported elsewhere, the young age-at-death distribution for the subset of individuals with dental attrition data precluded using them as a population-specific reference sample for HK43.

Results of the analysis of three aggregate age measures have a number of implications. The results suggest that juvenile mortality may have improved during the period of cemetery use at HK43. Further these results suggest that birth rate and population growth rates increased during the period of cemetery use at HK43, and the rates of population growth during this period may have been higher than previously assumed.

In an examination of adult mortality patterns using hazard analysis, this study finds that males and females of HK43 had a different mortality experience. Generally, males exhibit higher rates of mortality

than females. Further, results suggest that female mortality, specifically for those during child-bearing years, improved over the period of cemetery use. This may be attributed to the increasing frequency of males being conscripted for activities not related to regular agricultural production. The observed improvement in mortality for reproductive-age females (and juveniles) likely had a positive impact on the birth rate and population growth rate. These results suggest that Hierakonpolis may have enjoyed a demographic advantage over rival administrative centers in Upper Egypt during middle and latter parts of the Predynastic.

Finally, the use of more-recent methods, proposed in the Rostock Manifesto (Hoppa and Vaupel, 2002a), produced an age-at-death distribution slightly younger than that using a more traditional approach to paleodemographic reconstruction. Thus, these newer statistical techniques, by themselves, may not completely address the peculiar age-at-death distributions and associated demographic estimates for archaeologically-derived skeletal samples. This study illustrates that, despite its critics, paleodemography has much to offer to the study of past population dynamics. At the same time, the field must continue working toward theoretically-grounded approaches of modeling the complex process that leads from a living population to one that may be studied hundreds or thousands of years in the future.

This dissertation is approved for
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Dedication

For my grandparents

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Chapter 1 Introduction

> "The tragedy of Egyptian archaeology is that it once provided a wealth of cemeteries with large skeletal populations. Until quite recently, however, this material was effectively destroyed rather than studied scientifically. [The] basic paleodemographic problem remains, for the present, unsolvable" (Butzer, 1976:81).

1.1 Opening Remarks

Karl Butzer made the above statement over thirty years ago in his landmark publication *Early Hydraulic Civilization in Egypt*. It reflected, and to a degree still does, the irony of bioarchaeological studies of in Egypt. Even though more than a century of archaeological investigations in Egypt have historically focused on cemeteries, most of the subsequent publications would present detailed descriptions and analyses of the nonbiological aspects of mortuary practices (e.g., shape/size of graves, types/amounts of grave goods, etc.), while information on the human remains went unpublished or was relegated to appendices (Zabecki, 2009). This casual treatment of the research potential of human skeletal remains—in Egypt and elsewhere—stemmed from the prevailing paradigms during the early- and mid-1900's within archaeology and skeletal biology that focused upon the identification of cultural sequences, unilineal progression of the major "stages" of cultural evolution, and typological approaches to human variation (Goodman and Martin, 2002). Not until the late 1960's and 1970's did population approaches and a biocultural perspective begin to gain ground (Buikstra, 1991).

The present study is part of a continuing and growing effort to set studies of human remains from archaeological sites in Egypt within a broader, biocultural context. During a salvage project from 1996 to 2004, a team of archaeologists and bioarchaeologists excavated a portion of HK43, a large cemetery associated with the Predynastic period (ca. 4000–3100 BC) at Hierakonpolis. This dissertation is one of a number of recent investigations of the skeletal biology from the remains recovered at HK43.

Recent studies of the HK43 assemblage have addressed a number of questions: dental attrition and age estimation (Huard, 2006, 2008), diet and dental health (Greene, 2006; Gamza and Irish, 2010), physical stress due to workloads (Zabecki, 2008, 2009), and paleopathology (Kumar, 2009; Larsen, 2009). The current research explores the application of recently-developed methods in paleodemography in estimating age-at-death distributions at HK43 in order to better understand population dynamics for a nonelite portion of the population that used the cemetery during a formative period in Egypt's past.

1.2 Background

Hierakonpolis, or ancient Nekhen, has long been recognized as a major center in the development of the ancient Egyptian state and may likely have served as an early capital of Upper Egypt (Midant-Reynes, 2000b). Hierakonpolis is intimately associated with kingship and the birth of the ancient Egyptian state. The ancient city was the major cult center of the god Horus, with whom every pharaoh of Egypt was associated. In the main Predynastic town, a sprawling settlement area running along the modern line of cultivation, there is the earliest-known Egyptian ceremonial complex (ca. 3400 BC) that may have been a prototype for later Dynastic religious structures.

Slightly before 4000 BC, groups of people, perhaps from the north, had settled the area at Hierakonpolis (Hoffman et al., 1986). Growth of the settlement at Hierakonpolis, especially from ca. 3800–3300 BC, underscores the site's importance as a regional center and possibly its role as the capital of an early "proto-kingdom" prior to unification. Population growth at the site, assumed from both increases in number and spatial expansion of settlement, has been partially attributed to the ecological diversity of its location and the exceptional agricultural potential of the region. At its peak during the mid-fourth millennium BC, population size may have reached as high as about 10,000 people in the central area of the site (Hoffman et al., 1986:181).

Archaeological evidence suggests that, by this time, the community at Hierakonpolis was already functionally differentiated. Craft specialization was present, including areas designated for the production of pottery and fine stone objects such as maceheads and cosmetic palettes. Further, by the middle of the fourth millennium BC, there is evidence for the centralization of processing, production, and storage of food, such as bread and beer (Geller, 1992). In addition to harvesting cereal grains like barley and wheat, people also gathered wild cultigens (acacia and date palm), practiced animal husbandry (domesticated cattle, sheep, goats, and pigs), and exploited river resources such as Nile perch (Allen, 1997; Midant-Reynes, 2000a).

The discovery of nonlocal ceramic vessels and objects throughout the site indicates contact with other groups in Upper Egypt and surrounding regions (Friedman et al., 1999). During the fourth millennium BC, Hierakonpolis grew to have features commonly associated with sociopolitical complexity: elites, national religious cults, economic interdependence within the immediate area and among communities outside of the region (Wenke, 1989). At the time of its dominance at ca. 3500 BC, Hierakonpolis was one of the largest, if not the largest, settlements anywhere on the Nile (Hoffman et al., 1986).

Mortuary archaeology provides some of the best evidence of cultural changes during the fourth millennim BC. Mortuary data at Hierakonpolis and other large Predynastic sites suggest that, beginning ca. 3800 BC, there was an increasing demand for nonsubsistence goods and a growing unequal distribution of wealth (Castillos, 1982; Hassan, 1988). The presence of coeval, formal cemeteries that are spatially segregated and differences in tomb size and contents are consistent with a community operating within the context of significant social ranking (Wenke, 1989).

By ca. 3700, styles of artifacts had become highly standardized, limiting the degree to which craft specialists could contribute to agricultural labor. As a consequence, each new artisan or skilled craftsperson may have required the support of as many as 50 agricultural producers (Midant-Reynes, 2000b:198). Thus, as elite members sought to acquire prestige goods that would eventually furnish their lavish tombs, a segment of the population that was mainly engaged in non-agricultural pursuits also emerged. Ultimately, this process likely required an increase in an administered population through territorial expansion, resulting in some groups moving up or down the Nile Valley to escape emerging polities (Trigger et al., 1983). Indeed, the archaeological record shows a rapid expansion of Naqada cultural elements to the north and south during this period, eventually replacing expressions of northern material culture.

From about 3500 BC onward, Hierakonpolis followed a trajectory toward settlement nucleation, as settlement distribution only reached about 13% of its previous spatial expansion (Harlan, 1985). This phenomenon would occur in other regional centers (e.g., Naqada and, later, Abydos), as small towns became larger ones. Population size, though, does not appear to have decreased, as agglutinated settlement architecture is consistent with an increases in population density. The geography of the Nile Valley, though, may have provided a means whereby the population there was stable around its equilibrium density, as members of the group made cost-benefit decisions about moving away from local cultivated land and pasture. So, even if local population densities increased, the entire valley held plenty of space into which groups could expand. A combination of individual choices to move and a need of emerging elites for territorial expansion to gain control over resources and trade networks are points of departure for understanding the rapid spread of Upper Egyptian culture during the Naqada II phase.

In the absence of an outlet mitigating continued increase in population density, the population at Hierakonpolis would have entered a space-limited regime in which density-dependent checks would eventually take hold. From a strictly Malthusian view, increasing pressure would eventually lead the population into a Malthusian trap, where the population size would outgrow the mode of production and a catastrophic event such as famine or economic collapse would ensue (Artzrouni and Komlos, 1985). The archaeological evidence, though, suggests that the population at Hierakonpolis did not collapse, but was strong enough to become what most agree was the early capital of a unified Upper Egypt, which occurred prior to the unification of the Upper and Lower Egypt.

At Hierakonpolis, then, it is unlikely that the limits on population were set by a starvation-level carrying capacity, but by a point where external conditions would have a density-dependent effect on choices related to fertility, survival, and parental investment such that mean fertility and mean survival balance one another (Puleston and Tuljapurkar, 2008; Shennan, 2009). In addition, if one assumes that individuals had the opportunity to spread to less populated areas along the Nile Valley as a “frontier” economy in an expansion regime (Allen, 1997), higher population densities may have been possible, allowing for a longer period of time before density-dependent effects took hold. In this type of system, food is a major determinant of human health, mortality, and fertility, and thus of the growth rates and sizes of preindustrial populations (Lee and Tuljapurkar, 2008:473).

Since it was not until the Third and Fourth Dynasties of the Old Kingdom (ca. 2600 BC) that the administrative scope of the state required more detailed records and an annual census for taxation was folded into the economic system (Bard, 2000), what sources offer information about the human demographic experience in Egypt’s prehistory? For the Predynastic period (and much of the historic period), archaeological evidence—human skeletal remains recovered from cemeteries, in combination with settlement data—provide the best demographic record for Egypt (O'Connor, 1972). Unfortunately, due to the nature of excavation strategies typical of the early 20th century, there exist but a few sizeable collections of human skeletal remains with good provenience. Most of the data that have been published, even recently, do not contain estimates of age and sex in sufficient detail to be included in a paleodemographic analysis. Based upon the small number of skeletal assemblages that have been studied, there is a general interpretation that Predynastic Egyptians were undergoing a regime of low fertility and high mortality, with average life expectancy at around 30 years of age (Masali and Chiarelli, 1972).

Alternative explanations for the patterns previously reported include differential burial practices and poor taphonomic preservation of the bones of infants and young children. During the Predynastic, children were commonly buried within the settlement, either under houses or in areas that were no longer in use (Midant-Reynes, 2000b). Further, a combination of these factors may have affected the eventual recovery of the very young from these cemeteries. In a survey of Predynastic and Early Dynastic cemeteries, Castillos (1982) noted that the frequency of juvenile burials dropped from the early to late parts of the Predynastic period, implying a decrease in infant and child mortality.

The problems involved with the above interpretations may be addressed by looking at historical developments within paleodemography. First, they assume that simple frequencies of age groups within the burial population accurately reflect the living population. Also, they based interpretation largely on mean age-at-death, which does have a specific relationship with average life expectancy, but only in the case of a stationary population—one that is closed to migration and has equal and unchanging birth and death rates such that population growth equals zero. As discussed in further detail in Chapter 3, the assumption of stationarity and the associated wholesale application of life tables in paleodemographic analyses has been roundly criticized. As noted in a recent review of advancements within the discipline, had populations truly been stationary in the past, we would still comprise small groups of hunter-gatherers (Milner et al., 2008). A less restrictive approach would be to allow for growing (or, declining), but *stable* populations.

Because data quality is poor, estimates of population growth rate during the Predynastic period are tenuous at best. Assuming an initial population size of about 10,000 and a Late Predynastic population size between about 100,000 to 200,000, Butzer (1976) estimated an annual growth rate of about 0.08% from 4000 to 2500 BC. Hassan (1993) has estimated a considerably higher annual rate of population growth at 0.18%. The immense agricultural potential of the Nile Valley could have allowed for constant population growth, leading to estimated population sizes as high as 3.2 million during the Greco-Roman period (332 BC–AD 395) (Hassan, 1993:170). In the long run, then—even while local populations likely experienced periods of decline or instability—Egypt's population continued to increase throughout the prehistoric and historic periods.

Cemetery-based estimates of population size (i.e., burial counts) offer a alternative interpretation, that at any one settlement during a specific point in time, Predynastic societies were composed of populations in the hundreds, not thousands (Mortensen, 1991; cf. Hassan, 1981; Hoffman, 1982). These lower estimates allow for immigration and emigration, a condition that is more likely than the assumption of true population stationarity. Although some local populations may have experienced increases in density, population size and density in Egypt, as a whole, was probably low during the run up to unification (Allen, 1997). The archaeological evidence suggests that, in contrast to other regions, such as the Near East, state formation in Egypt probably did not occur under conditions of high population density.

1.3 Objectives

Provided recent theoretical and methodological developments within paleoanthropology (Hoppa and Vaupel, 2002a) the ultimate objective of the current study is to gain understanding of the demographic processes influencing overall population dynamics for the nonelite segment of the population at Hierakonpolis, as represented by the HK43 skeletal assemblage. In order to do so, the first step will be to reliably estimate an age-at-death distribution for the burial population at HK43. In the second step, archaeological evidence and the estimated paleodemographic parameters will be incorporated into a broader theoretical framework of population dynamics at Hierakonpolis, and the Upper Egyptian Nile Valley, more generally.

Early reports of the age-at-death structure at Hierakonpolis suggested that adult mortality was extremely high. A primary goal of the current research is to evaluate the application of a number of methods, some more recently developed, for estimating age-at-death distributions of the remains recovered from cemetery HK43. Since the main critiques of paleodemography in the 1980's, a number of methods have been proposed to mitigate problems that have often plagued the field. And though each round of criticism has strengthened the field, recently developed approaches have not yet become widely adopted. Further, the field still lacks consensus on a number of issues, as major schools of thought sometimes talk past each other (Konigsberg and Frankenberg, 2002). In an effort to promote continued improvements within the field, this study includes appendices with raw data and samples of computer code, so that others may reproduce the results and offer detailed critical analysis.

1.4 Research Design and Hypotheses

After an auspicious beginning as a specialization within biological anthropology, paleodemography has been subject to criticism and a healthy re-examination by scholars within and outside of the discipline (Buikstra and Konigsberg, 1985; Meindl and Russell, 1998; Konigsberg and Frankenberg, 2002; Milner et al., 2008). Major concerns that have warranted investigation include inaccuracies in ages estimated using skeletal morphology (e.g., Bocquet-Appel and Masset, 1982), systematic biases in skeletal age-at-death distributions that result from the use of modern skeletons as reference samples (Saunders et al., 1993; Bocquet-Appel and Masset, 1996; Konigsberg et al., 1997), the effect of multiple levels of sampling bias on the representativeness of archaeological skeletal assemblages (e.g., Petersen, 1975; Wood et al., 1992b; Hoppa, 1999), application of the principle of biological uniformity to prehistoric populations (e.g., Howell, 1982; Paine, 1997c), and the effect of demographic nonstationarity on age-at-death distributions (e.g., Sattenspiel and Harpending, 1983; Johansson and Horowitz, 1986; McCaa, 2002).

In response to these legitimate criticisms of the field, the "Rostock Manifesto" (Hoppa and Vaupel, 2002b:2–3) called for four changes to the practice of paleodemography. First, reference collections of known age-at-death skeletons must be re-examined and validated for reliable morphological indicators of chronological age. Second, researchers need to develop better statistical methods to estimate the probability of certain morphological characteristics given a known age. Third, in order to properly estimate age-at-death for an individual from an archaeological skeletal assemblage, one must apply Bayes' theorem to calculate the inverse probability of a particular chronological age given an observed suite of skeletal characteristics and the age-at-death distribution of that same "target" population.

Fourth, researchers must develop statistical models for expressing the age-at-death distributions in prehistoric populations. Of these, the realization that one must estimate the full age-at-death distribution for a target sample *prior* to estimating age for any one individual has been a paradigm shift.

Though the theoretical approach adopted in Hoppa and Vaupel (2002a) was a critical step for the future of the field, few have implemented these new methods and models on sizeable archaeological samples (see Wilson, 2009, for a notable exception). The current study is an attempt to do just that. The first stage of this study involves an evaluation of the use of dental attrition to estimate age-at-death for a subset of the HK43 skeletal assemblage. The second part looks at well established, aggregate age measures (e.g., Buikstra et al., 1986; Bocquet-Appel, 2002) to investigate a number of demographic measures, including juvenile mortality, birth rate, and population growth rate. The final stage incorporates the use of parametric hazard models (i.e., mortality models) to investigate adult mortality at HK43 and a number of comparative samples, as well a re-assessment of the adult age-at-death distribution using recently developed maximum likelihood methods (e.g., Boldsen et al., 2002; Herrmann and Konigsberg, 2002; Konigsberg and Herrmann, 2006).

Given what is known about demographic patterns in human populations, including small, ethnographic (and preindustrial) groups, well known theories of population dynamics and their relationship to the environment (physical, sociocultural, and economic) provide a framework in which archaeological evidence may be used develop expectations of the demographic profiles of skeletal assemblages. Accordingly, this study includes the following hypothesis for investigation:

- **Hypothesis 1**: A cornerstone of paleodemographic research is the assumption of biological uniformitarianism (Howell, 1976). While some have argued that preindustrial populations may have experieced markedly different demographic regimes than modern "anthropological" populations, others have shown that, with more appropriate statistical treatment, the demography of preindustrial populations is within the range of modern groups. Assuming biological uniformity, it is predicted that population dynamics of the living population represented by the burial population at HK43 will approximate those of known small-scale, preindustrial societies. Contrary to previous research on demography of Predynastic Egyptians that concluded life expectancy was low—between 20 and 30 years at birth (Masali and Chiarelli, 1972; Podzorski, 1995, Batey, 2008)—it is hypothesized that many members of the nonelite population at Hierakonpolis lived well into old age (i.e., over 50 years).

- **Hypothesis 2**: Previous research has characterized Predynastic Egyptians demography as reflecting low-fertility/high-mortality, non-expanding populations(Masali and Chiarelli, 1972; Masali, 1980). This demographic regime seems implausible for the living population represented by HK43, if Hierakonpolis did experience rapid population growth between 3800 and 3400 BC, as suggested by the archaeological evidence (Hoffman, 1982; Hoffman et al., 1986). During this time period, the population at Hierakonpolis became increasingly reliant on agricultural production as part of the subsistence strategy and less mobile, as settlement patterns and domestic architecture are consistent with a permanent, village-based settlement pattern Midant-Reynes (2000a). It is likely that these changes had biological consequences. Compared to hunter-gatherers, agriculturalists likely spend less parental investment producing successful adults, and individuals have the potential to be productive at younger ages (Boone, 2002). Further, a reduction in daily mobility and energy expenditure relaxes reproductive suppression (Jasienska, 2001). These scenarios would be conducive to increased fertility.

  If the nonelite population at Hierakonpolis was growing, it should be reflected in the age-at-death distribution, which, in a non-stationary population, is sensitive to the birth rate and population growth rate (Sattenspiel and Harpending, 1983; Johansson and Horowitz, 1986; McCaa, 2002). In order to investigate this, two aggregate age measures demonstrated to be highly correlated with birth rate and population growth rate will be examined at Hierakonpolis and a number of comparative datasets. Further, the Gompertz hazard model will be used to assess possible changes in female mortality that may have contributed to increasing birth rates

- **Hypothesis 3**: For Predynastic populations in Upper Egypt, the Nile Valley may be considered a variable environment. Resource availability, especially agricultural yield, varied as a function of oscillations in Nile flood levels (Hassan, 1997). If population density was low and available land was not limited, the living population represented by HK43 could have responded in a number of ways to environmental variation (Lee and Tuljapurkar, 2008). Empirical evidence from ethnographic populations suggests that a decrease in the dependence on extracted resources (e.g., hunting and gathering) is associated with a decrease in juvenile mortality (Sellen and Mace, 1999). Given the archaeological interpretation that HK43 represents a population increasingly reliant on food production, rather than hunting and gathering, it is predicted that juvenile mortality would improve during the period of cemetery use. This could have mitigated any negative effects of reduced fertility or increases in mortality due to environmental fluctuations.

From another perspective, demographic transition theory suggest that, historically, human population grew as a result of time lag in between a decrease in mortality and a late decrease in fertility (Gage and DeWitte, 2009). A decrease in mortality for the nonelite population at Hierakonpolis—specifically for reproductive-age females—may have resulted in population growth by allowing more births during the average female's lifespan. The Gompertz hazard model will be used to test for possible changes in female mortality during the period of cemetery use.

1.5 Significance

The study of mortality, fertility, and migration patterns in human populations is a common point of interest across many disciplines within the social and behavioral sciences. Since reliable demographic records only date back several centuries, paleodemography has the potential to extend the study of human population dynamics into the distant past. Given that population dynamics, expressed in terms of differential fertility and mortality, constitute the core of micro- and macro-evolutionary processes, paleodemographic analyses may reveal a tremendous amount of information about human demographic and life history.

Recent bioarchaeological research has provided insights into the life of the living population represented at HK43. Greene's (2006) analysis of dental wear and disease support hypothesized dietary reconstructions based upon botanical and faunal remains at the site. Contrary to previous thought, Zabecki (2009) concluded those represented at HK43 were not overly stressed due to labor activities, as evidenced by low scores at muscle attachment sites. Biomechanical data suggest that populations may have been more mobile during the Predynastic at Hierakonpolis than at the New Kingdom urban center at Amarna (Schaffer, 2010). Using a health index developed for archaeological populations in the Western Hemisphere (Steckel and Rose, 2002), Larsen (2009) found that Hierakonpolis scored very high (i.e., better health), particularly in parts of the index related to childhood health. Finally, studying paleopathological data, Kumar (2009) found relatively low frequencies of nonspecific markers of stress and interpreted those results to indicate that the people buried in cemetery HK43 had access to adequate nutrition and that parasite loads were low and their immune systems were strong enough to counter infections.

A rigorous study of how human population dynamics interacted with the changing physical and cultural landscapes is critical to understanding of the process that ultimately led to the unification of Upper and Lower Egypt. Unfortunately, previous investigations of Egyptian paleodemography have been informal, with researchers basing interpretations upon features such as mean age-at-death and average life expectancy or creating abridged life tables. This study will add to the growing body of literature on skeletal biology of the individuals buried at HK43 and the once-living population the cemetery served. Further by including raw data and computer code for the statistical analyses involved, this research will foster similar applications in the future and collaboration across various fields, such as Egyptology and economic history, as well as archaeology and biological anthropology.

1.6 Organization of Chapters

Chapter 2 provides a general overview of Egyptian prehistory, with special attention to developments during the Predynastic period. This includes a summary of current interpretations of Predynastic Hierakonpolis, given the the archaeological evidence recovered there. The chapter concludes with a summary of the evidence for population growth at Hierakonpolis.

Chapter 3 provides a brief overview of some of the basic principles of demography and theories of population growth. This chapter includes a discussion of our current understanding of demography and population dynamics in small-scale societies. This chapter concludes with a review of historical developments within paleodemography with particular attention to recent developments over the last decade.

Chapter 4 details the method of recovery and data collection for the HK43 skeletal assemblage. Also, the statistical methods used to estimate age-at-death distributions and other paleodemographic information are detailed, including rationale for choosing the particular analytical procedures used in this study.

Chapter 5 presents the results and discussion of the statistical analyses. The chapter follows the general presentation of the previous chapter, as each analysis and the associated results fold into the next. The chapter concludes with a summary of the main results and implications for the population dynamics of the population represented by HK43.

Chapter 6 provides a summary of this study's main findings and conclusions. This chapter considers the implications of the results to current interpretations of the interaction between the nonelite population at Hierakonpolis and socioeconomic changes that preceded the rise of the Egyptian state. Lastly, this final chapter includes ideas for future research directions, closing with thoughts of what types of contributions paleodemography, despite nagging methodological and theoretical issues, still has to offer anthropology.

Chapter 2 Egyptian Prehistory

Egypt's long and rich cultural history cannot be denied. As far back as 400,000 years ago—likely longer—groups of Paleolithic hominins had a presence there (Hendrickx and Vermeersch, 2000). The geographical location of Egypt would have provided small bands of individuals with an attractive, natural migration route between northern Africa and southwestern Asia. Geographic ranges of later archaic and modern humans varied over time, as groups made decisions of where to move that were influenced by the effects of unpredictable oscillations in climate. It was not until the Nile River's headwaters finally reached the highlands of Ethiopia (about 100,000 years ago) that a fertile floodplain and delta became permanent features of Egypt's often hyper-arid landscape (Hendrickx and Vermeersch, 2000; Wengrow, 2006).

Ahead of the early fifth millennium BC, small communities living in the northern Nile Valley had incorporated domesticated plants into a broad subsistence strategy that already included hunting, gathering, fishing, and animal husbandry. To our knowledge, domestic plants would arrive later in Upper (southern) Egypt. In contrast to the early agricultural communities in the Levant, though, those in Egypt showed little evidence of village-based existence (Wengrow, 2006). In a relatively short period, the cultural landscape of Egypt underwent a remarkable transformation. By about 3100 BC, villages strung along the Nile, and towns and religious cult centers stood out on the high, natural levees of the river. By then, much of Egypt was under the control of a single king, and within a few centuries thereafter, a cohesive state had emerged under the rule of a dynasty of the first pharaohs, whose power was reflected by the pyramids at Giza, some of the most impressive monuments of antiquity (Hassan, 1993).

Although subjected to extensive archaeological investigation for over a century, the Nile Valley of Upper Egypt has provided relatively little information about the population dynamics of the people living during the Predynastic period. While written documents, the most useful records for economic historians and demographers, emerge in after about 3100 BC and into the Old Kingdom (Bard, 2000), archaeological evidence (e.g., settlement data and skeletal remains from cemeteries) continue to provide the best, continuous demographic record up to the end of the fourth millennium BC. In order to formulate hypotheses about the population processes experienced by Predynastic Egyptians, we must consider the complex, historical context to which they belonged.

This chapter is divided into four sections. The first section reviews early human prehistory in Egypt, from the Paleolithic to about 5000 BC. The second section provides a review of current archaeological interpretations of the evidence for cultural developments during the Predynastic period. The discussion then turns to the history of archaeological investigations at Hierakonpolis and current interpretations of the data with respect to the development of Egyptian culture during the fourth millennium BC. This chapter concludes with a review of the settlement and mortuary data at Hierakonpolis in developing a framework for interpreting population dynamics of the population served by cemetery HK43.

2.1 The Paleolithic to ca. 5000 BC

The presence of *Homo erectus* in Asia after about 1.7 million years ago suggests that early *Homo* had migrated there soon after evolving in Africa. Due to its geography (Figure 2.1), Egypt likely served as a natural route for movement of hominins back and forth between northern Africa and southwestern Asia. Lithic artifacts, dating as early as 400,000 years ago, provide evidence that groups may have stayed in the Nile Valley throughout this period (Hendrickx and Vermeersch, 2000:17). Although silts deposited over millennia of annual flooding may have buried or destroyed Lower Paleolithic sites in the Nile Valley, archaeological evidence suggests that, during the Middle Paleolithic, small groups in the Western Desert (Eastern Sahara) occupied seasonal camps near ephemeral lakes during wet phases and abandoned these areas during phases of hyper-aridity (Hendrickx and Vermeersch, 2000). Associated faunal remains suggest that these Middle Paleolithic groups exploited both large and small species, with gazelle dominating the assemblages. As for mortuary evidence, a juvenile skeleton representing one of the oldest-known African burials of an anatomically modern human was discovered at the site of Taramsa-I near Qena in Upper Egypt (Vermeersch et al., 1998).

Toward the end of the Middle Paleolithic, a continuation of arid and hyper-arid climate conditions likely restricted resources to the river's flood plain, forcing human groups living in what is now desert

Figure 2.1: Selected archaeological sites mentioned in the text. (Hierakonpolis marked with star.)

to seek better conditions closer to the Nile Valley. For the period preceding the Late Paleolithic, archaeologists have found scarce evidence of human occupation in the Nile Valley, the result of a level of depopulation due to environmental degradation and those sites becoming buried by more recent alluvial deposits. In contrast, many Late Paleolithic sites have been found in Upper Egypt. Sites generally consist of few, circular huts and likely reflect use by small groups of no more than about 40 individuals (Hassan, 1988).

A northward shift of annual monsoon rains brought about a wet phase during the early Holocene (ca. 9300 BC) and resulted in the return of populations to the Western Desert, which had been abandoned since the late-Middle Paleolithic (Wengrow, 2006). Based upon similarities in lithic technology, people likely migrated into the Western Desert from the southern Nile Valley. By about 8000 BC, the first Neolithic cultures—the Saharan Neolithic—had developed in the Western Desert. It is important to note that, in contrast to Neolithic economies in the neighboring Levant, the early Egyptian Neolithic developed without any sign of agriculture. These groups are defined as Neolithic based primarily on the presence of ceramics and evidence of the herding of cattle. Thus, the early Egyptian Neolithic developed in a manner readily distinguishable from that which emerged around the same time in the Levant, where animal domestication was adopted soon after the earliest farming villages appeared. As a further contrast between the two regions, the process of state formation in Egypt occurred relatively rapidly—about 1000 years after the first farming villages appeared in the Nile Valley—while state formation in the Near East lagged behind the adoption of agriculture by perhaps 5000 years (Allen, 1997).

Archaeological investigations suggest that human occupation during the early phase of the Neolithic (ca. 8300–6900 BC) in the Western Desert was characterized by small, short-term habitation by small groups of hunter-gatherers. Faunal assemblages from these sites typically include some bones of cattle, although it is generally accepted that they were not domesticated at this point (Hendrickx and Vermeersch, 2000; Wengrow, 2006; cf. Wendorf and Schild, 1980). During the following phases of the Saharan Neolithic, desert population reached its peak. Most sites were small, possibly outposts for herders, while the increase of waddle-and-daub structures at larger sites likely reflects permanent habitation. By about 5600 BC, sheep and goats were present, but wild game appears to have continued as the primary source of meat.

In the Nile Valley, populations practiced a mixed-subsistence economy, exploiting wild game and plants and, especially, fishing. By this time, fishing technologies had become more sophisticated since the Paleolithic; people were not only catching fish in small lakes supplied by annual flooding, but also catching deep-water species from the main channel of the river, which provides indirect evidence for boat use (Hendrickx and Vermeersch, 2000:32). Beginning around 7000 BC, the cooler, wetter climate began to shift, reaching conditions similar to present-day aridity by about 5000 BC.

The popular interpretation follows an ecological approach: climate change reduced the amount of resources available, particularly with respect to the desert, forcing hunter-gatherer populations to adopt agricultural practices in order to avoid increased competition for resources (Hassan, 1980a; Bard, 1994b). At this point, perhaps more than at any time previously, populations depended upon the annual cycle of Nile inundation and drought. Thus, permanent settlements and decreased mobility provided

Table 2.1: Chronology of Predynastic Egypt (terms used here in parentheses).

Period	Hassan (1988)	Shaw (2001)
Early Predynastic (Badarian)	ca. 5000–3900 BC	ca. 4400–4000 BC
Middle Predynastic (Naqada I)	ca. 3900–3650 BC	ca. 4000–3500 BC
Late Predynastic (Naqada II)	ca. 3650–3300 BC	ca. 3500–3200 BC
Terminal Predynastic (Naqada III)	ca. 3300–3050 BC	ca. 3200–3000 BC

the advantage allowing for food storage that could offset short-term shortages due to environmental stress (Hassan, 1980a).

2.2 The Predynastic Period

Several chronologies have been developed for the Predynastic period in Upper Egypt. Using ceramics from cemeteries at Naqada and two other sites, in the early 1900's, Flinders Petrie developed the first relative chronology of Upper Egypt (Petrie et al., 1896; Petrie, 1901). Petrie began his sequence dating (SD) system at SD 30, intentionally leaving room for earlier phases yet to be discovered. He divided the sequence dates into three cultural periods: Amratian, Gerzean, and Semainean. Kaiser (1957) produced another ceramic-based, relative chronology using material from Cemetery 1400-1500 at the site of Armant. Kaiser called his three main phases Naqada I–III and further separated these into eleven subdivisions called "Stufen." Although Petrie's system still approximates Kaiser's divisions of the Naqada phase, Kaiser's system remains the most-commonly used relative chronology for the Predynastic period in Egyptian (Greene, 2006).

A number of researchers have attempted to refine the relative chronologies with radiocarbon dates (e.g., Hassan, 1980b, 1984b, 1985, 1988; Savage, 1998, 2001b). These efforts provide the following dates: Naqada IA–IIB (3900–3650 BC), Naqada IIC–IID2 (3650–3300 BC), Naqada IIIA1–IIIB (3300–3100 BC), Naqada IIIC1 (3100–3000 BC), and Naqada IIID (2900 BC and after) (Hendrickx, 1996). The number of available chronologies, time differences among them, and variations in naming conventions (Table 2.1) have created much confusion in interpreting the archaeological evidence for Egypt's past. On the other hand, the development of regional chronologies has fostered a reinterpretation of existing data (Savage, 2001a). With a few exceptions, the remainder of this discussion focuses on cultural developments in Upper Egypt. When necessary, contemporary developments in Lower Egypt are considered.

2.2.1 Nile Valley Neolithic: Merimde and Badari

The era commonly referred to as Predynastic loosely refers to the appearance of settled, agricultural communites and can be divided into two phases. From the early phase, scholars recognize two distinct culture groups. Although there is some disagreement on the exact temporal spans of each, they are thought to be roughly contemporaneous, only separated by geography (Trigger et al., 1983). In Lower Egypt, the Merimde culture centered at sites around the Fayum and the site of Merimde in the southern Delta. In Upper Egypt, the Badarian culture was centered around large sites at el-Badari and el-Hammamiya. Our knowledge of these two groups comes from different lines of evidence. The Merimde culture is known primarily from excavations of settlements, while cemeteries have contributed more data on the Badarian culture (Midant-Reynes, 2000b).

In Egypt, the earliest archaeological evidence for populations practicing at a least some degree of agriculture comes from the Fayum region. Investigation of sites that date to the mid-sixth millennium BC along the beaches of Lake Fayum have produced remains of emmer wheat and six-row barley (Hendrickx and Vermeersch, 2000:33). By about 5000 BC at the site of Merimde on the southwest edge of the Delta, settlement took on a formal, village organization, as inhabitants there constructed oval-shaped houses that were densely organized along narrow streets. The presence of grain storage pits inside the houses suggests that family units operated with some degree to economic independence. Human burials frequently occur among the houses, but the small number of graves and demographic profile—a low proportion of adults, especially males—suggest that juveniles may have been originally buried within the settlement, while most adults were buried in areas that only later became occupied by houses (Hendrickx and Vermeersch, 2000:33).[1] On the other hand, the burial of the dead within the village space may reflect real differences from contemporary burial practices in Upper Egypt. The lack of grave-goods within burials at Merimde is a less ambiguous departure from the usual practice further south (Spencer, 1993:21).

[1]The burial of infants and young children within settlement areas also occurs at sites in Upper Egypt, a practice that factors into the under-representation of these individuals from cemetery samples—a point discussed later.

In the south, the Badarian culture represents the earliest-known Upper Egyptian group using agricultural practices to some degree. Prior to the early fourth millennium BC, though, agricultural food production was likely only a supplement to other, well-established subsistence strategies. Inhabitants of the region would have exploited multiple ecological zones (i.e. the river, its immediate floodplain, and the surrounding desert areas), which is supported by isotopic studies of faunal and human remains (Thompson et al., 2005). Remains of emmer wheat, six-row barley, lentils, tubers, as well as remains of domesticated sheep and goats occur at Badarian sites (Watterson, 1997; Wengrow, 2006). These groups do not appear to have relied heavily on hunting, though fishing may have constituted the major economic activity (Hendrickx and Vermeersch, 2000).

Temporally, the Badarian culture dates to at least about 4400 BC, though results of thermoluminescence analysis on Badarian ceramics suggest it may date as early as 5000 BC (Hendrickx and Vermeersch, 2000:36). Origins of the Badarian culture remain elusive. Once thought to only exist in the area near el-Badari, characteristic Badarian finds have been recovered to the south at Hierakonpolis and east at Wadi Hammamat (Hendrickx and Vermeersch, 2000). Artifactual evidence suggests affinities with Neolithic groups in the Western Desert (Midant-Reynes, 2000b), while bioarchaeological analysis of dental traits cannot rule out possible influence from the Levant and Eastern Desert (Irish, 2006).

In contrast to the Neolithic communities in the north, Badarian sites lack evidence of permanent habitation structures. Badarian settlement sites, such as Matmar, Mostegedda, and el-Hammamiya, consist mainly of hearths, trash deposits, and grain storage pits (Spencer, 1993). Small hamlets appear to have been occupied, then moved horizontally after short periods of time. Excluding graves of young children that were often placed in areas of abandoned settlement, Badarian burials generally occur in cemeteries located away from settlement. Graves were typically shallow, oval-shaped pits. Common treatment of the body included a flexed position with the head oriented south and facing west (Castillos, 1982). The individuals were commonly interred with belongings such as jewelry, pottery, reed mats, and, occasionally, wrapped in an animal hide (Midant-Reynes, 2000b). Further, signs of social stratification, which had been virtually nonexistent to this point, begin to show as unequal distribution of grave goods in Badarian cemeteries (Hendrickx and Vermeersch, 2000).

2.2.2 Naqada I

The early Naqada I phase in Upper Egypt shows little difference from the Badarian period, though significant differences in material culture develop over a relatively short period (Midant-Reynes, 2000a). Unfortunately, compared with the amount of data from Naqada I mortuary contexts, evidence of settlement has been less forthcoming. This may be in part due to the nature of land-use practices during this period (Midant-Reynes, 2000a:49). The mud and organic materials used to construct houses have not survived well. Where better preserved remnants of habitation structures do occur, such as in Naqada I levels at el-Hammamiya, Mostegedda, and Naqada (from which Petrie developed his original chronology), it appears that residential structures commonly consisted of small, circular huts as evidenced by post holes and features identified as hearths (Wengrow, 2006:78–79). Although settlement areas have not produced much information regarding subsistence practices, offerings in burial contexts suggest that hunting, mostly of gazelle, continued to be important, as did herding of goats, sheep, and pigs, based on the common occurrence of what are interpreted as animal enclosures. Also, there is evidence that barley, wheat, and peas were cultivated (Midant-Reynes, 2000a:49).

Most of our knowledge of the Naqada I phase comes from cemeteries. Similar to the preceding Badarian period, early Naqada graves tend to be small, oval-shaped pits, and bodies are commonly found lying on top of a reed mat, on the left side with the head oriented south and facing west (Castillos, 1982; Midant-Reynes, 2000a). Single burials are the norm, although double burials do occur. In these instances, the grave usually consists of an infant with an adult female (Castillos, 1982). Burial customs started to become more differentiated during the Naqada I. Small numbers of larger, rectangular graves, sometimes with wooden coffins are found at a number of sites, including Hierakonpolis and Naqada. These larger graves are typically separated from the rest of the cemetery and contain more (and more-elaborate) artifacts such as painted pottery, figurines, cosmetic palettes made of stone, and mace-heads (Spencer, 1993). Increasing social differentiation, as implied by the larger, "wealthier" graves, is argued to represent the emergence of a class of chiefs (Midant-Reynes, 2000b). As described below, this pattern continued to an even greater degree throughout the Naqada II phase.

2.2.3 Naqada II

Major transformations took place during the Naqada II phase (ca. 3500–3200 BC). The differences in Naqada I and Naqada II prompted early scholars to view the latter as representing a population of Asiatic invaders. As more and more evidence accrued, it became clear that the the Naqada II developed out of the Naqada I (Midant-Reynes, 2000a), effectively putting the "invasion" hypothesis to rest. Increases in social differentiation and cultural complexity manifest in nearly every aspect of material culture: settlement, burial, craft specialization, and differential access to prestige items (Bard, 1994a; Geller, 1992; Midant-Reynes, 2000b). Since the data for this study largely represents the Naqada II phase, developments that took place during this time in Upper Egypt deserve detailed consideration.

Over the Naqada II phase, many settlements grew larger, with some growing into towns and, eventually, urban centers. Strings of agricultural villages began to cluster near the river, resulting in an increase in both number and size of associated cemeteries (Midant-Reynes, 2000a). People began constructing residential units out of more-permanent materials, abandoning simple combinations of mud and plant material. Large, rectangular buildings with stone foundations became increasingly common. By the end of Naqada II phase, the larger population centers became nucleated and surrounded by defensive walls (Midant-Reynes, 2000b). Increases in the sophistication and artistic styles of ceramic production, copper metallurgy, bread and beer production, and stone working, as well as expansion of specific production areas for different technologies, suggest that division of labor related to craft specialization would have created the need for a subsistence economy productive enough to support a nonagricultural portion of the population, at least for part of the year (Midant-Reynes, 2000a:52).

Sites were located in areas where groups could exploit resources in a number of ecological zones: river, floodplain, wadi, and low desert. By this time, agriculture and animal husbandry had taken over as the primary subsistence activities. In an analysis of diet during the Predynastic at Hierakonpolis and Naqada, Greene (2006) concluded that wheat bread and raw vegetables likely played a primary role in the diet of the nonelite segments of the population at both sites. Naqada II peoples exploited a number of domesticated species, including cattle, goats, sheep, and pigs. The presence of dogs in burials at Adäima, located about 30 km north of Hierakonpolis, suggest that they held a special status (Crubézy et al., 2002). Fish continued to be an important resource, while hunting of wild animals (e.g., gazelle, hippopotami, lions, etc.) slowly became an activity restricted to elite groups.

In the latter part of the Naqada II, a number of factors probably contributed to a gradual movement of populations closer to the floodplain. A climatic shift to more arid conditions resulted in reductions in the level of annual Nile floods, which would have reduced productivity in the wadis. At the same time, the low desert ecosystem may have been more affected by human agents, as acacia and tamarisk trees were used to fuel kiln fires. These events would have left the floodplain as the best choice for concentration of settlement in order to be closer to agricultural fields (Hoffman, 1982; Hoffman et al., 1986).

Burial treatment during the Naqada II generally follows earlier patterns (flexed bodies, head oriented to the south, facing west), but variation in positioning increases over time (Castillos, 1982). Double burials become more common in some regions, coffins continue to be used (Castillos, 1982; Midant-Reynes, 2000a). The construction of rectangular graves increased during the Naqada II, and these tend to be larger and wealthier (i.e., more grave goods) than those from the the Naqada I phase (Castillos, 1982; Midant-Reynes, 2000b). Some of these rectangular graves were lined with bricks, partitioned, and had roofs (Spencer, 1993).

Over time, the mortuary program became more and more diversified, reflective of social differentiation among the population. During the early Naqada II, social hierarchy is evidenced by the quantity and variation in materials and types of artifacts, burial architecture, and location of the burials (Rowland, 2003). Though wealth does not necessarily relate to social status in many parts of the world (Cohen and Middleton, 1967), they do appear to have been highly correlated in Predynastic and Dynastic Egypt (Bard, 1989; Rowland, 2003). Cemeteries associated with Naqada II gradually displayed an ever-increasing range of grave types. Tomb internments become rarer throughout the period, but those that have been examined are larger and have more elaborate architecture (Midant-Reynes, 2000a). Within sites, spatial segregation of cemeteries differentiated by grave wealth (e.g., size quantity of grave goods, nonlocal grave goods, etc.) occurs at larger sites, such as Hieraknonpolis and Naqada (Friedman, 1994). In elite cemeteries, separation of grave goods from the body became common and more deliberate. Disarticulation of the body and body wrapping also appear at this time (Midant-Reynes, 2000a).

Most of these changes are interpreted as resulting from an increase in social complexity that would eventually form the Egyptian bureaucracy of the Dynastic Period. With the adoption of agriculture and the urbanization of the largest sites along the Nile Valley, activities and choices available to people began to change. The potential for an agricultural surplus of storable, cereal grains may have allowed some people to be relieved of farming chores (Allen, 1997). These individuals could represent the skilled craftspeople thought to have begun specializing in different production activities during Nagada II. Ultimately, this process provided a source for a prestige-good economy, so that by the end of the Naqada II, elite members of society had access to the status symbols that would distinguish them in death (Bard, 2000; Wilkinson, 1999).

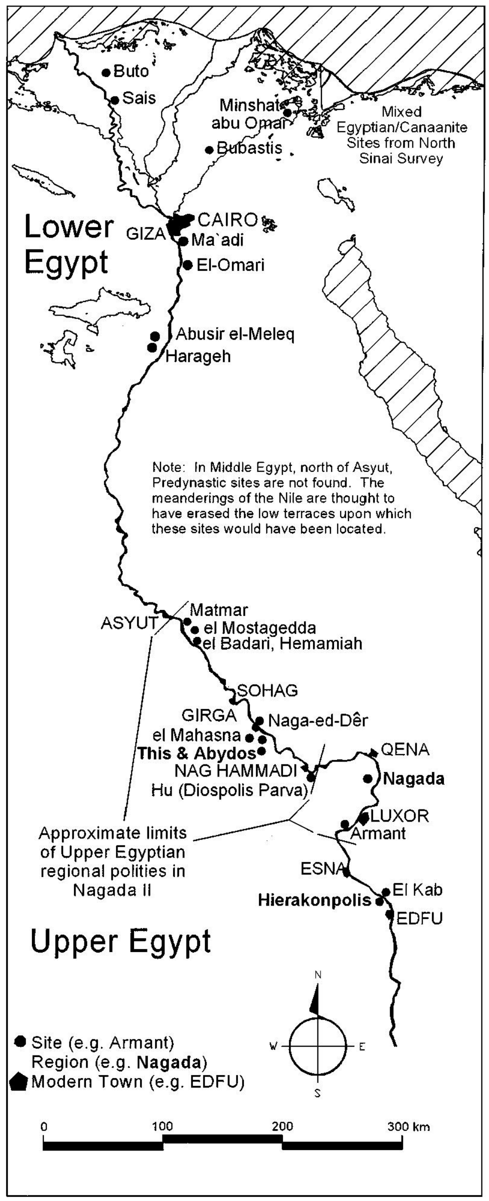


Figure 2.2: Major Predynastic sites and hypothesized Upper Egyptian "polities" in relation to modern towns (Savage, 2001a:103).

2.2.4 Naqada III

Naqada III (ca. 3200–3000 BC) is the final phase of the Predynastic period. By the end of this period, Upper and Lower Egypt had unified into a large, territorial state. As early as the beginning of the Naqada III, cultural traditions in the north had been replaced by those from Upper Egypt. Artifacts originating from Naqada cultural groups in Upper Egypt replaced material culture in sites to the north and had spread south towards Nubia. A consolidation of power in Upper Egypt preceded political unification of Upper and Lower Egypt (Bard, 2000). Settlements, as well as the majority of the population had moved closer to the river valley, and larger centers included monumental architecture such as palace and temple complexes (Hoffman et al., 1986; Hassan, 1993). As larger settlements became more urbanized, desert settlements declined, and agriculture began to dominate the subsistence economy (Midant-Reynes, 2000b).

Anthropologists have contributed to the literature debating the various explanations of the development of the Egyptian state. Early causal factors, such as the need to control irrigation projects (Wittfogel, 1957) and population pressure vis-á-vis Carneiro's circumcription model (Carneiro, 1970; Bard and Carneiro, 1989) have subsequently been rejected. The annual Nile floods mitigated the need for large-scale irrigation (Endesfelder, 1984), while it is generally accepted that population density was insufficient to create circumscription (Hassan, 1988; Allen, 1997; Wilkinson, 1999) because the productivity of the floodplain was always sufficient to support the people. The yearly harvest was such that the Egyptians never needed to develop a system of multiple harvests until the Roman period (Wengrow, 2006). On the other hand, population density, not necessarily growth, may have resulted in locally-circumscribed areas (Harlan, 1985). What emerged at the end of the Naqada III phase was likely the result of many interacting factors—trade, iconography, descent group competition, etc.—that influenced the developmental trajectory of the Egyptian state. As Kemp (1989) suggests, a probable scenario is of a gradual process in which smaller villages coalesce eventually becoming the "proto-kingdoms" of Upper Egypt—a process that may have begun as early as the Badarian period.

2.3 The Predynastic at Hierakonpolis

Hierakonpolis is an expansive, multi-component site located on the west bank of the Nile in Upper

Egypt, about 95 km south of Luxor and 750 km south of Cairo (Figures 2.2 and 2.3). The site's name means "City of the Hawk" and relates to the falcon-headed god Horus, the Dynastic town's patron deity. The site is also sometimes called Nekhen, referring to the ancient walled town that currently lies surrounded by modern cultivated land.

The Predynastic area, which runs 1.5 km along the desert edge and 3.5 km into the desert, may have been settled by about 4000 BC and quickly grew to be a major population center in the region (Hoffman, 1987). The site contains cemeteries of different social groups, settlement areas, ceremonial sites, and craft production locations (Hoffman, 1982). The site is considered to be a regional capital during the the Naqada period (Wilkinson, 1999).

Several artifacts suggestive of the site's importance have been discovered. The most well-known object is the Narmer Palette, a large, slate palette with a relief showing the defeat of a group of people—thought to represent Egyptians from Lower Egypt—by one individual identified as Narmer, a leader of Upper Egypt. Artifacts made from nonlocal materials such as lapis lazuli and obsidian, as well as ceramics from Palestine provide evidence of extensive trade networks and indicate that the inhabitants at Hierakonpolis had the ability and power required to procure this material and information (Friedman and Adams, 1992).

2.4 Population at Hierakonpolis

As Milner and colleagues (2008) note, any paleodemographic analysis must operate within a theoretical framework of population processes based largely on empirical evidence from the archaeological record. Thus, in order to interpret the paleodemographic data from HK43, it is necessary to consider other lines of evidence for population growth (or decline). This section provides a summary of the archaeological evidence for population growth at Hierakonpolis.

2.4.1 Settlement Patterns

There are three distinct physiographic zones at Hierakonpolis: alluvium, the relatively flat desert terraces, and desert hills (Hoffman, 1982). Settlement areas do not appear to have been uniformly dispersed, but locally aggregated. Further, the diverse nature of site location in the larger concession area suggest that site location was likely influenced by resource distribution. This may be the reason

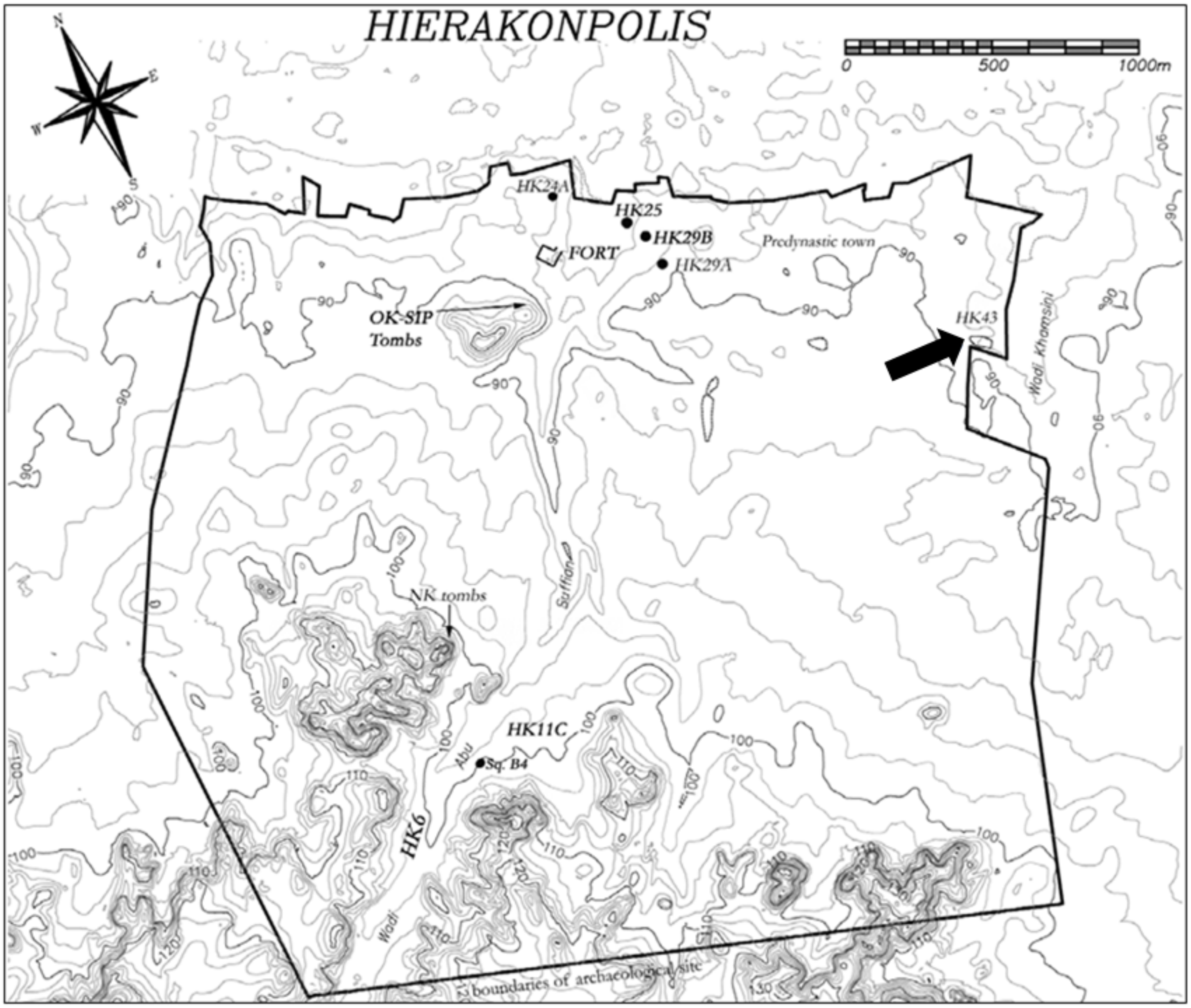


Figure 2.3: Topographic map of the Hierakonpolis concession (Friedman, 2006:2). Boundaries of the archaeological site and major localities marked; HK43 marked by arrow.

Hierakonpolis exhibits a settlement pattern somewhat atypical for the Predynastic in that settlement runs both parallel and perpendicular to the river.

Hoffman et al. (1986) suggested that Hierakonpolis was first used as a seasonal campsite and later settled during the early part of the Naqada I phase. Regional surveys illustrate that the site was likely a major population center during Naqada I and II phases (Hoffman, 1982). During the Naqada I–Naqada II transition, settlements began to shift away from the low desert toward the floodplain. Hoffman suggested that the annual Nile floods likely limited settlement growth by limiting the cultivation zone, but toward the end of the the Naqada I phase, Nile flood level decreased, opening up more land for settlement and agriculture.

Production, herding, and settlement areas at Hierakonpolis were located in the low desert (Hoffman, 1982). Harlan (1985) suggests that dwellings within the central area were arranged in a variety of ways.

Some were spaced far apart and surrounded by large, fenced-in areas, while others shared common walls. Over time there was a tendency for dwellings to become more densely arranged. The urban center was surrounded by outlying settlements that extended northwest and southeast along the valley and low desert for approximately 2 km (Harlan, 1985).

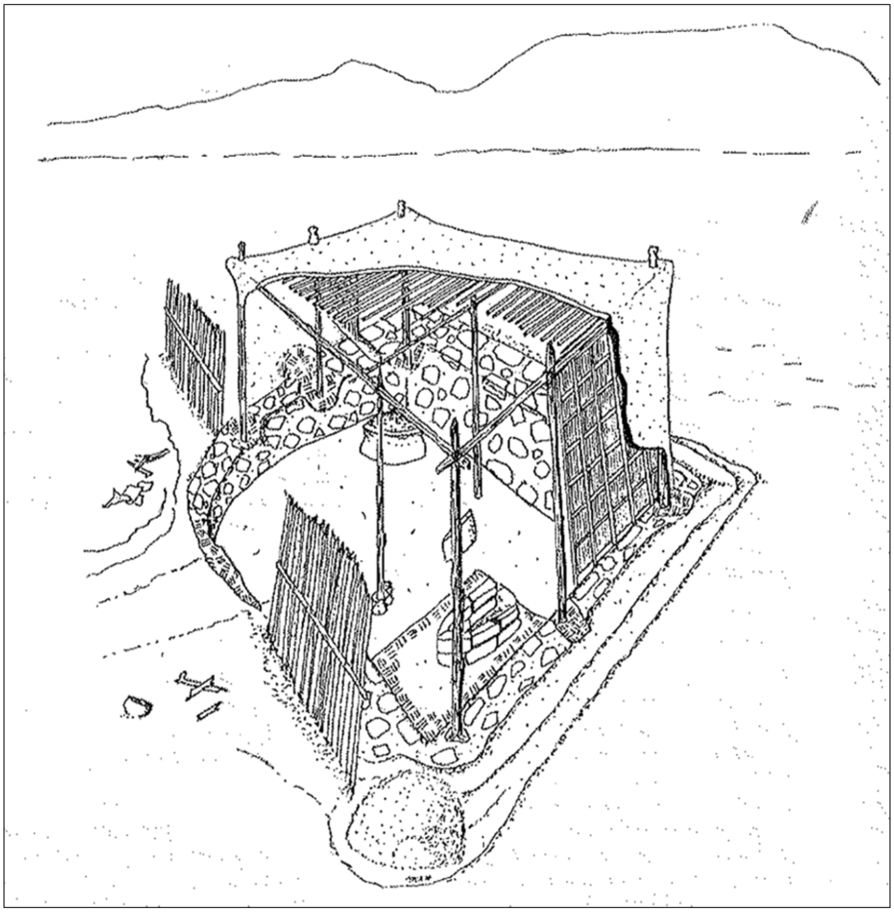


Figure 2.4: Reconstruction of a house from Locality 29A, Hierakonopolis (Hoffman, 1982:138).

Using Hierakonpolis to investigate urban development in prehistoric Egypt, Hoffman et al. (1986) divided occupation there into six phases: colonization, growth, centralization, political hegemony, provincialization, and decline. They suggested that populations from the north began settling in the Hierakonpolis area about 4000 BC. At this time, the local population was practicing a mixed-subsistence strategy, including farming and pastoralism (Wengrow, 2006). Settlements were probably small, with two to three residential communities scattered throughout both the riverine and desert savanna ecosystems (Hoffman et al., 1986:178). Results of the analysis of burials suggest that cultural features of the mortuary system were well established by this time, with sufficient evidence for the presence of social ranking, interpreted to reflect tribal social organization (Castillos, 1982; Hoffman

Table 2.2: Published estimates of Naqada I–II population size at Hierakonpolis based on settlement data.

Source	Range	Midpoint/"Best" Estimate
Hoffman (1982)	2544–10,922	5000
Hassan (1984a)	1500–2500	2000
Harlan (1985)	–	1500

et al., 1986).

Toward the end of the Naqada II into the Naqada III, there appears to have been a reduction in areal coverage at the site. By about 3500 BC, settlements become concentrated on a narrow strip about 300 m wide parallel to the current line of cultivation, and cemeteries shift to the edge of the alluvium, farther away from the desert wadis (Harlan, 1985). Despite the reduction in area, though, there does not appear to have been a similar reduction in population. During later stages of the Naqada II, settlements become more densely inhabited with agglutinated architecture

Based upon density and area of settlement, (Hoffman, 1982:132–137) has estimated that the population of Hierakonpolis ranged from 2,455 to 10,922 individuals and favors the higher figure. Using a formula for rural settlement in southwestern Asia, Hassan (1984a:14-15) argued for a more conservative estimate, more likely in the range of 1500 to 2000 people. Applying Hassan's (1981) density formula of 61 persons/km^2 for the Nile Valley during the Naqada II phase, Harlan (1985:233) obtained a similar estimate of about 1500 individuals.

2.4.2 Migration

As to why groups initially colonized the Hierakonpolis region, both "push" and "pull" factors would likely have affected those decisions. Hoffman and colleagues (1986:178) argue that groups had an incentive to settle the area due to population growth to the north and the "innately expansionist nature" of groups practicing a mixed-subsistence strategy of farming and pastoralism. Further, they argue that Hierakonpolis, because of its particular location, was an attractive area for settlement because of the following: (1) the site was at the center of a relatively small region covering several ecozones; (2) the land had good soil and raw materials; (3) availability of regular summer rainfall; (4) the presence of a Nile channel near the desert border; and (5) the hydraulic features of the Wadi Abul Suffian (Hoffman et al., 1986:178).

The degree to which migration contributed significantly to population growth is elusive. As mentioned above, the natural ecology of the site would have attracted groups moving toward the Nile Valley from desert areas. However, there is little biological or artifactual evidence supporting a hypothesis of large-scale migration into the area (Irish, 2006; Zakrzewski, 2007). On the other hand, it seems unreasonable to view the population at Hierakonpolis as one closed to migration. The question, though, is: can one assume that *net* migration was effectively zero? If so, then Hierakonpolis may be treated as a closed, stable population whose dynamics were governed by fertility and mortality alone. Trigger (1987) suggests that the northward expansion of the Naqada culture during the Naqada II–III period was due to emigration from refugees moving from emerging kingdoms in the south. This is a plausible scenario, given that by the First Dynasty, the north exhibited a higher population density than the south (Mortensen, 1991). Thus, in the long run during the period of cemetery use at HK43, immigration and emigration may have nearly balanced each other.

2.4.3 Mortuary and Bioarchaeological Evidence

Compared with methods using the data described above, paleodemographic analyses based upon osteological data from ancient Egypt are relatively few. This results from the fact that, relative to other disciplines related to Egyptology, bioarchaeology is a young discipline in Egypt (Zabecki, 2009). This is ironic, considering that cemeteries have been the focus of excavations in Egypt since the middle of the 19th century. Paleodemographic data have previously been interpreted as reflective of populations under a system of high mortality and relatively low fertility. Under this demographic regime, the populations in Upper Egypt, including Hierakonpolis, would have struggled to grow and support the processes leading up to unification. If the population size was, in fact increasing, we need testable hypothesis of the underlying mechanisms of this process.

In 1969, Brunetto Chiarelli of the University of Turin and Don Brothwell of the British Museum of Natural History organized a symposium on population biology of the early Egyptians. In 1972, those symposium papers were published together in the first volume of the *Journal of Human Evolution*. Here, Masali and Chiarelli (1972) produced one of the earliest paleodemographic analyses using a large skeletal series from prehistoric Egypt, though most of their sample dated to the Dynastic period. In addition to the small proportion Predynastic individuals, most of their sample consisted only of skulls, limiting the accuracy of age and sex estimation.

Most investigations of Egyptian paleodemography have been informal, with researchers basing interpretations upon the then standard approaches (see Chapter 3), such as calculating the mean age-at-death and average life expectancy (e.g., Masali and Chiarelli, 1972) or creating abridged life tables (e.g., Podzorski, 1990). In general, these authors have concluded that Predynastic populations experienced low fertility and high mortality. Average life expectancy is thought to have been between 20 and 30 years for both men and women (Masali and Chiarelli, 1972). Podzorski (1990) arrived at similar estimates based upon her analysis of a small portion of a skeletal collection from the site of Naga ed-Der. The majority of people buried in the cemeteries at Naqada and Cemetery N7000 at Naga-ed-Dłr died between the ages of 20 to 39 years (Podzorski, 1990).

Since 1989, a French team headed by Beatrix Midant-Reynes and Éric Crubézy have excavated Predynastic and Dynastic cemeteries at the site of Adaïma, which is located about 30 km north of Hierakonpolis. Excavations at two cemeteries there have provided some additional paleodemographic information (Coqueugniot et al., 1998; Crubézy et al., 2002), with a life expectancy at birth estimated to be about 20 years. Adäma is a special case, though, as it has two cemeteries that seem to be differentiated based upon age. Unfortunately, detailed demographic data for the main necropolis are not published. It is interesting to note that there is evidence of tuberculosis at Adäma, where the majority of burials date to the Naqada III phase—about 200 year after the burials recovered at HK43. This is not entirely surprising since epidemiological theory predicts an increase in disease load, as increases in population size and density create an environment conducive to the spread and maintenance of infectious diseases.

2.4.4 General Health and Paleoepidemiology

Information about the health of the individuals from the main data set at Hierakonpolis is just coming to light, as newly collected data are beginning to be analyzed and published. Greene (2006) reconstructed dietary patterns of the individuals buried at HK43 using dental data. Based on the low frequencies of antemortem tooth loss, attrition, and caries, she concluded that the people had access to a good diet. Studies of the dental microwear "suggests that cultivated grasses (emmer wheat), raw vegetables, and probably meats and fish were being eaten by the working class at Hierakonpolis" (Greene 2006:256). She also stated that there was good childhood health, based on the relative lack of dental enamel hypoplasia (Greene 2006:257). This work was a major contribution to the study of Hierakonpolis as well as the study of ancient Egypt.

Contrary to previous thought, Zabecki (2009) concluded those represented at HK43 were not overly stressed due to labor activities, as evidenced by low scores at muscle attachment sites. Using a health index developed for archaeological populations in the Western Hemisphere (Steckel and Rose, 2002), Larsen (2009) found that Hierakonpolis scored very high (indicating better health), particularly in parts of the index related to childhood health. Finally, studying paleopathological data, Kumar (2009) found relatively low frequencies of non-specific markers of stress and interpreted those results to indicate that the people buried in cemetery HK43 had access to adequate nutrition and that parasite loads were low and their immune systems were strong enough to counter infections.

2.5 Summary

Based on the above discussion, a picture emerges in which one may frame the demographic experience of the population represented by those interred at HK43. Based upon the available archaeological and bioarchaeologial data, current interpretation of the population dynamics for the nonelite population at Hierakonpolis may be summarized as follows:

1. *The population was growing.* Based upon the expansion and diversification of settlements at Hierakonpolis, it is reasonable to assume that all segments of society experienced population growth. Mortuary data confirms the emergence of an elite class and provides evidence of craft specialization, which suggests the development of an additional, nonagricultural segment of the population—artisans and *skilled* laborers. An increase in the number of strictly consuming, nonagricultural individuals in the population would have likely required growth in a healthy population of agricultural workers (i.e., the nonelites of HK43).

2. *The population may be characterized as one experiencing an expansion regime.* As noted above, although regional populations were growing, population density in the Nile Valley was low during the Naqada period. This type of population may be defined as food-limited, as opposed to space-limited. As Lee and colleagues (2009) point out, the opportunity for geographic expansion

has a number of consequences potential for population growth and the time before equilibrium population densities cause density-dependent checks to take hold (Shennan, 2009).

3. *Migration had a negligible effect on population growth.* In reality, very few populations are going to be completely closed to migration. The osteological data (dental and cranial metrics and non-metrics) from HK43 do not support the argument that the population experienced a large influx of individuals from outside the region. Although it is very likely that nonelite individuals and families came to Hierakonpolis, it is reasonable to assume that this occurred within the context of kin-structured migration, in which members of the population were also leaving the population and joining communities at different points along the Nile Valley. This would have aided the elite at Hierakonpolis in building ties with other emerging leaders within the region and in neighboring polities. The result was that net migration was probably very small.

Chapter 3 Paleodemography

Paleodemography may be broadly defined as the study of past population dynamics. Within biological anthropology, this usually refers to the analysis of age and sex distributions from archaeological assemblages of human skeletal remains, or *osteological* paleodemography, though there is much more to paleodemography than just skeletons (e.g., Hassan, 1981; Paine, 1997a; Chamberlain, 2006). Some have even gone so far as to state that paleodemography "requires the most interdisciplinary efforts of all the fields of anthropology" (Meindl et al., 2008:603). Whether Meindl and colleagues overstated the case, the point remains that it is critical for any interpretation of paleodemographic results to be placed within a theoretical framework of the processes associated with population growth or decline, as determined from archaeological data, such as evidence of changes in settlement size and distribution (Milner et al., 2008).

After decades of practice, criticism, and re-evaluation, paleodemography remains a vibrant specialization within biological anthropology, despite its tendency to be "devilishly difficult" (Howell, 1976:25). This underscores the fact that many fields of study have an interest in prehistoric (as well as historic and modern) patterns of mortality and survivorship, fertility, and migration in human populations. Ultimately, these three demographic processes determine the fates of populations, which affects both micro- and macro-evolutionary outcomes. Unfortunately, the records typically studied by historical demographers only date back several centuries, and their reliability may be questionable, at least for those prior to the last couple hundred years. Thus, paleodemography has the potential to make significant contributions to our understanding of prehistoric and historic population dynamics. More broadly, paleodemographic studies may offer insight into trends in the evolution of human life history and longevity (i.e., maximum length of life). For these reasons, paleodemography stands as a bridge between anthropological demography and human evolutionary ecology (Roth, 2004).

This chapter provides an overview of the basic concepts and measures of demography, focusing on what we know about demographic variation in human populations. Interested readers may find detailed treatment of demographic theory and methods in a number of texts (e.g., Keyfitz and Flieger, 1971; Preston et al., 2001; Keyfitz and Caswell, 2005). The discussion follows with a review of historical developments within the field of paleodemography. This chapter concludes with a consideration of recent trends in paleodemographic method and theory.

3.1 Demography of Human Populations

Before looking at the demography of past human groups, it is informative to explore what is generally known about the demography of modern human populations. A good starting point for examining human demographic patterns is the timing of life-history events (i.e., birth, reproduction, and death). Even though all members within a species share a suite of evolved life-history characteristics, each individual varies in his or her probability of reproduction, death, and migration, all of which are highly structured by age. For example, the probability of death is generally highest among the very young and old, while rates of reproduction usually peak during the early and middle periods of adulthood (Chamberlain, 2006). Though migration is influenced by nonbiological factors (perhaps more so than fertility and mortality), it generally occurs most frequently among young-adults and their children (Rogers and Castro, 1984).

Humans and most large mammals share a reproductive-survival strategy termed K-strategy(Livi-Bacci, 2007). The K term stands for *carrying capacity*, a concept central to ecology and population studies. K-type organisms inhabit relatively stable environments and generally reach an equilibrium population size governed by available resources. This equilibrium results from the fact that K-strategy animals have few offspring (relative to r-strategy organisms like insects, fish, and small mammals) and, thus, slower rates of population growth. Because the environments occupied by K-strategy animals are generally stable, there is little selective pressure for individuals to have great numbers of offspring; rather, increased parental investment in fewer offspring, who have higher rates of survival, characterizes K-strategy animals. These demographic strategies and the current structure (the number of individuals by age/sex) of a population are determined by age-specific vital rates (i.e., mortality and fertility), migration, and population growth.

A living population's age/sex structure is often recorded during a census, which also contains information on the structure of a mortality sample taken from that population. Generally, the age distribution of deaths produced by a living population over a given period of time will look different than the living age structure (Chamberlain, 2006). This is due to a number of factors, one being that in most populations, the risk of death varies considerably with age and results in a proportionally greater number of deaths in high-risk ages (i.e., often the very young and very old). Even within an age-cohort, individuals are not homogeneous in their risk of death, or *frailty* (Weiss, 1990). Further, the age distribution of deaths is not a function of mortality alone, but is also influenced by fertility and migration, which greatly impact the living age distribution from which deaths come. The subsections below consider what is known about mortality, fertility, and growth in human populations. Since paleodemographers necessarily deal with the dead, a good starting point is mortality.

3.1.1 Mortality

Mortality is a measure of deaths as a component of population change and can be measured in a number of ways. The *crude death rate*, often simply referred to as the *death rate* (d), is the number of deaths per 1,000 individuals in a population per year. According to publicly available data from the World Bank (http://data.worldbank.org/indicator/SP.DYN.CDRT.IN), from 2007 to 2011, averages for nation-level crude death rates range from 1 to 17 per 1,000 people per year. As a measure of population health, though, the crude death rate can be misleading. A population's age structure affects the death rate; for example, a population with a high proportion of old individuals will have a high death rate. Thus, the death rate, itself, may not necessarily reflect actual health conditions or other factors.

Since most demographic measures, mortality included, vary with age, they are often presented as age-specific rates. Age-specific death rates—also known as the central death rate, or force of mortality ($\mu(a)$)—are calculated by dividing the number of deaths at age a (or in a given age interval) over the number of individuals in the population at age a (usually multiplied by 1000). Demographers, including paleodemographers, are often more interested in the variation in age-specific death rates, rather than crude death rates. Empirical data from contemporary (national) and historical populations (mostly from Europe over the last 400 years) suggest that human populations share a common age pattern of mortality. Generally, human mortality rates are highest at birth and during infancy, decrease in childhood until about the onset of puberty, then slowly increase until about 40 years of age, when mortality rates increase roughly exponentially with age (Keyfitz and Flieger, 1971; Wood et al., 2002). Because of its characteristic shape, the typical human mortality curve is commonly called the "bathtub curve" (Figure 3.1).

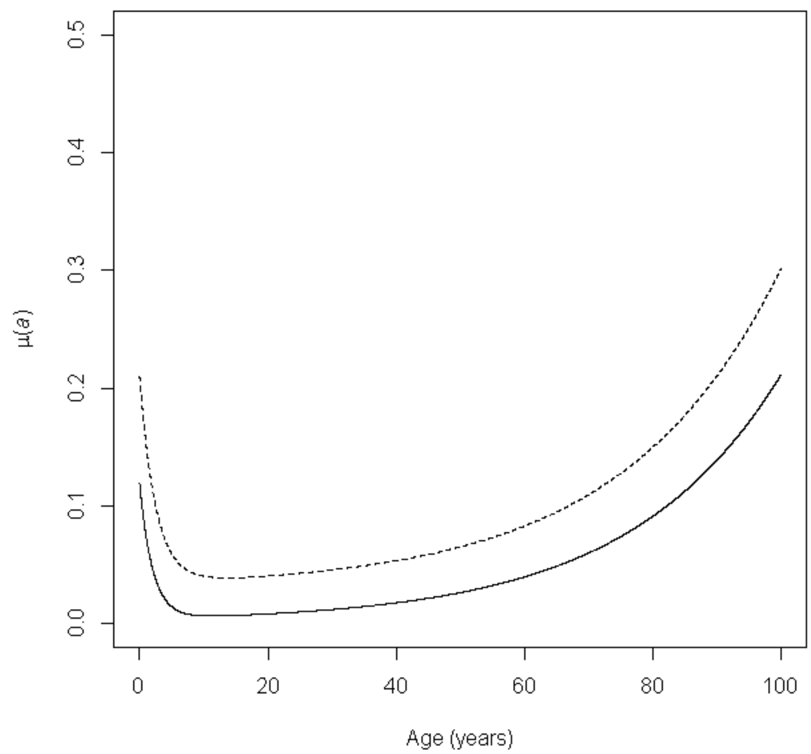


Figure 3.1: Characteristic "bathtub" shape of the general, human mortality curve. The two lines illustrate similar age patterns of mortality, but different *levels* of mortality.

Less is known about the mortality experience of small populations typically studied by anthropologists because data from these groups is often unknown and/or inaccurate. Whether collected ethnographically or archaeologically, demographic data for these groups may be affected by incomplete census coverage, lack of information on vital events (i.e., births and deaths), and misreporting of ages (Gage, 2010). In these circumstances, anthropologists often resort to indirect estimation using stable or stationary population methods (see below) to correct for these deficiencies. These issues notwithstanding, it seems that variation in mortality patterns among preindustrial and contemporary, ethnographic populations is low enough that several generalizations can be made about the age-specific mortality in these types of small populations.

As mentioned above, mortality rates are generally highest at birth and during the first year of life (Chamberlain, 2006). In a survey of published data from a over 50 ethnographic populations, including mobile hunter-gatherers, sedentary foragers, horticulturalists, and pastoralists/agro-pastoralists, Hewlett (1991) found that infant mortality—the percent of children dying during the first 12 monthes of life—was highly variable, ranging from 7.8% to 34%. This contrasts with modern, industrialized nations, where infant mortality is often around 1% (Hewlett, 1991). Prior to the modern demographic transition, characterized by a decrease in mortality rates across the entire lifespan (markedly so for infants), infant mortality rates were likely higher than those at any other age.

In contemporary populations, the rapid decrease in mortality rates to a low between 5 and 10 years of age (Gage, 1990; Wood et al., 2002) means that, generally, the juvenile period is one of high survivorship. At the same time, in small, ethnographic or preindustrial populations, the juvenile period is perilous, with about 20% to 56% of all children born dying before they reach 15 years of age (Hewlett, 1991). Typically, mortality rates remain relatively low until mid-adulthood, after which rise, eventually exceeding those observed during infancy (Wood et al., 2002). Additional features of the human mortality profile that appear to be more population-specific include an early childhood increase in mortality associated with weaning, an abbreviated increase in mortality during early adulthood associated with risky behavior (i.e., the "accident bump"), and a plateau in the risk of death for the oldest of the old with exceptional longevity (Gage and Mode, 1993). Generally, paleodemographers are not as interested in these minor deviations in human mortality as they are in broad trends over time and space.

Other than age, the most obvious biological covariate of mortality is sex. Demographic data for most contemporary, national-level populations show that, in general, females experience lower mortality rates than males (Lopez and Ruzicka, 1983). In some populations, females experience higher mortality rates in young adulthood, a phenomenon often linked to the dangers associated with childbirth during the peak years of fertility (O'Connor, 1995; Kruger and Nesse, 2006). On the other hand, the probability that females experience higher mortality rates than males is often higher in small, contemporary ethnographic populations (Gage, 2000). Higher levels of female mortality may have also been more common in prehistory (Angel, 1969; Acsádi and Nemeskéri, 1970). Investigations have attributed this modern trend of higher mortality among males to a combination of biological and behavioral proximate causes, as well as the interaction of cultural and environmental factors with evolutionary processes, such as sexual selection (Kruger and Nesse, 2006). Proximate causes like risky behavior can be linked to life history traits (e.g., the timing of reproduction, which affects when males enter into competition for status, resources, and access to mates). Thus, evolutionary theory, vis-á-vis life history theory, provides a framework for understanding the demographic patterns common in human populations.

While there seems to be general age pattern of mortality for our species, considerable variation in both the age pattern and level of mortality exists among human populations. The level of mortality affects the height of a mortality curve above the x-axis (again, see Figure 3.1) and is often presented by the summary measure *life expectancy*. Life expectancy is the average number of additional years that an individual could expect to live, given mortality rates remained the same until the end of his or her life. This measure may be calculated for any age, though the level of mortality is most commonly expressed by life expectancy at birth. Though age-specific mortality and overall mortality level appear to be correlated, these two features also exhibit independence (Gage, 1990; O'Connor, 1995). Populations at the same overall level of mortality may experience a different age pattern of mortality. Conversely, two populations with markedly different levels of mortality may exhibit a very similar age-pattern of mortality (Figure 3.1).

Demographers make use of a number of tools for representing mortality. One of the oldest and most popular tools for this is the ironically-named life table (Preston et al., 2001). A life tale includes a column of ages or age intervals (x) and a number of columns different quantities describing the mortality experience for a population or cohort of individuals (Table 3.1). One of the most widely used columns from a life table is l_x, or cumulative survivorship. The values for l_x range from from one to close to zero (the value for l_x after the last age or age interval is assumed to be zero since no one lives longer than the oldest observed age). Thus, survivorship is a strictly decreasing value with age. Other popular columns include the age-specific probability of death (q_x) and life expectancy (e_x). Even though the life table presents mortality information for discrete ages or age intervals, mortality is a continuous process. Alternative methods for modeling mortality as continuous functions of age (i.e., hazard models) are discussed later.

3.1.2 Fertility

For demographers, the term *fertility* refers to the number of children born to an individual, while

Table 3.1: Sample life table showing the most common columns; data from the 1967 US population (Keyfitz and Flieger, 1990)

x	q_x	l_x	d_x	L_x	T_x	e_x
0	0.0191	1.000	0.0191	0.983	74.25	74.25
1	0.0031	0.981	0.0030	3.916	73.27	74.69
5	0.0018	0.978	0.0017	4.886	69.35	70.91
10	0.0015	0.976	0.0015	4.878	64.46	66.03
15	0.0029	0.975	0.0028	4.867	59.59	61.13
20	0.0036	0.972	0.0035	4.851	54.72	56.30
25	0.0042	0.969	0.0041	4.832	49.87	51.49
30	0.0061	0.964	0.0058	4.807	45.04	46.70
35	0.0092	0.959	0.0088	4.771	40.23	41.97
40	0.0136	0.950	0.0129	4.716	35.46	37.34
45	0.0207	0.937	0.0194	4.635	30.74	32.82
50	0.0303	0.917	0.0278	4.517	26.11	28.46
55	0.0444	0.890	0.0395	4.349	21.59	24.27
60	0.0646	0.850	0.0549	4.113	17.24	20.28
65	0.1031	0.795	0.0820	3.771	13.13	16.51
70	0.1568	0.713	0.1118	3.286	9.36	13.12
75	0.2364	0.601	0.1422	2.651	6.07	10.09
80	0.3660	0.459	0.1681	1.876	3.42	7.45
85	1.0000	0.291	0.2911	1.544	1.54	5.30

fecundity refers to the physiological potential for childbirth (Gage, 1998; Chamberlain, 2006). Since the reproductive potential of females sets the pace of reproduction, discussions of fertility almost always mean *female* fertility. For anthropologists, of particular interest is the variation observed among so-called "natural-fertility" populations. Generally, natural-fertility populations are considered to be those not practicing deliberate birth control (in order to meet a maximum target size), and the term is often thought of as synonymous with fertility in preindustrial societies (Wood, 1990). Like mortality, fertility in human populations tends to follow a general pattern related to age. The age pattern of fertility seems to be less variable than the level of fertility observed in human groups. Generally, fertility peaks during young adulthood (early twenties), decreases slowly at first, then rapidly decreases to zero at about age 50 (Wood, 1990). This pattern is consistent in contemporary, industrialized populations, except that for these populations, the decline in fertility is much more rapid due to the use of birth control.

Fertility can be quantified in a number of ways. One of these, the *crude birth rate* (CBR or b), is the number of births per year per 1000 people. The CBR can be misleading, though, as larger populations

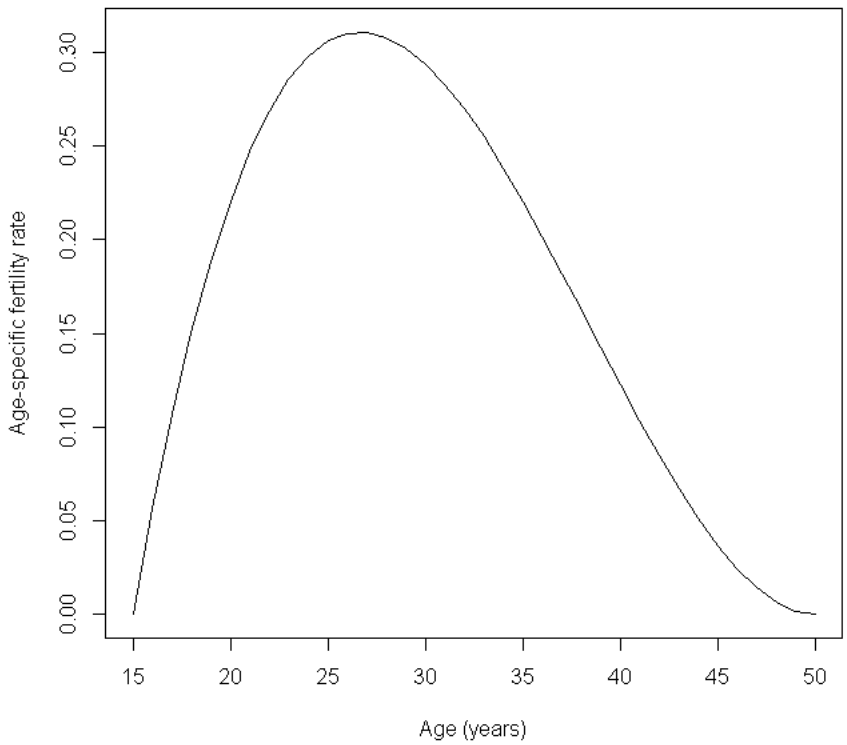


Figure 3.2: General shape of the human age pattern of fertility; modified from model fertility schedule in Gage (1998).

will typically have more children than smaller one, even if both have the same level and age-pattern of fertility. Thus, age-specific fertility rates (ASFR) are often a preferred measure of fertility since they effectively account for population size and a population's age structure. Age-specific fertility rates are often given for five-year age categories, beginning with 15–19 years of age and ending at age 45–49 years of age. Another useful measure of fertility is the total fertility rate (TFR). TFR equals the sum of the ASFR (multiplied by the length of the age interval, if reported as such). This summary measure equates to the average number of children born to a female who survives until the end of the reproductive period. TFR has been observed to be more variable, and generally higher, in natural-fertility populations than those practicing effective birth control.

A number of factors are known to directly affect fertility rates in human populations (Bongaarts and Potter, 1983). Wood (1990) lists at least nine proximate determinants of fertility, divided into exposure factors (e.g., age at first marriage, age at menarche, etc.) and susceptibility factors (e.g., length of lactational infecundability, length of gestation, etc.). These proximate, generally biological, determinants of fertility have been investigated in populations from developed nations, as well as contemporary, ethnographic populations.

For anthropologists, observations in small-scale societies are more relevant, particularly with respect to the response of fertility to changes in subsistence and mobility strategies, a topic central to the discussion of the Agricultural Demographic Transition (ADT)—a more-general term synonymous with the Neolithic Demographic Transition (Bocquet-Appel, 2009)—which began in some regions of world about 10,000 years ago. There is evidence that higher caloric intake among agriculturalists may result in improved ovarian function. Valeggia and Ellison (2004) focused on maternal nutrition and breast feeding behavior in an integrated model of maternal energetics to explain variation in ovarian function. The research of the Ache (Hill and Hurtado, 1996) and !Kung (Howell, 1979) generally support this model. Other attempts to account for a systematic relationship between fertility and subsistence often take a characteristic associated with an agricultural subsistence strategy and illustrate how it affects a proximate determinant of fertility. For example, Buikstra and colleagues (1986) suggested that the introduction of grain-based gruels may have lowered the weaning age of children, resulting in a shortened period of infecundability related to lactation. Similarly, Sussman and Hall (1972) argued that the effort related to child transport among foraging mothers would be incompatible with caring for more than one child at a time. Alternatively, Boone (2002:17) has suggested that, when looking at long-term trends, it may be more useful to consider *intermediate* determinants of fertility—factors that affect the overall energy budget of a household.

The relationship between subsistence and fertility remains unclear. Campbell and Wood (1988) found no significant differences in TFR across subsistence strategies—foragers, horticulturalists, and agriculturalists. Similarly, Hewlett (1991) found that pastoralists had slightly higher fertility rates than foragers, but the difference was not significant. On the other hand, Bentley and colleagues (1993) reanalyzed the data from the Campbell and Wood study, controlling for groups with high rates of sterility and the effects of closely related ethnic groups. They found that no significant differences between foragers and horticulturalists, though agriculturalists had significantly higher TFR than the other two groups. Sellen and Mace (1997) reported similar results in a cross-cultural study of fertility and subsistence strategies. Even still, in these analyses, the modal TFR for all subsistence strategies was about 6.0. These results suggest that increased sedentism and productivity associated with the initial experimentation in domestication cannot, by themselves, explain the increase in growth rates thought to be associated with domestication (Boone, 2002). What is clear from all of these studies is that fertility is just one factor affecting the dynamics of a population.

3.1.3 Population Dynamics

Even though the mathematics of these interacting demographic processes can be simple, their effects are sometimes counter-intuitive. As should be clear from the discussion above, the human demographic experience operates within highly variable range of fertility and mortality (and migration). An attempt to examine the population growth as a result of all possible combinations of the range of mortality and fertility schedules would be exhaustive and uninformative. A better approach is to consider what can be understood about the space of human population growth from a small number of summary measures for fertility and mortality. Taking the approach of Livi-Bacci (2007), one may view the area of human demographic space according to TFR and life expectancy at birth (e_0) with respect to population growth rate (Figure 3.3).

The figure above clearly illustrates how mortality and fertility generally relate to population growth. In the simplest terms, the change in population size over a given period of time depends upon the difference between births, deaths, and migration. In the absence of migration, then, rate of population growth (r) is the difference between the birth rate (b), death rate (d), which yields a basic demographic equation $r = b - d$. Since birth and death rates are not only functions of time, but also of the starting number of individuals, population growth is similar to the compounding of interest in a bank account (i.e., exponential growth). This characteristic feature may be expressed by the equation $N(t) = N(0)e^{rt}$, where N is the size of the population, t is time, e is the base of natural logarithms, and r is population growth rate. These properties are useful for examining the implications for certain rates of population growth. If one knows, or can approximate, population growth rate, the time it takes for a population to double in size takes the form $t = \frac{log(2)}{r}$.

Throughout the course of human history, there have been three notable increases in worldwide population growth associated with major cultural/technological shifts—the shift from hunting-foraging to agricultural food production and the shift from an agrarian lifestyle to the Industrial Revolution.

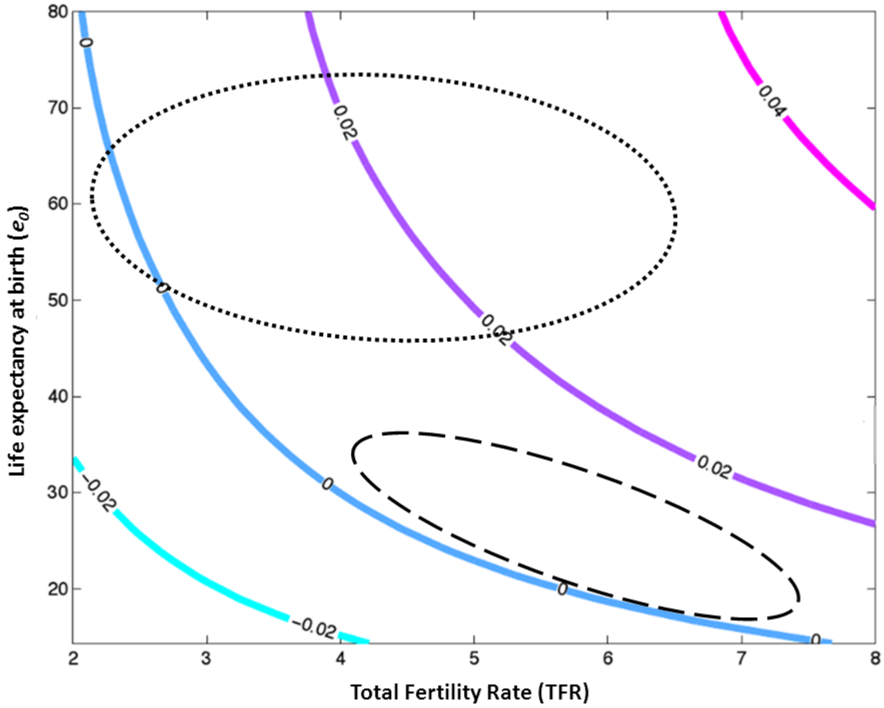


Figure 3.3: The human demographic space. Isometric curves representing different rates of population growth, as they relate to two demographic summary measures—life expectancy at birth and total fertility rate. The long-dashed line represents the general space occupied by prehistoric and historic populations; the short-dashed line represents the space for modern populations. Adapted from Livi-Bacci (2007) and Jones (2009).

More recently, human populations in developed nations have witnessed what is known as the "modern demographic transition," that is characterized by decreases in mortality (associated with better sanitation and advances in medical science) and a fertility decline.

There is a general consensus among scholars that, on average, human population growth during prehistory must have been very close to zero, maybe as low as about 0.008% up until about 10,000 years ago (Livi-Bacci, 2007). Assuming paleodemographic estimates of life expectancy at birth for prehistoric populations—about 20 to 25 years of age—are correct, the corresponding TFR would about 6, which is in agreement with the data from contemporary, ethnographic populations. Generally, modern developed nations exhibit much higher life expectancies and a wider range of TFR, resulting in a wider range of population growth rates.

Anthropological investigations of population dynamics, often concerning prehistoric or contemporary, ethnographic populations, have typically focused on ecological relationships and population growth (and/or density) in the evolution of social complexity (Paine, 1997b). Thus, these discussions almost always include the application of one of two contrasting models. The first model is that originally proposed by Thomas Malthus in his *Essay on the Principal of Population* (1798). Malthus recognized the "principle of populations" to grow exponentially, but argued that this system could not persist in the long term. He viewed population growth as constantly putting pressure on limited resources (i.e., food). According to this model, as a population grows, it will eventually hit a threshold that surpasses available resources. This, in turn, would cause poverty, and increases in mortality would effectively prevent further population growth. The importance of Malthus' concept that available food resources limits population growth cannot be overstated. This is exemplified in virtually any introductory text in biological anthropology that stresses the influence that Malthus' writings had on Charles Darwin and Alfred Wallace as they developed their ideas regarding the process of natural selection. Even today, ecological models of human population dynamics stress the importance of food (Wood, 1998; Lee and Tuljapurkar, 2008).

The contrasting model is that proposed by Danish economist Ester Boserup in *The Conditions of Agricultural Growth* (1965). Boserup's model turned the Malthusian perspective on its head, as population becomes an independent variable, extrinsic to the model itself. Here, population becomes a "prime mover" to technological innovation and culture change. For example, population pressure might cause an agricultural group that has run out of land to intensify cultivation by improving the land or changing land-use practices, thereby increasing production and facilitating even greater population growth. Boserup's model dealt specifically with agricultural economies, and suggested that the adoption of agricultural practices is a choice that groups make, once their size or density make foraging an untenable method of subsistence (Ellison and ORourke, 2000). In support of her thesis, she pointed to historical accounts of population decline, such as the collapse of the Roman Empire in Europe, that resulted in the "regression" to less intensive agricultural practices.

Each of these models has empirical support, but neither can explain all trajectories of cultural development throughout history. Malthus' model explains many historical processes in the short-term, whereas Boserup's model fits well to trends of sustained population increase. In reality, populations have probably gone through both types of growth during different phases of existence. Anthropological demographers (e.g., Lee, 1986; Wood, 1998) and economic historians (e.g., Artzrouni and Komlos, 1985; Steinmann and Komlos, 1988; Komlos and Nefedov, 2002) have noted that, in the past, populations most likely experienced both limitation and expansion regimes and have developed models that incorporate both Malthusian and Boserupian phases. In an attempt for develop a comprehensive theory of preindustrial population dynamics, Wood (1998:113) described what called the "MaB Ratchet" (MaB = Malthus and Boserup), a cyclical model Malthusian limitation and Boserupian expansion. While a population is undergoing a Boserupian expansion, quality of life improves, but, given enough time, the population will always return to a level of "marginal immiseration" (Wood, 1998:114). This type of density-dependent model appears to have some support from a meta-analysis paleodemographic data from over 130 sites in the New and Old World (Bocquet-Appel, 2009). Building upon Wood's work, Tuljapurkar and others (Lee and Tuljapurkar, 2008; Puleston and Tuljapurkar, 2008; Lee et al., 2009) have explicitly incorporated food availability, geographic space, and demographic parameters (i.e., fertility, mortality, and age structure) into a sophisticated model describing preindustrial population dynamics. Such models have much to offer paleodemography and, hopefully, will become adopted by researchers within the field.

From a historical perspective, anthropologists have used two main theories that define the effects of mortality and fertility on population age structure and growth rate—*stable* and *stationary* population theory. Both of these theories work under the assumption that populations are closed to migration (in or out). Stationary population theory assumes that fertility and mortality are constant and that the population growth rate is zero (neither growing, nor declining). Of course, it is extremely unlikely that any real population, in the long run, could have been stationary. This assumption, however unreasonable, and the mathematical properties that follow, are the basis for most life tables presented in the anthropological literature. This is especially true for paleodemographic life tables. In stationary populations, the birth rate and death rate are the same and equal to the reciprocal to the mean age-at-death, which is the same as life expectancy at birth. If the population is growing (or declining), these convenient relationships do not hold.

Stable population theory also assumes that mortality and fertility rates are constant, but allows for nonzero population growth. Thus, a stationary population is just a special case of a stable population. The mathematical relationships among birth rates, death rates, and age structure in stable populations were originally described by Lotka (1922). If subjected to a period of stable conditions, a population will eventually converge on its stable age structure, after which the proportion of individuals at each age (or in each age interval) remains the same, as the population increases or decreases at a constant rate. Empirical studies have shown that a population perturbed from its stable state (perhaps due to some type of mortality crisis) will regain its stable age structure in as little as 75 years, as long as fertility and mortality remain constant during that period (Gage, 2010). The importance of stationary and stable population theory to paleodemography is considered in more detail below.

3.2 Paleodemography

In the US, the earliest application of paleodemographic concepts and methods appeared with E. A. Hooton's work during the 1920's and 1930's at Madisonville (Hooton, 1920) in Ohio and Pecos Pueblo (Hooton, 1930) in New Mexico. Hootons primary interest was estimating living population size and survivorship from cemetery samples. Though he did not apply any published, formal demographic methods (e.g., Lotka, 1922), his work was well ahead of its time (Frankenberg and Konigsberg, 2006). It was not until J. Lawrence Angel, one of Hooton's students, began publishing on human longevity in ancient Greece (Angel, 1947) that paleodemography began to gain interest among skeletal biologists (Hoppa, 2002). Following Angel's early work, it became common to publish tables or graphs illustrating and comparing age and sex distributions between skeletal samples (e.g. Vallois, 1960; Johnston and Snow, 1961; Blakely, 1971). Even though these studies ignored much of the method and theory from contemporary demography, Armelagos and VanGerven (2003) point out that they were at least framing questions in terms of population processes during a period in which description and typology dominated studies in biological anthropology.

3.2.1 Early Critiques

Following the pioneering works of Angel (1947, 1969), paleodemography became more commonplace in bioarchaeological studies. During the 1970's, the developing field of bioarchaeology witnessed a boom in the publication of abridged life tables (e.g., Acsádi and Nemeskéri, 1970; Ubelaker, 1974; Lovejoy et al., 1977; Hassan, 1981; see Hoppa (2002) for more references), despite Angel's cautionary notes regarding the assumptions underlying such techniques (see below). It was during this period that paleodemography began receiving some of its earliest critiques.

Petersen (1975) was one of the first to criticize the then young field. As a demographer, he argued that (1) anthropologists studying past populations did not have a strong grasp of demographic theory, and (2) the nature of paleodemographic data (i.e., small samples of skeletons) force researchers in the field to use ethnographic analogy in models about past population dynamics. While some early paleodemographic studies certainly had methodological issues, these problems (and even some discovered by paleodemographers themselves) have been addressed over the years. It was Petersen's second criticism, related to the problems associated with small and incomplete samples and what they can tell us about past population dynamics, which has been more significant in the development of the field (Milner et al., 2008).

By necessity, our models of past population dynamics must, at least to some degree, rely on empirical observations of contemporary, ethnographic populations. Thus, the study of extant populations has often focused upon forager and horticultural groups, as well as historical records of preindustrial European populations. Although these populations are not truely analogous to the prehistoric populations of primary interest to paleodemographers, demographic patterns observed in these groups are more reasonable to assume than those for modern, industrialized populations (Gurven and Kaplan, 2007). At the same time, data from anthropological and historical demography are not deficiencies. These data suffer from any number of issues, including missing or incomplete information on vital events for the time period covered and mis-estimation of current ages for individuals. Further, the demographic rates observed in comtemporary, ethnographic populations have likely been affected by some contact with larger, national populations (e.g., exposure to infectious disease or, conversely, access to immunization).

The use of modern and historical data to develop models for past populations necessarily relies on the uniformitarian principle. This concept was highlighted by Nancy Howell (1976) in another early critique of paleodemography. The concept of biological uniformity assumes that basic biological components (e.g., gestation, maturation, aging, etc.) of the human species were present in past populations. This is not to say that demographic processes are invariant across human populations, but that variation is constrained in predictable ways (Milner et al., 2008). In other words, demographic patterns in the past should not be incredibly different than those observed in modern populations. For example, before the demographic transition, human populations had an average life expectancy at birth of 20 to 40 years, and annual population growth rates were probably low, between 0% and 0.5% (Weiss, 1973). This predictability, then, allows for developing models of demographic processes for use in paleodemography.

The importance of the uniformitarian assumption to paleodemographic analyses cannot be overstated. Based on paleodemographic data, one important implication that follows from uniformitarianism is that, in the past, very few individuals lived to old age (Konigsberg and Frankenberg, 1994). It was the demographic profile for the Libben site presented by Lovejoy and colleagues (1977), that prompted Howell raise issues with straightforward demographic reconstructions from skeletal samples. She argued that, based upon the paleodemographic profile and assumptions about fertility of the population, the living population at Libben would have suffered a number of social consequences, including an extremely high dependency ratio (Howell, 1982). Another implication of this assumption is that age-related changes in skeletal morphology should follow the same pattern in human populations across time and space (Hoppa, 2002). This implication is critical to the application of most methods of age estimation for skeletal remains. Hoppa (2000) has suggested that there is evidence that there is interpopulation variation in changes in skeletal morphology with age. More recently, Konigsberg and Herrmann (2006) have argued that these differences may be due to interobserver error and suggested methods for further testing the uniformitarian assumption, as it applies to skeletal aging, on samples of known-age skeletons from different locations.

3.2.2 Paleodemography's Rise and Alleged Fall

Bocquet-Appel and Masset (1982) were the first from within the field to criticize the paleodemographic age distributions and their associated interpretations. The title of their seminal paper, "Farewell to Paleodemography," highlighted the authors' somber assessment for the future of the field. Their criticism was two-fold. First, the authors argued that age-at-death distributions estimated for archaeologically-derived skeletal samples were artifacts of references samples used to develop the particular aging technique(s) used. This problem, often referred to as "age-mimicry," can systematically bias the age-at-death distributions of paleodemographic samples. Milner and colleagues (2008) point to an obvious example with the McKern and Stewart (1957) method of age estimation with the public symphysis developed on the Korean-War sample, which is almost entirely composed of young, adult males. Thus, any characteristic of the skeleton observed in that sample is going to be associated with a young age, even if that characteristic normally occurs in middle- or old-adults in most, general populations. This means that when any age-estimation method developed using the Korean-War sample will tend to yield young age-at-death distributions when applied to different skeletal samples.

Bocquet-Appel's and Masset's (1982) second main criticism was that the methods used to estimate age from skeletal remains were far too imprecise. They suggested that, for an age indicator method to be useful in yielding accurate age estimates, it would need a correlation coefficient of at least 0.9. This did not bode well for paleodemography, as many methods have correlation coefficients with actual age of less than 0.6 (Kemkes-Grottenthaler, 2002). The argument went back and forth over how highly-correlated with age a particular method would have to be in order to be useful (Lovejoy et al., 1985a; Bocquet-Appel and Masset, 1996). Recently, Kemkes-Grottenthaler (2002) has suggested that, for a number of reasons—including the discrete nature of most age-estimation methods and the non-liner relationship between stages/phases of an age-indicator their associated age ranges—correlation coefficients are not particularly useful in assessing the validity of an age estimation method. She argues, rather, that inspecting scatterplots of predicted age versus actual age should be part of any validation process.

Ultimately, Bocquet-Appel's and Masset's criticisms did not lead to the demise of paleodemography; in fact, they spurred a flurry of research to address these issues. The issue of age-mimicry, though problematic, is not an insurmountable problem with skeletal age estimation, as calibration techniques and more-appropriate statistical methods have largely addressed the bias introduced by reference samples (Aykroyd et al., 1997; Konigsberg et al., 1997; Konigsberg and Frankenberg, 2002; Konigsberg and Herrmann, 2002). Further, much progress has been made toward dealing with the error inherent in age estimation (Konigsberg and Frankenberg, 1992; Müller et al., 2002).

3.2.3 Do Skeletal Assemblages Reflect Fertility or Mortality?

The next serious criticism leveled at paleodemography related to fact that fertility, not mortality, has the greater impact on a population's living age structure (Figures 3.4 and 3.5) and, ultimately, its age-at-death distribution. As McCaa (2002) eloquently explains, the reason for this demographic truism stems from the fact that the effect of mortality gets diluted since it occurs at all ages, while the effect of fertility, on the other hand, is concentrated at one point in time—birth.

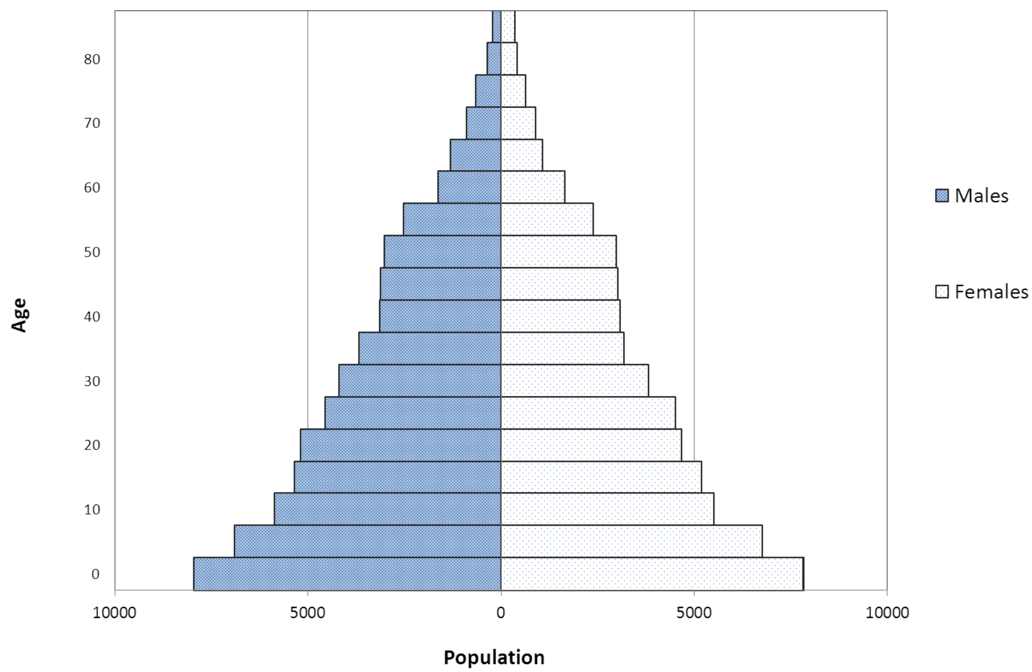


Figure 3.4: Example of what a population pyramid may look like for a growing population, showing higher numbers of younger individuals.

Though fertility's impact on a population's age structure was well known to demographers (Coale, 1957), this issue was not critically addressed within paleodemography until the 1980's. In their landmark paper, Sattenspiel and Harpending (1983) asserted that, in stable populations, the mean age-at-death—a measure typically used to calculate the crude death rate—is approximately the inverse of the crude birth rate. They went on to suggest that the mean age-at-death was not a good indicator of the crude death rate. These conclusions went against over a decade of paleodemographic research, suggesting that age-at-death profiles were interpreted as being a reflection of mortality. McCaa (2002) has suggested that, because of this fact of demography, previous arguments regarding uniformity and mortality have been misdirected.

In recognition of the weight of Sattenspiel's and Harpending's (1983) work, many researchers began investigating fertility through age-at-death distributions (Buikstra et al., 1986; Johansson and Horowitz, 1986; Corruccini et al., 1989; Paine, 1989; Paine and Harpending, 1996; McCaa, 2002).

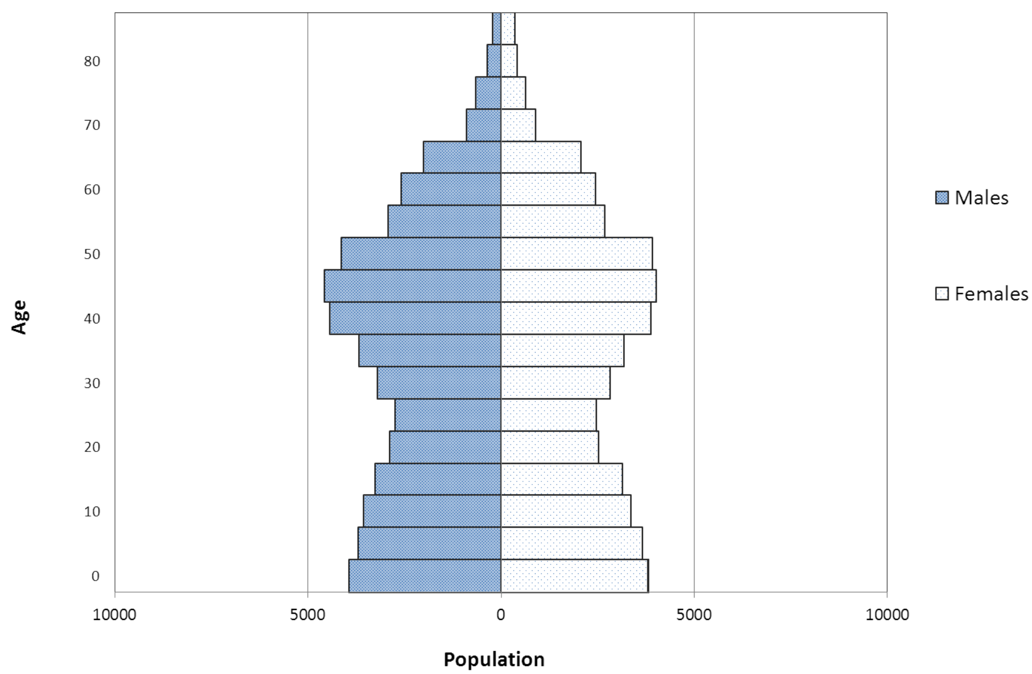


Figure 3.5: Example of what a population pyramid may look like for a declining population, showing higher numbers of older individuals.

This area of research has been useful in addressing questions regarding changes in fertility and population growth rates related to the adoption of agriculture. In related studies, researchers have investigated the application of aggregate age measures, such as age ratios and proportions (Bocquet-Appel and Masset, 1982; Buikstra et al., 1986). These approaches offer some practical advantages over attempting to estimate the full age-at-death distribution. Specifically, age ratios mitigate bias introduced by undernumertation of infants and old adults. Age ratios and proportions have been shown to provide good estimates of relative fertility and population growth rates, though these estimates exhibit high degrees of error when sample sizes are very small (Paine and Harpending, 1996, 1998). Two such measures are used in the current study and will be described in Chapter 4.

3.2.4 Representativeness of Skeletal Samples

Part of Petersen's (1975) original critique suggested that paleodemographic samples were far too small to reflect a real population, a criticism that remains valid (Milner et al., 2008). A number of natural and cultural filters produce samples that cannot be considered random samples of all members of a population that died within a period of time (Konigsberg and Frankenberg, 1994). One can think of a sampling hierarchy from a living population to a analyzable sample of human skeletal remains (Figure 3.6).

Biological mortality bias, occurring in the living-to-mortality transition, has received the most attention in the paleodemographic literature because this transition is inherently selective (Saunders et al., 1993; Wood et al., 1992b). While most paleodemographers would agree with the concept of selective mortality, arising from individual variation in the risk of death (frailty), it is not universally accepted. Cohen (1997) has argued that heterogeneity in the risk of death was unlikely to be important in preindustrial, especially “egalitarian,” societies and that mortality was more-or-less random. On the other hand, paleodemogrpahic analyses have illustrated that mortality risks were heterogeneous in some small, preindustrial populations (Milner et al., 1991; Boldsen, 1997).

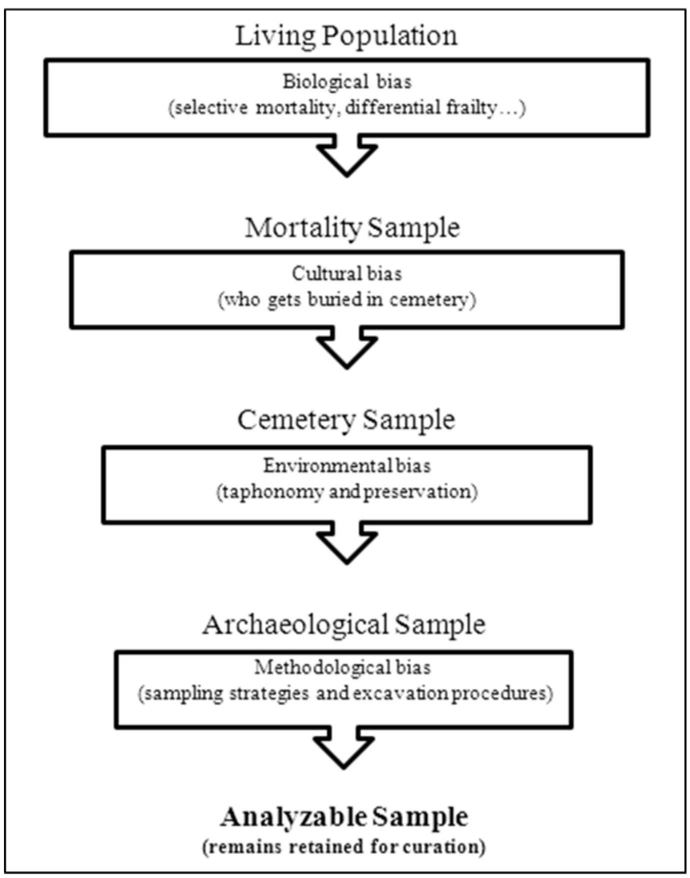


Figure 3.6: Different levels of bias affecting paleodemographic samples, modified from Hoppa (1999:230).

The mortality-to-cemetery transition has received a good deal of attention by archaeologists. Petersen (1975) argued that differences in mortuary rituals associated with age and sex would affect who gets buried in cemetery. Historical and ethnographic accounts of societies, similar to those studied by anthropologists, indicate that newborns and older infants were often not buried in village cemeteries (Milner et al., 2008). Additionally, unusual causes of death could result in atypical disposition of the body (Binford, 1972). Bias introduced during this transition may have a significant impact on the nature of archaeologically-derived skeletal assemblages; unfortunately, it may also be the most difficult to observe.

Most importantly, natural (environmental) taphonomic forces affect the cemetery-to-archaeological transition. A number of factors, including thickness of cortical bone (Waldron, 1987; Guy et al., 1997) and soil pH (Gordon and Buikstra, 1981), affect the survival of skeletal remains. Both Hooton and Angel recognized the effects of differential preservation due to age, and Walker and colleagues (1988) have illustrated that age and sex influence the likelihood of preservation of skeletal remains. It can be argued that filters acting on this transition have the greatest impact on the age and sex structures observed by paleodemographers. There remains, though, no formal model for how these process shape skeletal assemblages. Significant work along these lines would represent a major improvement to the field.

Methodological filters impact the archaeological-to-analyzable transition. Experience of the excavators and the particular excavation strategy can bias recovery. For instance, an emphasis on acquiring grave goods has led to uneven recovery because the places chosen for excavation are those likely to yield the most artifacts. Further, during the nineteenth and early twentieth centuries, the only bones recovered from cemetery excavations were pathological specimens or measurable skulls (Milner et al., 2000). Both of these circumstances have greatly affected the development of human skeletal collections in Egypt. The other aspect of this type of filter involves the inaccuracy and imprecision of the techniques used in analyzing skeletal remains. This includes biases in the estimation of age and sex from skeletal remains (Weiss, 1972; Walker, 1995).

Using computer simulation, Hoppa (1996, 1999) has illustrated the effects of a range of bias profiles on the calculations of abridged life tables. Two of the most common types of bias, undernumeration of infants and older adults, have the most impact upon life expectancy values for infants and young children

(0–4 years of age). High infant undernumeration leads to overestimation of life expectancy, while undernumeration of old adults tends to underestimate life expectancy for the youngest age groups. These studies illustrate that any *a priori* knowledge of selection biases possibly associated with a cemetery sample should be incorporated into models to compensate for such biases.

3.2.5 Methods of Modeling Mortality: Life Tables and Hazard Models

In one of his most-cited papers on paleodemography, Angel (1969:428) was explicitly opposed to presenting his results in the form of a life table, arguing that it ”falsified biological fact.” Thus, it is curious that, in the following years, biological anthropologists almost universally adopted the use of life tables in paleodemographic analyses. Acsádi's and Nemeskéri's *History of Human Life Span and Mortality* (1970) was the first major study that used life tables derived from skeletal data to study mortality across a number of populations. A number of publications describing the methods for calculating and using abridged life tables followed (Weiss, 1973; Swedlund and Armelagos, 1976), as did publications applying abridged life tables to the reconstruction of mortality in prehistoric populations (e.g., Bennett, 1973; Ubelaker, 1974; Asch, 1976; Lovejoy et al., 1977). Throughout the 1970's and 1980's, numerous life table were created by the general process of estimating an age-at-death for each individual in a skeletal sample, grouping individuals into age categories (often at 5-year intervals for juveniles and 10-year intervals past age 20), then using counts of individuals in each age category to calculate an abridged life table using established methods.

While the use of abridged life tables was an improvement over previous methods and brought a level of sophistication to paleodemography, this approach has been criticized for a number of reasons (Sattenspiel and Harpending, 1983; Konigsberg and Frankenberg, 1992; Milner et al., 2000). One issue is that paleodemographers do not know the number of deaths at each age and the number of person-years of exposure to the risk of death at that age over some specified period of time. Associated with this is the use of fixed age intervals, which suggests that the estimated age for all individuals is known within the same margin of error (Wood et al., 2002). This is, of course, not the case; generally, there is less error associated with age estimates of younger individuals than for middle and older adults. Another serious problem is that, by using life tables, one assumes a stationary population. If the population is not stationary, though, there is no straightforward relationship between the observed age-at-death distribution of an assemblage of skeletons and the cohort age-at-death column (d_x) of a life table (Moore et al., 1975; Konigsberg and Frankenberg, 1994). Finally, the life table is not an efficient use of paleodemographic data, typically small sample sizes in the tens, or maybe hundreds. The result is that most life tables based on paleodemographic data will be overparameterized (Wood et al., 2002).

An alternative to life tables that has gained popularity in anthropological demography and, more recently, paleodemography, is the use of parametric hazard models (Gage, 1988, 1989; Wood et al., 1992a). Hazard functions express the instantaneous risk of death as a continuous function of time, so they provide a method for modeling demographic structure as a continuous process, rather than a series of discrete values (Wood et al., 1992a). Especially during the last decade, the use of hazard models has begun to replace the life-table approach to modeling mortality in paleodemography (Frankenberg and Konigsberg, 2006).

The use of hazard models (i.e., hazard analysis, also referred to as survival or event-history analysis) is a method of modeling mortality across the lifespan using a small number of parameters. These methods have broad applications in a number of fields, including medical and clinical research, ecological studies, and demography. The analysis involves estimating model parameters that provide the best fit to an observed age-at-death distribution. Hazard models provide an efficient means of smoothing mortality data and have been useful as an indirect estimation method in anthropological demography (Gage, 2010). Because this approach involves the estimation of only a handful of parameters, it is better-suited to the small samples typically encountered by paleodemographers. Further, hazard models allow for the incorporation of nonzero growth rates and other covariates affecting mortality (Frankenberg and Konigsberg, 2006; Milner et al., 2008).

The primary limitation of using hazard models lies in choosing the appropriate model (Wood et al., 2002). Ideally, one wants to choose the simplest model (i.e., that with the fewest parameters) that captures the salient features of the mortality curve over the age range of interest. Also, there is hope that the parameters of the model will have some meaningful, biological interpretation. There are several parametric hazard models that have been applied to human demography (see Wood, 1992, for a review). The best model may depend, in part, on the data. For example, some models cover mortality over the entire lifespan, while others were developed specifically to explain adult mortality. An additional advantage of hazard models is they do not impose a predetermined, rigid age structure onto the data. A well-chosen mortality model, then, will allow the actual age structure of mortality in the population of interest to come into better view (Wood et al., 2002).

The measures of demography (including some of columns in a life table) are closely related to the basic quantities in hazard analysis, another reason why hazard models are a useful tool in paleodemography. For example, the survival function, $S(a)$, is analogous to the l_x column of a life tale. The function is strictly decreasing as age (a) increases. Two other important quantities in hazard analysis are the hazard function—written as $\mu(a)$ or $h(a)$—and the probability density function, $f(a)$. The hazard function is equal to the demographic force of mortality (i.e., the central death rate, m_x, in a life table). Finally, the probability density function is analogous to the cohort distribution of age-at-death (the d_x column in a life table). What makes these values so useful is, based on some principles of renewal theory outlined by Cox (1962), once any one of these values is estimated, the other two may be calculated (Wood et al., 2002).

The earliest mathematical model describing human mortality was devised nearly two centuries ago by Benjamin Gompertz (1825). Gompertz model, which only describes the adult lifespan, contains two parameters—one for scale and one for shape. The scale parameter, α, represents the overall level of mortality, and the shape parameter, β, determines the pace with which mortality increases with advancing age. The force of mortality, $\mu(a)$, in the Gompertz model can be expressed as

$$\mu(a) = \alpha e^{\beta a}.$$

The survival function is

$$S(a) = \exp\left[\frac{\alpha}{\beta}(1 - e^{\beta a})\right].$$

Finally, the cohort age-at-death distribution may be written as

$$f(a) = \alpha \exp\left[\beta a + \frac{\alpha}{\beta}(1 - e^{\beta a})\right].$$

Most models of adult mortality that have been developed since are modifications of the Gompertz model (Wood et al., 2002). For example, the Gompertz-Makeham model (Makeham, 1860) adds an age-independent parameter to the Gompertz model, creating a three-parameter model that has been shown to fit fairly well to the adult lifespan. The final model mentioned, one that has found some popularity in the among anthropological demographers and paleodemographers, is the Siler model. The Siler competing hazards model (Siler, 1979, 1983) is a five-parameter model that is divided into three separate, or competing, forces of mortality that spans the entire lifespan. This model adds an immature component to the Gompertz-Makeham model. Siler's juvenile component begins high then decreases by a negative exponential, which generally conforms to the observed, rapid decrease in mortality after infancy. Figure 3.7 illustrates survival curves based on Siler models parameters for a paleodemographic model and ethnographic populations. This figure also clearly shows how mortality in paleodemographic samples deviates from ethnographic and model populations beginning at about age 30.

The Siler model has been shown to be quite parsimonious in describing mortality across the entire human lifespan. Timothy Gage has used this model extensively in investigating several aspects of variation in the age pattern of mortality, including specific causes of death and the affects of nutrition (Gage, 1990, 1991; Gage and O'Connor, 1994). Gage and others have also used this model to investigate patterns of mortality in nonhuman primates (Gage, 1998). This model has been used in a number of paleodemographic analyses, including O'Connor's (1995) meta-analysis of nearly 30 published, paleodemographic life tables. It should be noted that the Siler model does have some limitations. First, the juvenile component has no biological etiology and is often difficult to estimate and interpret for paleodemographic samples where infants are underrepresented. Also, if individuals from the population in question are heterogeneous in their risk of death, the components of the Siler model (or any competing hazards model) cannot be interpreted in a straightforward manner (Wood et al., 2002).

3.2.6 Recent Advances: Rostock and Beyond

The last major paradigm shift in paleodemography came a decade ago, following a series of workshops in Rostock, Germany, hosted by the Max Planck Institute for Demographic Research during the summers of 1999 and 2000. These workshops were attended by biological anthropologists, demographers, and biostatisticians who had a goal of coming to some consensus on how paleodemographic analyses should proceed. Attendees were concerned primarily with improving methods for adult age estimation, particularly with regard to the oldest of the old. Secondly, participants were interested in

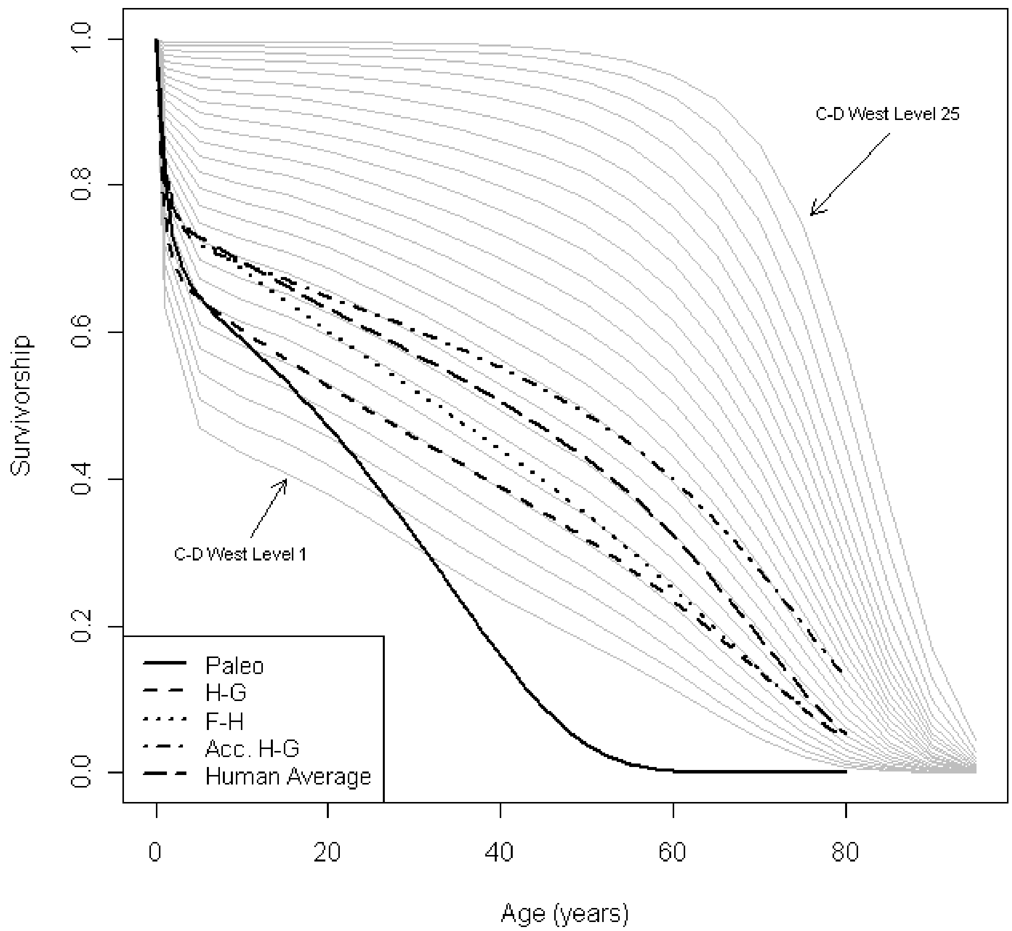


Figure 3.7: Comparison of survival curves—O'Connor's (1995) paleodemographic model (Paleo) and ethnographic populations from Gurven and Kaplan (2007) (averages for H-G = hunter-gatherers, F-H = forager-horticulturalists, Acc. H-G = acculturated hunter-gatherers, and their entire human sample). Grey lines represent the Coale-Demeny (1983) Model West (female) life tables.

a number of issues related to the reconstruction of demographic parameters from skeletal data. What came out of these workshops was an agreed-upon theoretical approach that has come to be known as the "Rostock Manifesto," which was outlined in an edited volume (Hoppa and Vaupel, 2002a). The Rostock Manifesto outlined areas (summarized below) toward which paleodemographers should focus their attention (Hoppa and Vaupel, 2002b:2-3).

Of immediate concern was the need for osteologists to identify novel skeletal features and age indicator stages/phases that relate skeletal morphology to chronological age. This challenge applies to methods applied to estimate age across the lifespan, but is particularly important with respect to age indicators used in the estimation of age for adults. As Bocquet-Appel and Masset (1982) had pointed out in their initial critique, many of the skeletal age indicators commonly used in adult age estimation have low correlations with true age. Further, adult age indicators have been found to overage young and middle adults while, at the same time, underaging old adults (Molleson et al., 1993). Another persistent problem is that lack of age indicators that perform well in identifying the very old, those skeletons that typically are lumped into the age category of “50+.” This step involves examining existing and new reference samples of known age using traditional, macroscopic aging methods (e.g., pubic symphysis, auricular surface, cranial sutures, etc.) and developing new methods that are reliable and can be validated to relate skeletal morphology with chronological age (Hoppa and Vaupel, 2002b). In a chapter that addressed this issue, Boldsen and colleagues (2002) reworked the scoring systems of several well-known age indicators for a system they termed “transition analysis.” Another contribution was a validation study of a technique using dental microstructure—cementum annulation—to obtain very precise age estimates for skeletal remains (Witter-Backofen and Buba, 2002).

Another aspect of the Rostock Manifesto suggested that paleodemographers need to find statistically appropriate and robust methods for estimating $\Pr(c|a)$, the probability of observing particular phase/stage of an age indicator (or combination of phases/stages in a suite of age indicators) conditional on age. It is $\Pr(c|a)$ for a particular trait or suite of traits that osteologists observe in known-age reference samples. Also, contributors to the Rostock volume stressed that osteologists must recognize that this value is not the same thing as $\Pr(a|c)$—the probability that a skeleton is a specific age conditional on observing particular phases/stages of an age indicator. $\Pr(a|c)$ is traditionally considered the estimate of age-at-death that would be used to classify an individual skeleton to a predefined age category.

One element of the Rostock Manifesto that runs counter-intuitive to most biological anthropologists is that, in order to estimate age for any individual skeleton, one first needs to estimate (or supply prior information on) $f(a)$, the age-at-death distribution in the *target* sample (i.e., the archaeological skeletal assemblage of interest). This concept signaled a marked departure from traditional approaches to estimation of both age of individual skeletons and the age-at-death distribution for an entire sample. Table 3.2 illustrates differences in the sequence of steps involved in the estimation of age and an age-at-death distribution using a traditional approach versus the approach advocated by Hoppa and Vaupel (2002b).

Table 3.2: Comparison of traditional versus Rostock approaches to age estimation and the reconstruction of demographic parameters in paleodemography.

Traditional (Johansson and Horowitz, 1986)	Rostock (Hoppa and Vaupel, 2002b)
Observe skeletal morphology in the target sample	Observe skeletal morphology in the target sample
Using a reference sample, relate skeletal morphology in the target sample to chronological age	Using a reference sample, relate skeletal morphology in the target sample to chronological age
Based on a point-estimate of age-at-death, assign each individual skeleton into an age category	Estimate the age-at-death distribution for the entire target sample
Estimate age-at-death distribution and related demographic parameters, typically through calculation of an abridged life table	Using Bayes' theorem, estimate age-at-death of an individual skeleton

Rostock participants drew attention to the well-known fact that age estimation techniques, either implicitly or explicitly, make use of Bayesian probability, in that the age-at-death distribution of the target sample is influenced by the age structure of the reference sample (Bocquet-Appel and Masset, 1982; Konigsberg and Frankenberg, 1992; Hoppa and Vaupel, 2002b). Bayesian probability also underlies the contingency table approach to paleodemography. Chamberlain (2000) has argued that this approach alleviates bias introduced by the reference sample by using a uniform prior distribution and model life table data. While the application of contingency tables to age estimation in paleodemography is relatively straightforward, this approach is limited by the nature of age estimates generated by skeletal age indicator data (Frankenberg and Konigsberg, 2006; Konigsberg and Herrmann, 2006).

The approach commonly referred to as "transition analysis" was described by Boldsen and colleagues (2002). The name refers to the method of modeling the age at which an particular skeletal age indicator transitions from one phase/stage to the next. The sequence of phases/stages is assumed to be unidirectional. Since transition analysis incorporates the use of maximum likelihood estimation (MLE) within the framework of a generalized linear model (Boldsen et al., 2002), there are a number of different statistical techniques that may be used. Boldsen and colleagues (2002) opted for using logit regression, while others have chosen to use probit regression, which has some advantages when dealing with age indicator data recorded on an ordinal scale (Herrmann and Konigsberg, 2002; Konigsberg and Herrmann, 2002, 2006).

Generally speaking, paleodemographers are interested in the age-at-death distribution, rather than the age for any one individual. However, for bioarchaeologists or forensic anthropologists who need an age estimate for an individual skeleton, Bayes' theorem can be used to estimate age in the final step of the Rostock approach. Again, in order to do this, one must have already estimated the age-at-death distribution, $f(a)$, in the target sample from which the skeleton comes. Thus, to estimate age at death for a particular skeleton, one needs information on $\Pr(c|a)$ in the reference sample and $f(a)$ in the target sample. The prior distribution for $f(a)$ is usually specified as a parametric mortality model, like those described above. What is most promising about the Rostock approach described here is that the choice of a the prior distribution for $f(a)$—a uniform, uninformative prior, or an informative prior, if one has some idea about the population from which the target sample was drawn—does not appear to bias the posterior (estimate) of the target age-at-death distribution (Konigsberg and Herrmann, 2002). The transition analysis approach used in the current study is described in Chapter 4.

3.3 Summary

Though paleodemography had even earlier beginnings, it has had a a presence as a recognized specialization within biological anthropology for about 40 years now. During that time, the field has undergone periods of blind acceptance; been labeled as completely useless and, then, vehemently defended; and witnessed resurgence using fertility-centered theoretical approaches to age-at-death distributions. Critique is an inherent part of the scientific process, and accordingly, each round of criticism has served to strengthen the field, rather than sending it to its demise. The Rostock Manifesto represented a culmination of increasingly sophisticated paleodemographic methods developed over the past few decades. Although some issues that have plagued the field since its inception continue to persist, much progress has been made. As long as interested researchers across disciplines continue collaborating to improve the field, paleodemography has a rich future in furthering our knowledge of past population dynamics and its relationship to phenomena related to the evolutionary and cultural history of our species.

Chapter 4 Materials and Methods

As illustrated in the previous chapter, paleodemography has come a long way since Hooton's studies in the early 20th century. Older and more-current debates over methods in age and sex estimation of skeletal remains, the effects of demographic rates on age-at-death distributions, and taphonomic and other processes creating bias in archaeological skeletal assemblages have all strengthened the field. Further, practitioners have begun to adopt a theoretical perspective recognizing that there are a limited number of questions we can hope to answer by analyzing mortality distributions (Milner et al., 2008).

Demographers studying contemporary populations have access to huge datasets, known ages, and some information about specific causes of death. These are things to which paleodemographers will never have access. Paleodemographers usually deal with samples numbering in the few hundreds, in the best cases. Thus, paleodemographers can only hope to observe general trends in the level and age pattern of demography and try to understand the circumstances associated with that variation (Wood et al., 2002:132).

The following chapter describes the materials and methods used in the present study. Throughout the discussion, it will become clear that the skeletal assemblage recovered from HK43, though relatively large and well-preserved, is not immune to many biases affecting the recovery and subsequent analysis of archaeologically-derived human remains. After a brief history of archaeological investigations at HK43 and data recording procedures, the remainder of the chapter focuses on the particular methods used in estimating age, age-at-death distributions, and other demographic characteristics of interest. Data analyses were performed using a combination of programs, including Microsoft Excel, SPSS 15.0 for Windows, and R (R Core Team, 2012). R is an open-source, statistical computing and programming environment that is constantly updated and released for download (www.r-project.org). Excel and SPSS were used primarily for data management and some basic statistical analysis. R (release 2.11.1–2.15.1) was used primarily for maximum likelihood estimation and graphics production.

4.1 Archaeology at HK43

Locality 43 (HK43) is the largest cemetery currently known from Hierakonpolis. The cemetery is located on the southeastern edge of the Hierakonpolis concession near the bank of the Wadi Khamsini. Portions of the area were surveyed by Michael Hoffman in 1979, and he identified several sites, including a series of small Predynastic settlements, cemeteries HK43 and HK44, and a Roman-era village site.[1] Originally identified as three separate cemeteries, Localities 43, 44, and 45 have since been renamed as one cemetery, HK43. Emergency excavations began in 1996, when the construction of an elevated canal within the concession boundaries drew the attention of the project director, Dr. Renée Friedman. The canal had cut the cemetery in half, and scatters of pottery and human bone had been exposed by a bulldozer. Larger than previously thought, HK43 extends to the north, south, and westward to the edge of HK54, a settlement site that is part of a larger settlement area referred to as the "Predynastic town." It is thought that HK43 probably served the population living at HK54 (Friedman et al., 1999:3), but this site has yet to be studied.

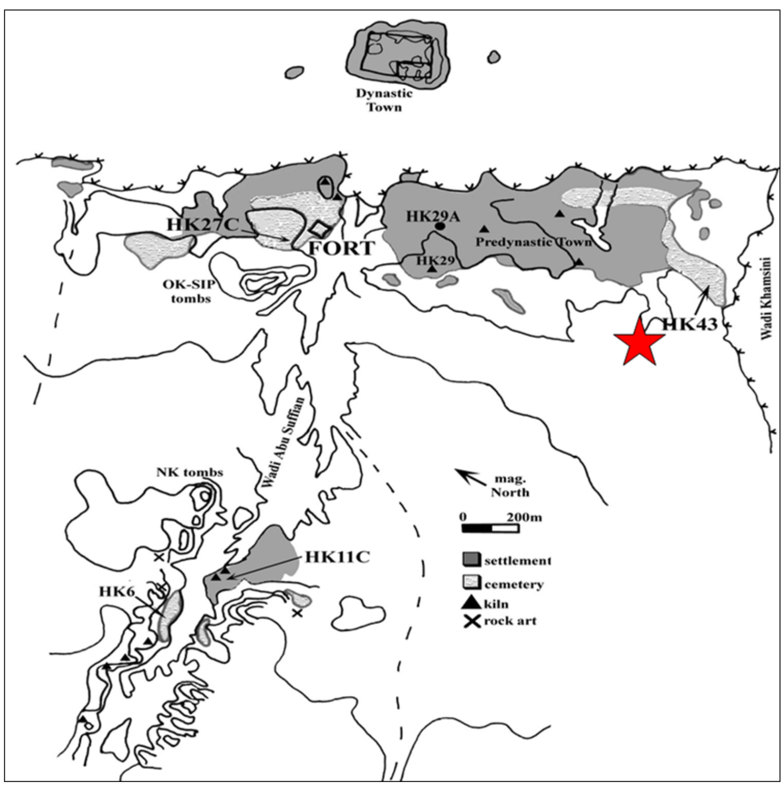


Figure 4.1: Map of the Hierakonpolis archaeological concession, showing major localities, including HK43 (Friedman, 2004b:2).

[1] See footnote 9 in Friedman et al. (1999) and Hoffman (1982:123–127)

After the first three field seasons, over 153 burials had been recovered, and it became clear that the cemetery was large and its contents were well-preserved. Graves at HK43 are simple, conical pits lined with a wet mixture of sand and ash, presumably in order to help maintain shape of the burial in the sand (Wrobel, 2001). Burials tend to be arranged in large circles with a relatively empty center, a pattern unlike most other Predynastic cemteries. There seems to be no discernible spatial patterning with respect to age or sex. Though the relationships within and between these circular groupings remain unclear, one possibility is that the circles represent family units that extend over several generations (Friedman et al., 1999; Wrobel, 2001). Further bioarchaeological analysis is needed to test this hypothesis.

Most burials at HK43 are single internments, though there are 39 cases of double burial (Greene, 2006). Unlike most double burials from previous periods, those at HK43 contain almost any combination of age/sex (e.g., infant/adult male, infant/adult female, two adult females, adult male/adult female, etc.). As in previous periods, bodies are in a flexed position, placed on the left side, facing west. However, due to a bend in the Nile at the site, there is a difference of 23° between true west and "Nile-west." Nearly twice as many burials face true west, and these have little margin of error from exact orientation, which suggests these people had a clear knowledge of cardinal directions (Friedman et al., 1999).

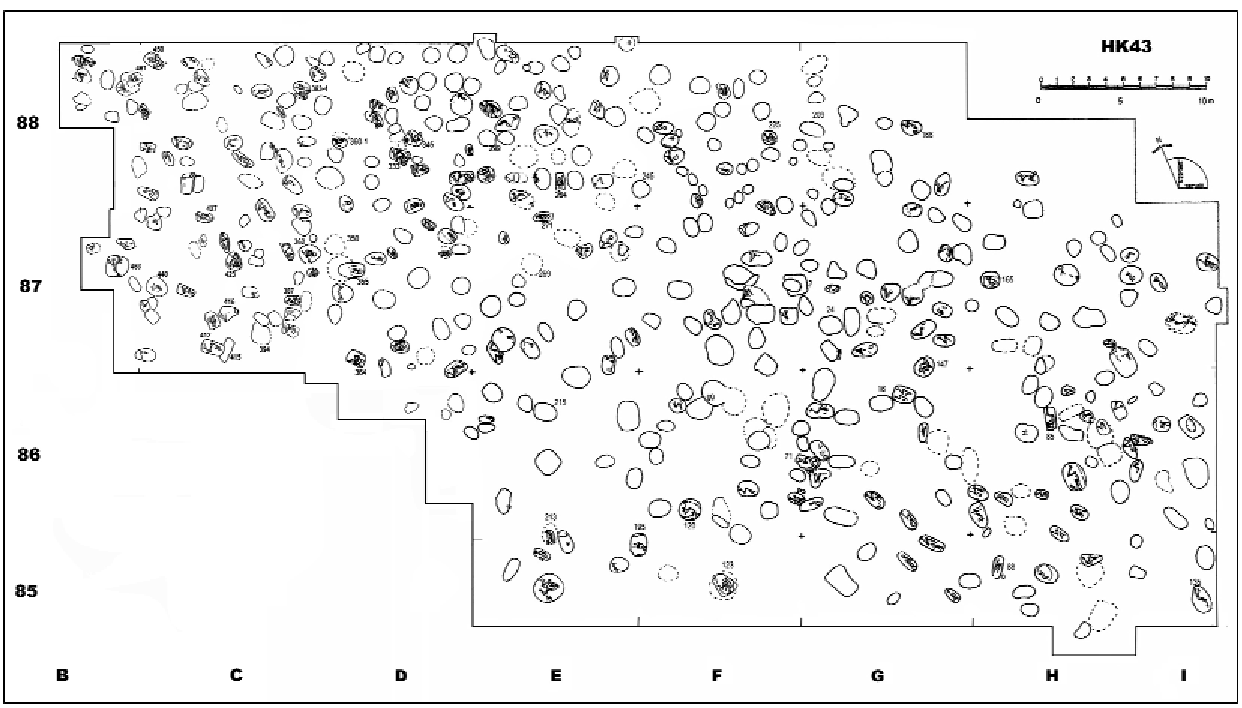


Figure 4.2: Final map of excavated portion of HK43 (Friedman, 2004a:4).

Grave goods are uncommon at HK43. Some graves contain beads or cosmetic palettes, but coarse, straw-tempered pottery is the most common item recovered. Given the general lack of grave goods, even in the undisturbed burials, the current interpretation is that HK43 represents internments of a nonelite segment of the population that once lived at Hierakonpolis. This is reasonable interpretation, as HK43 stands in stark contrast to contemporaneous elite cemeteries HK6 and HK33 (see Section 2.3). Unfortunately, the relative paucity of grave goods and the fact that most of the graves had been disturbed have made the assignment of a refined chronology for HK43 a difficult task. Based upon the artifacts that have been recovered, the excavated portion of the cemetery likely spans about 300 years within the Naqada IIA–C (ca. 3600–3200 BC), with most a majority of the graves dating to the Naqada IIB phase (Friedman et al., 2002; Dougherty and Friedman, 2008). Excavations continued at HK43 until 2004; by that time, 453 discrete burials had been recovered.

As discussed previously, the link between a once-living population and an archaeological skeletal assemblage is complex, as individuals are subject to a number of biases that affect the probability of being analyzed. While the archaeologist has no control over biological, cultural, and environmental biases, he or she does have control over methodological biases introduced by sampling and excavation strategies. Archaeological survey at HK43 and the immediate vicinity suggest that cemetery use shifted laterally over time, expanding toward HK54 to the north and west. Even though the sample analyzed here likely represents only a portion of the entire cemetery, archaeological evidence suggests that the recovered burials do, in fact, represent a cemetery sample interred over a relatively well-defined temporal period.

4.1.1 Data Collection

All remains excavated from HK43 are curated in a secure dig-house facility on site. Each field season, a team of bioarchaeologists made observations and recorded data in the field and at the on-site laboratory. Laboratory teams consisted of at least one senior bioarchaeologist (sometimes more) and three experienced graduate students. As a general rule, data were collected according to protocols outlined in *Standards for Data Collection from Skeletal Remains* (Buikstra and Ubelaker, 1994). Additional types of data were collected, as certain participants had specific research questions. Completed data forms were photocopied and brought to the Bioarchaeology Laboratory at the

University of Arkansas, where all data were entered into a Microsoft Access database.

4.1.2 Primary Burials

During the summer and fall of 2004, the author and two other graduate students began a project to make counts of primary burials and estimate the total number of individuals represented by the skeletal assemblage. From counting primary burials, we calculated a count of "persons of certain provenience," or PCP. Essentially, PCP were individuals clearly associated with a defined grave. Through the assistance of Dr. Rene Friedman, who provided us with descriptions of her assessments of the condition of the burials (e.g., general preservation/completeness and level of disturbance), and our own reading of the burial forms, we derived a minimum of 490 PCP. As a check to our count of PCP, a pair-matching analysis of skeletal elements was performed. Using an Excel spreadsheet provided by Lyle Konigsberg (http://konig.la.utk.edu/MLNI.html), the most likely number of individuals, or MLNI (Adams and Konigsberg, 2004), for the HK43 skeletal assemblage was estimated to be 472. Because the MLNI estimate was in general agreement with our PCP count from the primary burials, all 490 PCP were included as potential sources of data for this analysis.

Table 4.1 includes summary of the demographic characteristics from the HK43 assemblage. Following "traditional" approaches to age estimation (discussed in Chapter 3), each individual was assigned to an age category based upon all available observations. When the available data allowed, narrower age ranges were recorded as well. Although obtaining a more accurate estimation of the age-at-death distribution is one of the goals of this study, this table gives an initial preliminary assessment of the demographic composition of the assemblage and will be used in some analyses.

As seen in the above table, 75/490 (15.3%) individuals were not assigned to an age category (i.e., "Undetermined"). These remains were too incomplete or poorly preserved for any diagnostic age indicators to be observed. As a general rule, individuals estimated to be younger than about 20 years of age were not typically estimated for sex, though some older adolescents were assigned a sex estimation. Combining probable males/males and probable females/females, it is clear that females outnumber males—0.71 (male to female) sex ratio. Lastly, the age-at-death distribution represents a pattern common to prehistoric skeletal assemblages—low proportions of young children (0–5 years) and old adults (over 50 years), and an over-abundance of young and middle adults. These were precisely

Table 4.1: Original age/sex distribution of HK43 PCP's, as entered in the HK43 database.

	Sex						
Age category	Male	Male?	Female	Female?	Ambiguous	Undetermined	**Total**
Undetermined	3	7	2	4	12	47	75
0-5	0	0	0	0	0	42	42
5-10	0	0	0	0	0	21	21
10-15	0	0	0	0	0	24	24
15-20	10	3	6	2	3	26	50
20-35	36	22	54	28	3	23	166
35-50	22	6	36	12	2	10	88
50+	4	0	13	3	2	2	24
Total	75	38	111	49	22	195	**490**

the issues that precipitated this study.

4.2 Skeletal Age Indicators

The paleodemographic methods detailed below use data recorded for three skeletal features commonly used for age estimation: dental attrition, the pubic symphysis, and the auricular surface of the ilium. Table 4.2 highlights the fact that the HK43 assemblage suffers from a common problem in archaeologically-derived collections—missing data. For the pubic symphysis and auricular surface, the counts below are from 328 individuals, so the percent of individuals with data for each indicator is 42.4% and 53.7%, respectively. Because juveniles were scored for dental attrition, the count below is from 373 individuals, so the percent of individuals with at least one observation for dental attrition is 44.6%. Again, these percentages illustrate preservation bias affecting the quantity and quality of data available from skeletal assemblages.

Table 4.2: Number of individuals with each age indicator in the HK43 skeletal assemblage.

Age indicator	*n*
Pubic symphysis	139
Auricular surface	176
Dental attrition	174
At least one age indicator	**283**

4.2.1 Dental Attrition

Dental attrition is a degenerative process of the teeth and specifically refers to wear on the tooth surface resulting from tooth-on-tooth contact. As the occlusal (chewing) surfaces of the teeth come into contact with each other (and food) during mastication, the enamel slowly wears away. Since enamel does not regenerate after the teeth are fully formed, dental attrition may be viewed as a more-or-less linear, unidirectional process. Further, because teeth develop and erupt in a particular sequence, they provide a natural timeline of the effects of attrition. For these two reasons, and the high degree of preservation of dental tissues in archaeological assemblages, teeth are unique among other parts of the skeleton and are potentially useful in estimating age-at-death of skeletal remains.

Of course, a number of factors affect how teeth wear over time. Different diets, the amount and size of extraneous particles (e.g., grit) in food items, tooth loss or disease, behavior (e.g., habitually clenching a pipe stem, or deliberate modification), and biological differences (e.g., individual risk of developing dental disease, or differences in enamel integrity) all affect the rate, pattern, and degree of dental attrition. These factors preclude the existence of a universal pattern of dental attrition. Perhaps the complex nature of the process of dental attrition is why it has been such a point of interest among anthropologists. Diet, in particular, has been one of the principal issues investigated through dental attrition. In this respect, the analysis of temporal changes in the pattern and severity of dental attrition within and between populations undergoing subsistence change has dominated the literature (e.g., Walker, 1978; Smith, 1984; see Larsen (1999) and Rose and Ungar (1998) for references).

For the purposes of the current study, the remaining discussion focuses on the scales for recording dental attrition and their applications to age estimation. The development of scales of dental attrition dates to the late 19th century. These early attrition scales considered wear on the entire tooth, using different rank systems—an approach used in attrition scales developed later (Rose and Ungar, 1998). Murphy (1959a,b) developed an attrition scale based upon his research on populations of Australian Aborigines. Murphy's scale labels any tooth without dentine exposure as "N," and follows with a series of modal forms graded "a" to "h" that are illustrated by standard diagrams showing the pattern of dentine exposure. Later, Molnar (1971) produced an attrition scale based upon similar distinctions found in Murphy's system, but added the recording of secondary dentine exposure and separate scores for the specific orientation and form of the worn surface.

In an attempt to study the cross-cultural variation in patterns of dental attrition, Smith (1984) produced a revised version of Murphy's original attrition scale. Smith devised an eight-phase scale for scoring dental attrition in which all teeth, not just molars, could be scored. Like Murphy's scale, Smith's system treats the entire occlusal surface as a whole, but includes three stages of minimal dentine exposure, which allows one to record lower levels of attrition. Smith's scale is a widely used standard in bioarchaeology today (Buikstra and Ubelaker, 1994).

Despite the popularity of the Murphy (1959a,b) and Smith (1984) scales, their method of treating the entire occlusal surface as a whole has not gone without criticism. In an attempt to improve upon previous methods, Scott (1979) devised a more complex method of scoring attrition. Scott's attrition scale (Figure 4.3) defines stages of attrition that quantify wear *prior* to dentine exposure, as well as dentine exposure, unlike the other methods that only record dentine exposure (Murphy, 1959a,b; Molnar, 1971). Thus, the Scott method allows one to record enamel attrition on younger individuals, particularly those in low-attrition populations, in which dentine exposure may not occur until older ages (O'Connor, 1995). Further, this scale is appropriate for analyzing rates of attrition, rather than central tendencies of the degree of attrition, and the amount of enamel lost in each successive stage is approximately equal (Scott, 1979:216). In this method, each quadrant of the tooth is scored on a scale of 1 to 10; then, these scores are summed to produce the final attrition score, which may range from 4 to 40. Thus, it approximates an interval-level scale, which facilitates parametric statistical analyses (O'Connor, 1995:136).

Dental attrition data for HK43 were scored according to the Scott (1979) method. A least two previous studies have investigated dental attrition at HK43. Tammy Greene included dental attrition in her analysis of diet and dental disease during the Predynastic at Hierakonpolis and Naqada (Greene, 2006). She reported that males generally have higher attrition scores and that males and females show slightly significant differences in mean attrition scores for the maxillary first and second molars and mandibular first molar, but not mandibular second molars. Further, Greene reported on the frequencies of a number of other dental health measures: periodontal disease, abscesses, hypoplasias, calculus, antemortem tooth loss (AMTL) and dental caries. Generally, individuals at HK43 exhibited very low frequencies of all measures, except for elevated levels of hypoplasias. Caries and AMTL have the most potential to affect dental attrition. Only 22/145 (15.2%) individuals experienced AMTL, and there were

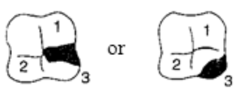
	Score	Description
	0	No information is available (tooth not occluding, unerupted, antemortem or postmortem loss, etc.).
	1	Wear facets very small.
	2	Wear facets large, but large cusps still present and surface features (crenulations, noncarious pits) very evident. It is possible to have pinprick size dentine exposure or "dots" which should be ignored. This is a quadrant with much enamel.
	3	Any cusp in the quadrant area is rounded rather than being clearly defined as in 2. The cusp is becoming obliterated but is not yet flat.
	4	Quadrant area is worn flat (horizontal) but there is no dentine exposure other than possible pinprick sized "dot."
	5	Quadrant is less flat, with dentine exposure ¼ quadrant or less.
	6	Dentine exposure greater: more than ¼ of quadrant area is involved, but there is still much enamel present. If the quadrant is visualized as having 3 "sides" (as in diagram) the dentine page is still surrounded on all 3 sides by a ring of enamel.
	7	Enamel is found on only 2 "sides" of quadrant.
	8	Enamel is found only on one "side" (usually outer rim) but the enamel is thick to medium on this edge.
	9	Enamel on only one "side" as in 8, but the enamel is very thin—just a strip. Part of the "edge" may be worn through at one or more places.
	10	No enamel on any part of quadrant—dentine exposure complete. Wear is extended below the cervicoenamel junction into the root.

Figure 4.3: Method for recording dental attrition for HK43; from Scott (1979:214).

no significant differences with respect to age or sex (Greene, 2006:171). It is also important to note that the frequency of caries at HK43 is very low, occurring in less than six percent of observed teeth (Greene, 2006:161). From Greene's study, then, it may be assumed that AMTL and dental caries had little effect on the overall distribution of dental attrition observed at HK43.

In general, attrition studies have found little difference in wear between left and right sides of the dentition (Hillson, 1997). To confirm this was the case at HK43, paired-samples t-tests were performed on dental attrition scores from the left and right sides. The results showed no significant difference between sides. Thus, attrition scores from the left side were used; if missing, the attrition score from the right side was substituted. An advantage to combining sides was to increase the sample size for further analysis.

4.2.2 Pubic Symphysis

The pubic symphysis refers to the to region of the pubic bone where the left and right os coxae articulate anteriorly at the midline. Here, the surfaces of the two adjacent pubic faces are separated by a cartilaginous disc. The shape of pubic symphyseal surface roughly resembles that of an ellipse, and the shape, texture, and external morphology of this surface change with age. English anatomist T. W. Todd was the first to describe age-related changes in the pubic symphysis, and related these to a specific method for determining adult age (Todd, 1920, 1921). Using a skeletal collection of individuals with documented age (18–over 50 years), Todd produced a 10-phase system of modal standards. Todd's studies investigated sex- and population-specific trends, although differences were not significant as to warrant using anything but the "white male" standards for any analysis. This method focuses on five characteristics: surface, the ventral and dorsal borders, and the superior and inferior extremities. As one ages, surface "billowing" is replaced with a granular appearance; the dorsal and ventral margins become well-defined; and, at older ages, the surface margins erode and osteophytic "nodules" may develop (Figure 4.4).

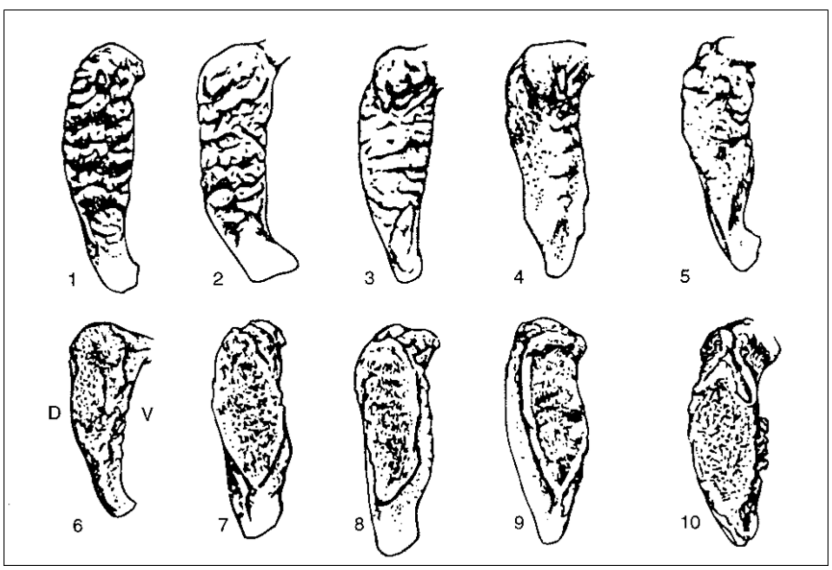


Figure 4.4: Todd's (1920) 10-phase scoring system for the pubic symphysis; from Buikstra and Ubelaker (1994:22).

There have been a number of attempts to refine the method (e.g., Meindl et al., 1985b; Suchey et al., 1986), mostly aimed at refining the age ranges originally set by Todd, or condensing the original 10-phase scheme. As an alternative to Todd's modal system, McKern and Stewart (1957) proposed dividing the pubic symphysis into three components—the dorsal plateau, ventral rampart, and symphyseal rim—each divided into five stages. The McKern-Stewart method is not without drawbacks, one of which is that it was developed on a sample American soldiers killed in the Korean War. Because most age estimation methods are dependent on the age composition of the reference sample (here, a sample of mostly *young* men), the McKern-Stewart method often under-ages individuals when applied to older samples of unknown age.

Comparisons of Todd's phase method and the McKern and Stewart's component approach suggest that the original phase system developed by Todd, and it's subsequent revisions, perform better than the component approach (Meindl et al., 1985b; Klepinger et al., 1992). Most criticisms have approached the phase-versus-component debate on purely methodological grounds, although, as Kemkes-Grottenthaler points out, based upon human brain's process of object recognition, "the modal phase approach, might, by its very nature, be the more adapt way of age attribution" (Kemkes-Grottenthaler, 2002:58). Thus, the Todd system continues to be a popular method to score age-related changes in the pubic symphysis.

The analysis presented here uses the Todd scores recorded in the HK43 database. By convention, scores from the left side were used. In cases where the left side was missing, the score from the right side was substituted, if present. In total Todd scores were available for 139 individuals.

4.2.3 Auricular Surface

In the same volume of the *American Journal of Physical Anthropology* in which Meindl and colleagues (1985a) published their critique of age estimation with the pubic symphysis, they also published a method of estimating age from the auricular surface of the ilium (Lovejoy et al., 1985b). The auricular surface is an ear-shaped feature, located on the posterior region of the ilium where it articulates with the sacrum. The main features of the auricular surface to consider with regard to this method include the apex, superior and inferior demifaces, preauricular sulcus, and the retroauricular area (Figure 4.5). Some of the age-progressive changes in the area involve granularity of the surface, increases in surface porostiy, a loss of transverse organization ("billowing"), and appearance of patches of dense bone. Changes in the apex and retroauricular are also used to modify age estimates within the range for a particular phase (Lovejoy et al., 1985b:27).

Lovejoy and colleague's (1985b) original scoring method includes eight phases with associated

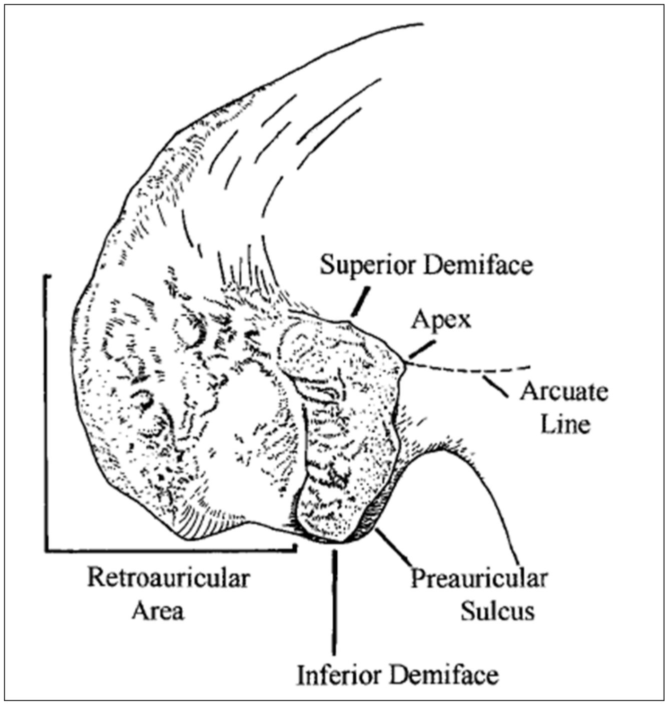


Figure 4.5: Auricular surface of the ilium with major features used in the Lovejoy et al. (1985b) scoring system; from Buikstra and Ubelaker (1994:25).

age ranges. Their method is widely used, and although there have been attempts to revise the method (Buckberry and Chamberlain, 2002), results have been mixed (Mulhern and Jones, 2005). As pointed out in the original publication, age-related changes of the auricular surface may be "more difficult to interpret than those used in pubic symphyseal aging," (Lovejoy et al., 1985b:15), but this method has one major advantage over the pubic symphysis in that due to the robustness of this part of the ilium, the auricular surface is frequently well-preserved (recovered and available for analysis) from archaeological contexts. That certainly is the case at HK43. The analysis presented here uses Lovejoy et al. (1985b) scores for the auricular surface recorded in the HK43 database. As with the pubic symphysis, the data are from the left side. In cases where an observation for the left side is missing, the score from the right side is substituted, if available. For this analysis, a total of 176 individuals have scores recorded for the auricular surface.

4.3 Age Estimation

4.3.1 Estimation of Developmental Age for Juveniles

The methods for estimating age-at-death in juvenile (infant through adolescent) skeletal remains have not changed significantly in recent years. These include a number of observations of growth and development in the teeth and skeleton. When observations were available, an age estimate was given based upon dental development (Moorrees et al., 1963a,b; Gustafson and Koch, 1974) and eruption. Additional information was provided by cranial and post-cranial measurements, which were used with reference tables and regression formulae published in Scheuer and Black (2000). Also, for adolescents, an age estimate was given based upon observations of epiphyseal fusion of the long bones.

In general, when compared to age-at-death estimates for adult skeletons, the margin of error and variation in age-at-death estimates for juveniles skeletons will not significantly affect the resulting mortality profile of a skeletal assemblage (Konigsberg and Holman, 1999; Milner et al., 2008). In the HK43 database, juveniles were assigned to one of four age categories (0-5 years, 5-10 years, 10-15 years, and 15-20 years). Because not all developmental changes in the skeleton cease by the arbitrarily-defined juvenile cut-off age of 20 years (e.g., complete epiphyseal fusion of the sternum, or fusion of the sacral vertebrae), when refined age estimates based upon the above criteria were recorded, a final point-estimate of age-at-death, labeled as "developmental age," was calculated based upon an average of those best-guess age estimates in the HK43 database.

4.3.2 Age Estimation Using Dental Attrition

Dental attrition is included in the present study for two reasons: (1) it increases the number of individuals with age indicator data, and (2) it will be used to develop and test the application of a population-specific reference sample to be used in estimating an adult age-at-death distribution with the skeletal age indicators (pubic symphysis and auricular surface). As previously mentioned, dental eruption generally follows a linear pattern. Ideally, the dentition will display a pattern of differential attrition that reflects the length of time each tooth has been exposed. Since the approximate times at which teeth erupt are known, if one assumes a constant rate of attrition over the lifespan, the degree of observed attrition should reflect an individual's age-at-death.

Although, dental attrition standards developed on reference populations do exist (e.g., Brothwell, 1981; Lovejoy, 1985), using dental standards developed on a different population is problematic due to the number of factors affecting inter-population variation in the rate, pattern, and degree of tooth wear. Thus, age-at-death estimation using dental attrition requires a population-specific method. The population-specific method employed in this study is a version of the Miles (1962, 1963) method. Unlike reference-sample based methods of age estimation, this method largely eliminates error due to inter-population variation. Of course, this method is not completely free of the effects of inter-population because it uses a juvenile baseline to estimate the population-specific rate of dental attrition, and the estimates of juvenile age-at-death are based upon standards developed on modern populations. However, as mentioned above, variation in developmental age-at-death indicators, especially dental development and eruption, is minimal (Saunders et al., 1993).

The Miles (1962, 1963) method is based on the assumption that toothwear is primarily a function of age. In the method's original application, functional ages (years a tooth has been in occlusion) of juvenile molar teeth are used to determine a population's specific rate of attrition. The juvenile group is seriated by the degree of attrition developed in approximately six-year periods from ages six to eighteen, then expanded to a "'baseline group' by intense study of the occlusal and approximal wear on M3 to 25 years of age" (Miles, 2001:975). The baseline, then, is extrapolated forward to any individual in the population by adding to the seriation or matching the degree of tooth wear to one already in the seriation. Because data were not directly collected by the author, visual seriation was not possible. The juvenile baseline sample consisted of individuals with developmental age estimates from 6 to 25 years old. As Miles (2001) noted, the extension of the baseline sample to 25 years allows for the inclusion of attrition on the third molar.

Essentially, the Miles method is based upon the ability to calculate a yearly attrition rate. In doing so, the underlying model is that of a slope/intercept, in which the slope is the yearly attrition rate and the intercept represents an eruption adjustment that accounts for the age of eruption of the particular molar used. Even though the molars erupt at roughly six-year intervals starting at age six, they do not wear in the exact same manner. Miles (1978) suggested that the proper wear ratio was 6:6.5:7 (M1:M2:M3). So, to account for the age of eruption of each molar, the slope is adjusted by 6, 12.5, and 19.5 (for M1, M2, and M3, respectively). To estimate age based upon attrition for a single tooth, Huard (2006:49) provides the model formula:

$$\text{Age at death} = \frac{\text{Attrition score}}{\text{Yearly wear rate}} + \text{Eruption adjustment}$$

For each individual with dental attrition observations recorded, all available scores were considered, so that the final age estimate represented the average of the age estimates for each tooth (Huard, 2006):

$$\text{Age at death} = \frac{\sum\left(\frac{\text{Attrition score}}{\text{Yearly wear rate}} + \text{Eruption adjustment}\right)}{\text{Number of molars}}$$

The application of the Miles method used in the current study differs in three respects from that presented in Huard's (2006; 2008) research on dental attrition and age estimation at HK43. First, Huard made a modification to the raw attrition scores. She noted one potential limitation in using the Scott (1979) system to estimate age—it does not have a category for "no wear." Thus, Huard suggested that the method would tend to overage juveniles and proposed adding an additional stage to the scoring system to indicate the absence of any observable attrition (Huard, 2006:50, 121). It is important to note, though, that occlusal surfaces begin to show attrition as soon as they have erupted enough to be exposed to substances being chewed, which occurs prior to the tooth's surface becoming level with the surfaces of neighboring teeth (Schwartz, 1995:210). Thus, it is more likely than not that emerging teeth develop small amounts of wear (Scott's stage one) prior to complete occlusion. By this rationale, the raw attrition scores were not adjusted in the current study.

The second difference relates to the calculation of the population's yearly attrition rate for each tooth. In calculating the yearly attrition rate, Huard (2006) first calculated the absolute difference in attrition scores of adjacent teeth (i.e., NM1-NM2, NM2-NM3, XM1-XM2, and XM2-XM3), which is the method that was applied in this study. Technically, the absolute difference in the attrition scores of adjacent teeth reflects the amount of wear that has occured over a six-year period, since the molars erupt at approximately six-year intervals, beginning at age six. So, the *yearly* attrition rate is the absolute difference in the attrition scores of adjacent teeth, divided by six. For the entire sample, then, the yearly attrition rate equals the mean difference in adjacent attrition scores, divided by six. Huard (2006), though, divided the standard deviation by six to calculate the yearly attrition rate for each tooth. Her rationale was that using the standard deviation of the difference in adjacent attrition scores, rather than the mean, would reduce the effects of individual variation.

As discussed in the next chapter, this approach has significant consequences for calculating the yearly attrition rate and, subsequently, age estimation. The current study uses the mean difference of adjacent attrition scores in calculating the yearly attrition rate for each tooth. Calculation of the yearly attrition rates for the first and second molars uses the mean difference in attrition scores for M1 and M2. The yearly attrition rate for M3 uses the mean difference in attrition scores for M2 and M3. The rationale for using the M1-M2 difference, instead of the M2-M3 difference, for calculating the yearly attrition rate for M2 is based upon the fact that rates calculated with M3 are less reliable, due to its higher degree of variability in eruption time (Huard, 2006, 2008).

Table 4.3: Summary statistics and ANOVA results for the difference in adjacent attrition scores—baseline versus nonbaseline; significance set at the 0.05 level.

	Baseline			Nonbaseline			ANOVA	
Teeth[a]	n	Mean	sd	n	Mean	sd	F	$\Pr(>F)$
NM1-NM2	49	6.92	2.64	76	7.36	3.86	0.482	0.489
NM2-NM3	34	5.03	1.88	70	5.41	4.03	0.280	0.589
XM1-XM2	50	7.82	2.56	75	7.71	5.22	0.020	0.887
XM2-XM3	36	4.83	2.84	71	5.72	3.36	1.827	0.179

[a]NM (mandibular molar); XM (maxillary molar); numbers for first, second, or third molar.

For the purpose of age-estimation, the main advantage of the Miles method is its population-specific approach. In other words, the relationship between dental attrition and age is determined from the population to be aged. Because juvenile age estimates, based upon developmental criteria, have a smaller degree of error, they approach a “known age” sample. The primary limitation of the Miles method lies in the assumption that the rate of wear derived from the juvenile sample applies to adult ages beyond the baseline. Huard (2006, 2008) used the entire sample, including adults, to calculate the mean difference in adjacent attrition scores and, hence, the yearly attrition rate. This current study uses only the juvenile baseline sample for this purpose. A analysis of variance (ANOVA) was performed to test for a significant difference between the juvenile baseline sample and remaining adult sample in the mean difference between adjacent attrition scores (Table 4.3). Results show no statistically significant difference between these groups. Thus, it is safe to assume that the attrition rates in the baseline sample may be properly applied to the rest of the population.

Table 4.4: Summary statistics and ANOVA results for the difference in adjacent attrition scores—males versus females; significance set at the 0.05 level.

	Males			Females			ANOVA	
Teeth	n	Mean	sd	n	Mean	sd	F	Pr($> F$)
NM1-NM2	42	7.05	3.15	56	6.95	3.46	0.022	0.882
NM2-NM3	35	5.31	3.68	55	5.25	3.48	0.006	0.938
XM1-XM2	33	8.79	2.86	59	7.44	4.40	2.498	0.118
XM2-XM3	37	5.62	3.17	53	5.57	3.33	0.006	0.937

Another possible source of error in age estimation from dental attrition is differential rates of wear in males and females. As mentioned above, Greene (2006) found significant differences in mean attrition scores between males and females. What matters more for the purpose of age estimation, though, is the rate of wear, which depends upon the mean difference in attrition of adjacent teeth. As with raw attrition scores, males have slightly higher mean differences in attrition between adjacent teeth, but these differences are not statistically significant. Thus, the calculated yearly attrition rates can be applied to both males and females.

4.4 Paleodemographic Analysis

The following section describes the specific methods used in the paleodemographic analysis of HK43. To start, these methods include the use of three aggregate age measures to directly investigate juvenile mortality, birth rate, and population growth rate, as well as to investigate mortality indirectly by calculating crude death rates. Next, in order to investigate patterns of adult mortality, hazard models are fit to the raw data from the HK43 database and a number of comparative samples. Lastly, this study employs more-recent methods that incorporate a transition-analysis approach with the estimation of hazard model parameters in order to reassess the adult age-at-death distribution for HK43.

4.4.1 Aggregate Age Measures

As previously discussed, the study of aggregate age measures (i.e., age ratios and proportions) have been of interest to paleodemographers since at least the early 1980's, as part of an effort to extract relevant demographic information from human skeletal assemblages, while mitigating (at least partially) error introduced by inaccuracies in skeletal age estimation and underenumeration of infants (McCaa, 2002). The current study makes use of three aggregate age measures—the D_{1-5}/D_{1-10} proportion, the ratio of immature skeletons, and the D_{30+}/D_{5+} proportion.

The D_{1-5}/D_{1-10} proportion is used to investigate possible changes in juvenile mortality. This measure, first investigated by Buikstra and colleagues (1986), is calculated by dividing the number of individuals 1–5 years of age by the number of individuals 1–10 years of age. By excluding individuals younger than one year old, this measure minimizes the effects of underenumeration of infants, a common occurrence in archaeologically-derived skeletal assemblages. In order to test for significant differences between samples, 95% comparison intervals were calculated according to the procedure outlined by Buikstra and colleagues (1986:534). The comparison intervals are more conservative than true confidence intervals, though they may be better suited to the quality of the data (Buikstra et al., 1986; McCaa, 2002).

The next two measures are used to investigate fertility (birth rate) population growth rate. The first measure used is the ratio of immature skeletons, also written as ${}_{15}P_5$ (Bocquet-Appel, 2002). The ${}_{15}P_5$ value is calculated by dividing the number of individuals 5–19 years of age by the total number of individuals (minus those under five years of age). Again, the exclusion of those under five years old minimizes error introduced by the underenumeration of the very young. Bocquet-Appel (2002:643, table 2) provides regression formulae for predicting birth rate and population growth rate (and their associated standard errors) using calculated ${}_{15}P_5$ values.

The final aggregate age measure used is the D_{30+}/D_{5+} proportion. As a complement to the ${}_{15}P_5$ value, this measure is used as a means of assessing relative changes in fertility. The D_{30+}/D_{5+} proportion is calculated by dividing the number of individuals over 30 years of age by those over five years of age. Using the Coale and Demeny (1983) Model West life tables, Buikstra and colleagues (1986) showed this value to be highly correlated with a population's birth rate. Comparison intervals were calculated in the same manner as for the D_{1-5}/D_{1-10} proportion.

4.4.2 Hazard Analysis of Raw Data

As discussed in the previous chapter, hazard models have begun to supplant the use of life tables for modeling mortality estimated from paleodemographic data. Gage (1988) described the methods for fitting hazard models to survivorship, death rates, and age-structure data. The general procedure uses maximum likelihood estimation to fit a Gompertz mortality model to the interval-censored, raw data in the HK43 database. As discussed in Chapter 3, the Gompertz mortality model contains two parameters—one for scale (α) and one for shape (β). In the following chapters, these parameters include the subscript "3." This denotes that these parameters relate to adult mortality, if they were included in the five-parameter Siler model. The R code has been modified from that given by Frankenberg and Konigsberg (2006), and examples of R code used here to structure the data and fit the hazard model are provided in Appendix B. The code can easily be modified to fit a more complex hazard model, such as the Gompertz-Makeham, or the Siler model, if juveniles are included.

4.4.3 Transition Analysis: Estimating an Adult Age-at-death Distribution

The final part of this analysis includes a reassessment of the adult age-at-death distribution for HK43 using a combination of transition analysis and the fitting of a Gompertz hazard model. This approach, outlined by the Rostock Manifesto, is essential before the age of any one individual can be estimated, if that is the researcher's goal. As mentioned previously, more often than not, paleodemographers will be more interested in $f(a)$, the full age-at-death distribution. To estimated this distribution for the adult sample at HK43, the current study adopts the "most appealing approach" (Hoppa and Vaupel, 2002b:6), which makes use of empirical data on the frequency of skeletal characteristics c in a target sample and information on $\Pr(c|a)$—the probability that a skeletal age indicator is observed to be in a particular stage or phase, conditional on age—in a reference sample of known age, along with a parametric mortality model to estimate the values of $f(a)$.

In order to proceed with the method described above, one needs a reference sample of skeletons of known age. In this study, reference sample data come from a subset of 746 individuals from the Terry Collection. The Terry Collection is comprised of skeletons representing unclaimed and donated individuals primarily from St. Louis, Missouri, during the first half of the twentieth century; a detailed history and demography of the collection is provided by Hunt and Albanese (2005). The data were provided by Dr. Lyle Konigsberg and contain information on age, sex, and phase scores for the pubic symphysis and auricular surface—Todd's (1920) 10-phase and Lovejoy and colleagues' (1985b) 8-phase scoring systems, respectively. These data are publicly available online (http://konig.la.utk.edu/terry.txt).

The first step in this process is to extract information on $\Pr(c|a)$ in the reference sample, a process for which both nonparametric and parametric methods exist. Müller and colleagues (2002) used kernel density estimation—a nonparametric technique to estimate the conditional expectation of a random variable—to estimate what they called "weight functions," or the conditional probabilities that a bone of exact age-at-death a will be classified into a specific age-indicator stage or category. This approach requires a minimum assumption of invariance with respect to the weight functions—meaning that a bone of age-at-death a will have the same probability of being assigned a specific age-indicator stage, regardless of the population from which the bone comes (an implication of assuming biological uniformity).

As noted by Konigsberg and Herrmann (2006), there has been little investigation as to whether or not phases for any particular skeletal age-indicator are distinguishable with respect to age, or whether some phases should be combined. Nonparametric techniques, such as kernel density estimation described above, provide a useful method to evaluate the degree of overlap in the distribution of age-indicator phases and should be applied as a preliminary step before attempting a parametric analysis (Müller et al., 2002:186). The current study takes this approach in order to assess the usefulness of collapsing some phases for the public symphysis and auricular surface (Figures 4.6 and 4.7).

It is clear from these figures that there is considerable overlap in the kernel density distributions for phases in both the pubic symphysis and auricular surface, so much so that the lines for each phase are not all easily distinguished, particularly in the lower phases. This may be a general drawback of any osteological age-indicator categorized into a phase-based system. Similar results were reported with Suchey's (Katz and Suchey, 1986; Suchey and Katz, 1986) six-phase scoring system for the pubic symphysis, and Müller and colleagues (2002) suggested combining some phases to reduce the amount of overlap. Others have advocated a similar strategy with scoring systems for the pubic symphysis and auricular surface (Herrmann and Konigsberg, 2002; Konigsberg and Herrmann, 2006). This rationale guided the present analysis, and a trail-and-error approach was used to determine the best combination of collapsed phases for the original Todd and Lovejoy scoring systems. Based upon a visual inspection of the original kernel density plots, each scoring system was collapsed into a scheme with fewer phases

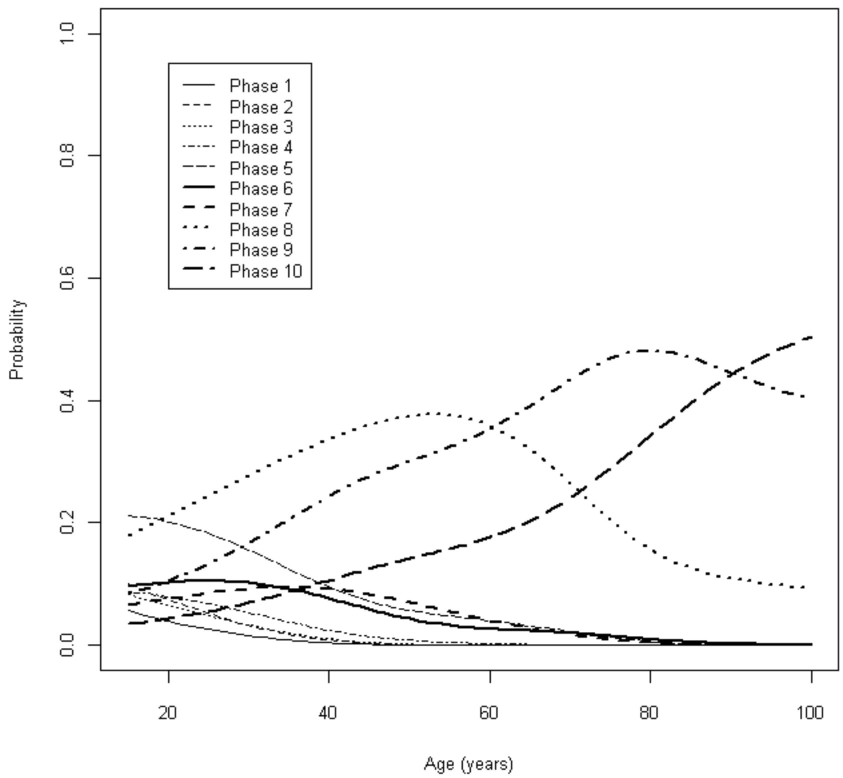


Figure 4.6: Terry Collection kernel densities—Todd's 10-phase system for the pubic symphysis.

(Figure 4.8). Todd's 10-phase system for the pubic symphysis was collapsed into three phases: 1 (Todd 1–5), 2 (Todd 6–7), and 3 (Todd 8–10). Lovejoy and colleagues' 8-phase system for the auricular surface was collapsed into four phases: 1 (Lovejoy 1–3), 2 (Lovejoy 4–5), 3 (Lovejoy 6–7), and 4 (Lovejoy 8).

A number of parametric methods are available to estimate $\Pr(c|a)$ in the reference sample. Following previous studies (Herrmann and Konigsberg, 2002; Konigsberg and Herrmann, 2006), this analysis uses a restricted cumulative probit regression model (or, ordinal probit model). Following the notation in Konigsberg and Herrmann (2002), the ordinal probit model may be written as

$$\Pr(C(A) = c_i | a = A) = \Phi(\alpha_i - \beta \times A) - \Phi(\alpha_{i-1} - \beta \times A),$$

where $\Phi(\cdot)$ is a standard normal integral, α is a set intercepts with α_0 equal to negative infinity and α_1 equal to positive infinity, and β is a slope. The parameters α and β can be estimated by maximum likelihood estimation. These equate to the "weight functions" estimated using the nonparametric kernel

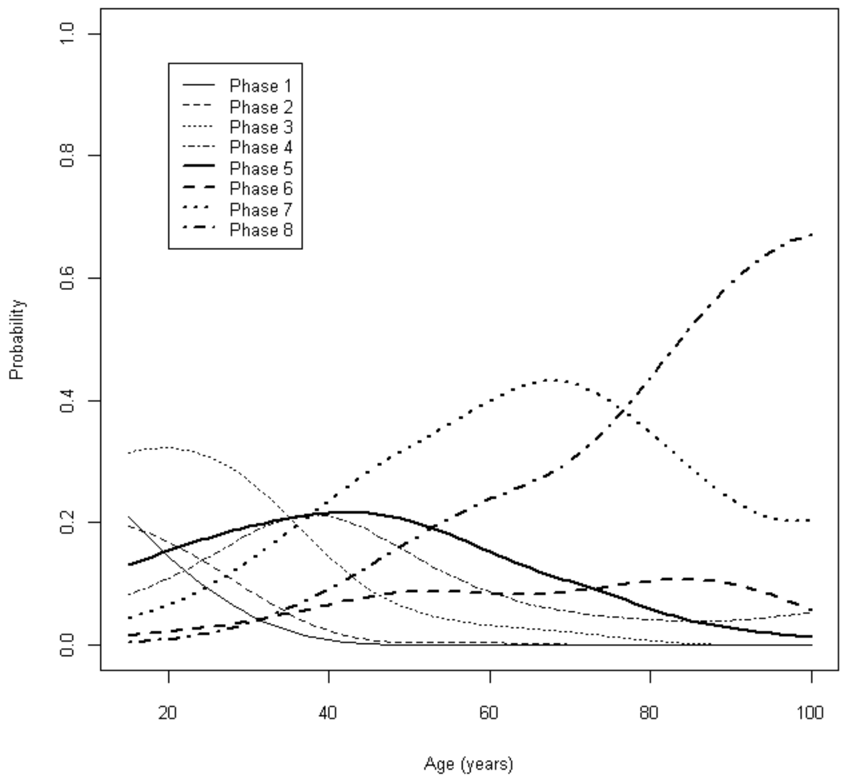


Figure 4.7: Terry Collection kernel densities—Lovejoy et. al's 8-phase system for the auricular surface.

density approach (Love and Müller, 2002), and the parametric and nonparametric densities may be compared to evaluate how well the parametric model performs (see Chapter 5).

In statistical terminology, the R function `polr` (proportional-odds logistic regression) uses a latent-trait approach for the ordinal probit model. The general method is is described in detail by Johnson and Albert (1999:127-130), and its application in a paleodemographic setting is described by Konigsberg and Herrmann (2002) and applied by Herrmann and Konigsberg (2002). In order to check the output from the transition analysis performed for the reference sample, Table 4.5 compares estimated ages-to-transition to those published by Herrmann and Konigsberg (2002:249, table 12.1). The two sets of results are in good agreement, and any discrepancy is likely due to a slight differences in the reference sample and R code used to perform these separate analyses.

Estimates for the mean ages-to-transition for the collapsed pubic and auricular scoring schemes are presented in Chapter 5. Once the ages-to-transition have been estimated from the reference sample, this information is combined with the frequency distribution of phases for each skeletal age indicator to

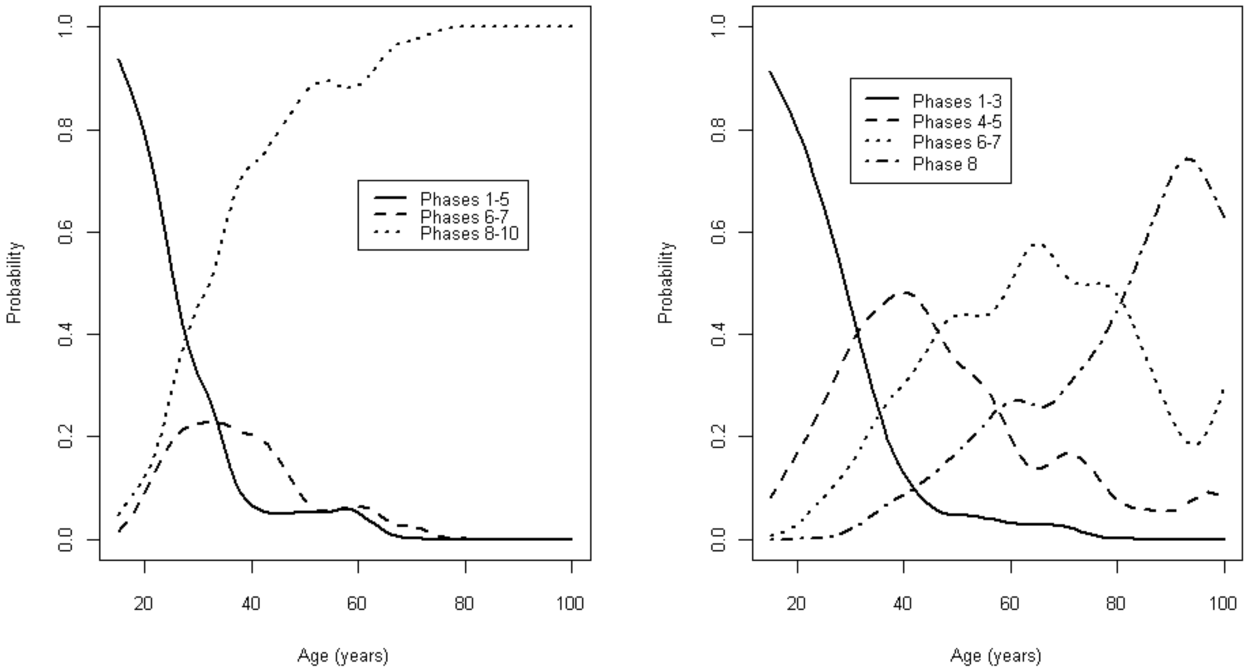


Figure 4.8: Todd Collection kernel densities—collapsed Todd phases for the pubic symphysis (left) and collapsed Lovejoy phases for the auricular surface (right).

estimate the age-at-death distribution for HK43. The prior distribution is unspecified, but takes the form of a Gompertz mortality model. These distributions are then compared with distributions for the raw data to evaluate the results using the traditional and transition-analysis approaches.

Table 4.5: Transition ages for pubic symphysis and auricular surface from the Terry Collection ($n = 746$); SD is the common standard deviation. Todd phases 1–4 collapsed; auricular phases 1–2 collapsed.

	Log age (estimate)	
Transition	Present study	Herrmann and Konigsberg (2002)
Pubic symphysis		
1/2	2.8743	2.8670
2/3	3.1913	3.1974
3/4	3.3329	3.3396
4/5	3.4603	3.4679
5/6	3.9326	3.9367
6/7	4.4249	4.4287
SD	0.4637	0.4724
Auricular surface		
1/2	2.9470	2.9350
2/3	3.3351	3.3481
3/4	3.5790	3.5920
4/5	3.8205	3.8257
5/6	3.9190	3.9227
6/7	4.3340	4.3275
SD	0.3986	0.3973

Chapter 5 Results and Discussion

This chapter presents the results of the paleodemographic analyses. For consistency, the results are separated and presented as outlined in the previous chapter. A discussion follows each section of results, which are summarized along with conclusions in the final chapter.

5.1 Dental Attrition

A total of 174 individuals had available attrition scores for at least one tooth. Of these individuals, 70 were included in the "baseline" sample—individuals for whom developmental age had been estimated between 6 and 25 years. Table 5.1 presents descriptive statistics for dental attrition data for the entire HK43 sample, and Figures 5.1–5.4 provide scatterplots that illustrate the pattern of attrition for adjacent teeth.

Table 5.1: Summary statistics for dental attrition.

Tooth	*n*	Mean	sd	Range
NM1	137	20.27	7.96	4–40
NM2	139	14.52	6.64	4–40
NM3	106	10.44	5.86	4–37
XM1	136	20.29	8.33	4–40
XM2	134	13.80	6.98	3–38
XM3	113	9.14	5.62	4–36

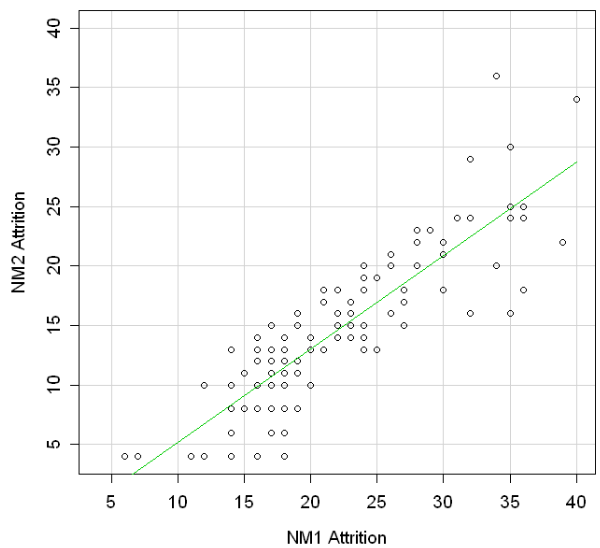


Figure 5.1: Scatterplot of attrition scores: NM1 vs. NM2 with least squares regression line ($r^2 = 0.76$).

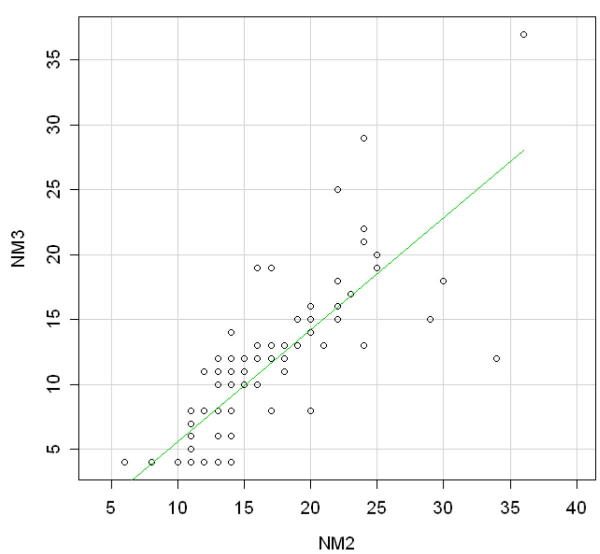


Figure 5.2: Scatterplot of attrition scores: NM2 vs. NM3 with least squares regression line ($r^2 = 0.67$).

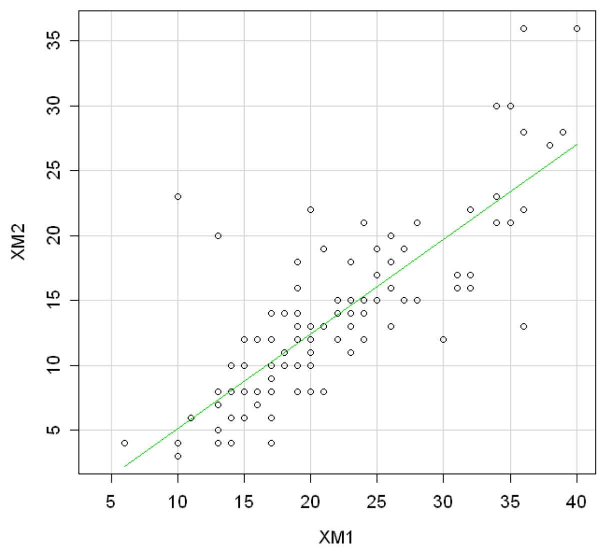


Figure 5.3: Scatterplot of attrition scores: XM1 vs. XM2 with least squares regression line ($r^2 = 0.65$).

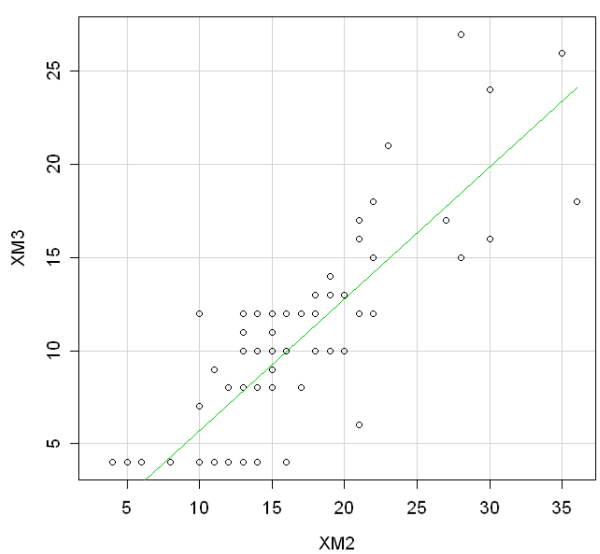


Figure 5.4: Scatterplot of attrition scores: XM2 vs. XM3 with least squares regression line ($r^2 = 0.74$).

As previously mentioned, the primary reason for inclusion of dental attrition was to evaluate the application of a population-specific reference sample. The rationale was based on the idea that a population-specific reference sample would mitigate interpopulation differences in age-related changes in skeletal morphology. By reducing bias introduced by a reference sample that differs in many respects (e.g., temporally, geographically, and culturally) with the target sample, the weight of the uniformitarian assumption could be relaxed. As described in the previous chapter, using a baseline sample—individuals with a developmental age of 6 to 25 years—a yearly attrition rate was calculated and applied in to estimate age for all individuals with recorded observations for dental attrition. Table 5.2 shows the means and standard deviations for the difference in attrition scores for adjacent teeth in the baseline sample.

Table 5.2: Summary statistics for difference in adjacent attrition scores in the baseline sample.

Tooth	*n*	Mean	sd
NM1-NM2	49	6.92	2.64
NM2-NM3	34	5.03	1.88
XM1-XM2	50	7.82	2.56
XM2-XM3	36	4.83	2.84

Values presented in Table 5.2 were used to calculate the sample's yearly attrition rate for each tooth type. As discussed previously, in her assessment of dental attrition as an indicator of age-at-death, Huard (2006) used the standard deviation—rather than the mean—of the difference in adjacent attrition scores for calculating the yearly attrition rate. For comparison, yearly attrition rates were calculated using the mean ("Mean6") and standard deviation ("SD6") method. This allowed for evaluating the impact on resulting age estimates of choosing one method over the other. Table 5.3 lists the calculations for the yearly attrition rate for each tooth type, as well as the yearly attrition rates (an average of the left and ride side) reported by Huard (2006). The Mean6 rates were calculated by dividing the mean by six, while SD6 rates were calculated by dividing the standard deviation by six.

Table 5.3: Yearly dental attrition rates calculated for each tooth type.

	Yearly Attrition Rate		
Tooth	Mean6	SD6	Huard (2006)
NM1 and NM2	1.15	0.44	0.56
NM3	0.84	0.31	0.44
XM1 and XM2	1.30	0.43	0.55
XM3	0.81	0.47	0.51

As shown in Table 5.3, the particular method chosen—Mean6 or SD6—clearly affects the calculations of the yearly attrition rate (most evident for the first and second molars). By extension, then, the method one chooses directly affects the estimate of age-at-death. Figure 5.5, which shows the resulting distribution of estimated age-at-death, illustrates this result. The SD6 method produces much older age estimates than does the Mean6 method.

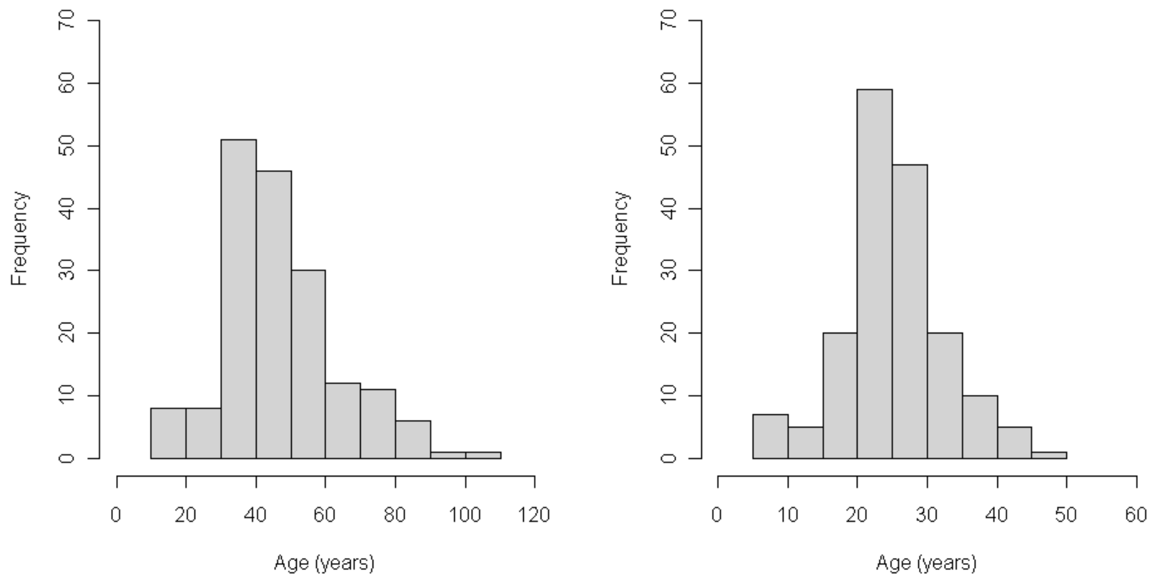


Figure 5.5: Distribution of estimated age-at-death for HK43 individuals with dental attrition data—(left) yearly attrition rate calculated using the SD6 method; (right) yearly attrition rate calculated using the Mean6 method.

The SD6 method for calculating the yearly attrition rate produces an age-at-death distribution with a range from 15.1 to 105.5 years and a mean of 46.6 years. The Mean6 method for calculating the yearly attrition rate produces an age-at-death distribution with a range from 9.3 to 47.6 years and a mean of 25.1 years. A paired *t*-test shows that the difference in these two distributions is highly significant ($p <$ 2.2E-16). Age estimates using the SD6 method are, on average, 21.5 years higher than those using the Mean6 method.

The obvious question is: which method is more likely to be closer to actual age? Since ages-at-death are not actually known, to assess each method's accuracy, the best measure available is developmental age. Figure 5.6 shows a scatterplot of developmental age versus age-at-death estimated using dental attrition for individuals in the baseline sample. Assuming that the age estimates based on developmental

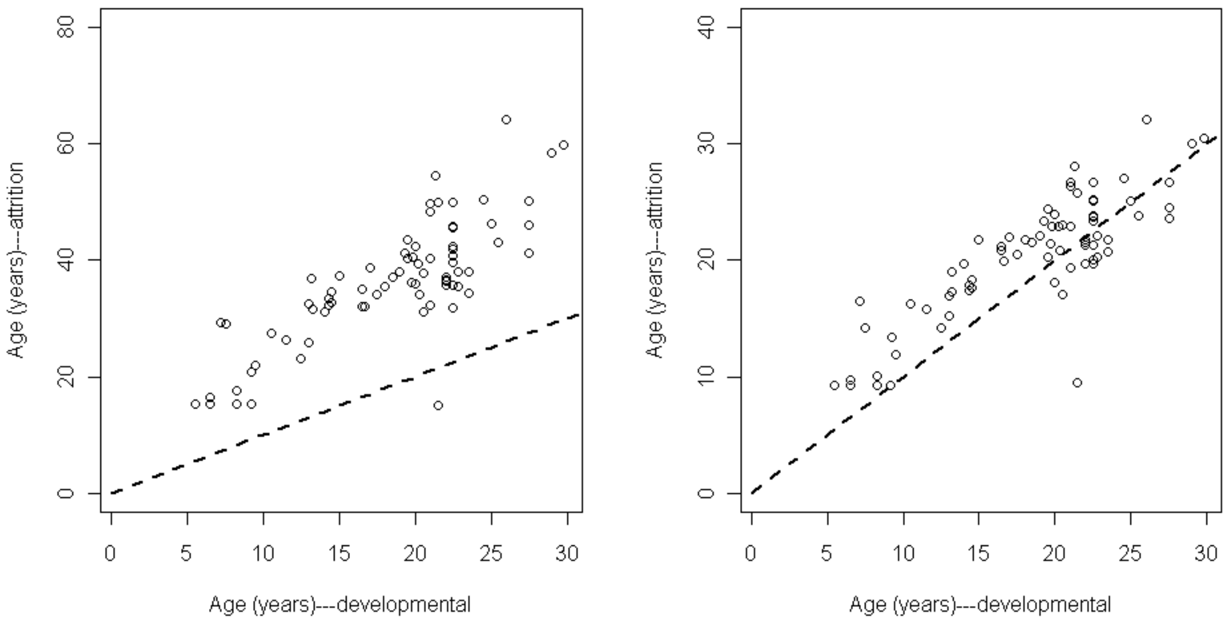


Figure 5.6: Scatter plots of estimated ages (developmental vs. attrition) for the HK43 baseline sample—(left) yearly attrition rate calculated according to Huard (2006); (right) yearly attrition rate calculated as described in this study.

criteria are close to true age, the dispersion of points around an identity line ($x = y$) reflects the accuracy of age estimates based on dental attrition. The results here suggest that the SD6 method for calculating the yearly attrition rate leads to gross over-estimation of age. On average, age estimates from the SD6 method are higher than developmental age by 17.3 years. In contrast, age estimates derived using the Mean6 method fall much closer to the identity line, with a mean difference from developmental age of 3.2 years.

5.1.1 Discussion

Huard (2006, 2008) investigated dental attrition at HK43 in a reassessment of the age-at-death distribution at the site. Using a modified version of the Miles method, she calculated a point-estimate of age-at-death for each individual with observed dental attrition scores and reassigned individuals to the appropriate age category as necessary. The result was an older age-at-death distribution, as the number of individuals classified as middle-adults (35–50 years old) and old-adults (50 years old and higher) increased, while the number of young adults (20–35 years old) decreased. Her results yielded a mean age-at-death of 38.5 years (Huard, 2006:65), more than 10 years higher than the value of 26.8 years produced by an abridged life table (Batey, 2008:257) calculated from counts of individuals within each age category from the HK43 database. Huard concluded that using dental attrition resulted in a more reasonable age-at-death distribution. The results presented here, specifically those illustrated in the figures above, suggest that her age-at-death estimates are likely too high.

Results presented here suggest that methodology—using the Mean6 or SD6 method in the calculation of yearly attrition rate—has a significant impact on the estimation of age-at-death. The current study differed from Huard's previous investigation in two additional respects. First, this analysis did not include any modification of the raw attrition data to account for the lack of a "no wear" score in the Scott system for recording dental attrition. Second, the yearly attrition rate was determined using the baseline sample (those aged 6–25 years) only. These two factors, though, made little difference in the results, especially when compared to the impact of using the SD6 or Mean6 method for calculating the yearly attrition rates.

These results also highlight problems in using age-at-death estimates from dental attrition to develop a population-specific reference sample to use in transition analysis with other skeletal age indicators. The first issue relates to small sample size. As one begins to divide the sample into individuals that have both age-at-death estimates from dental attrition and observations for one or the other two skeletal age indicators, *n* begins to decrease rapidly. This scenario is all too familiar to bioarchaeologists who typically work with small samples sizes (fewer than 100 individuals) and fragmentary skeletal remains.

The second issue, which will require future study in additional samples, is the attenuated age-at-death distribution estimated by dental attrition. O'Connor (1995) addressed this in a similar evaluation the applicability of dental attrition on a skeletal assemblage from the colonial period Maya site of Tipu. She concluded that age estimates based on dental attrition—using inverse calibration or a classical calibration, MLE approach—were free of bias introduced by reference sample age mimicry and variation in the rate of attrition. As a result, she argued that traditional methods of age estimation, specifically those using inverse calibration and popular reference samples (e.g., Terry, Hamann-Todd, modern forensic samples, etc.), may over-age individuals in the 20–40-year range (O'Connor, 1995:204). Thus, many published paleodemographic profiles falling into this category may be younger than previously thought. This would certainly be the case for HK43, where no individuals with dental attrition were estimated to have been over the age of 50 years. Though transition analysis, used in conjunction with a parametric hazard model, has been shown to be relatively immune to the problem of age mimicry, the population-specific reference sample from HK43 exhibits highly skewed (young) age distribution. Thus, additional procedures using transition analysis did not include individuals from HK43 as a population-specific reference sample.

5.2 Age Ratios and Proportions

As previously discussed, age ratios or proportions offer a number of practical advantages for paleodemographic analyses. Further, some of these aggregated measures have strong correlations with demographic rates affecting a population's age structure. The following section presents results for the analysis of the D_{1-5}/D_{1-10} proportion, ${}_{15}P_5$ ratio, and the D_{30+}/D_{5+} proportion—three measures that have become popular among paleodemographers.

5.2.1 Juvenile Mortality

Table 5.4 presents the calculated D_{1-5}/D_{1-10} values for HK43 and three comparative samples—Naga-ed-Dêr, Çatal Hüyük, and Taforalt. Data from Naga-ed-Dêr come from cemetery N7000, a large Predynastic cemetery represented by 853 individuals (Mortensen, 1991; Podzorski, 1990). Radiocarbon dating places the use of Cemetery N7000 at about 3800 to 3100 BC (Savage, 1997). Human skeletal remains from Çatal Hüyük, a large Neolithic settlement in central Turkey, date from about 6200 to 5720 BC and include 268 individuals with demographic data (Angel, 1971). Taforalt represents an assemblage of human remains from Morocco and dates from about 12,000 to 11,000 years BP during the Epipaleolithic period; data taken from Hassan (1981).

Table 5.4: Values calculated for the D_{1-5}/D_{1-10} proportion for HK43 and comparative samples (see text for details).

Sample	D_{1-5}	D_{1-10}	D_{1-5}/D_{1-10}	95% comparison interval
HK43 (early)	7	10	0.7000	0.3726–1.0274
HK43 (late)	12	31	0.3871	0.2012–0.5730
HK43 (total)	19	41	0.4634	0.3017–0.6251
Naga-ed-Dêr	76	106	0.7170	0.6164–0.8175
Çatal Hüyük	29	53	0.5472	0.4050–0.6894
Taforalt	82.8	93.4	0.8865	0.7794–0.9936

Buikstra et al. (1986) originally proposed the D_{1-5}/D_{1-10} proportion as a useful measure of juvenile mortality based on the assumption that populations that experience high levels of overall mortality would also experience high mortality among weaning-age children, which they defined as those between 1 and 5 years of age. Thus, this proportion reflects the mortality of young children relative to all children (1–10 years of age). In an analysis of model life tables, Buikstra et al. (1986) also showed that the D_{1-5}/D_{1-10} proportion is strongly correlated with the crude death rate of juveniles (0 to 15 years of age).

The late-period subset from HK43 exhibits the lowest value for the D_{1-5}/D_{1-10} proportion. Even when combined, the total HK43 sample exhibits the lowest D_{1-5}/D_{1-10} value. Not surprisingly, Taforalt, the only strictly hunter-gatherer population among the group, exhibits the highest D_{1-5}/D_{1-10} proportion. This result likely reflects high juvenile mortality, especially of weaning-age children, which would be expected in high-mortality populations thought to be characteristic of human prehistory.

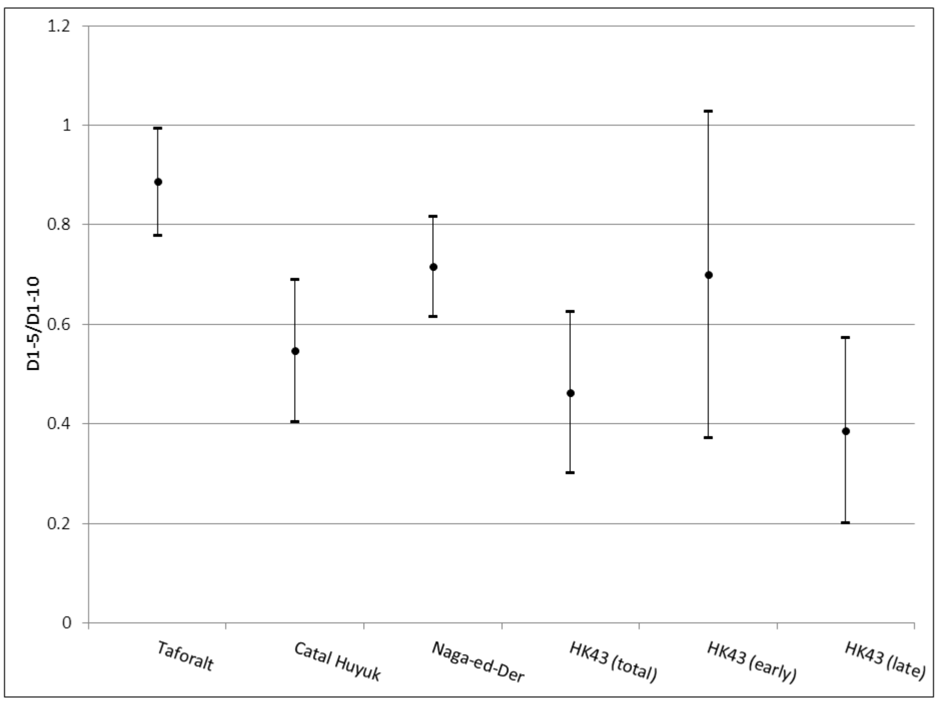


Figure 5.7: D_{1-5}/D_{1-10} proportion for HK43 and comparative samples.

Figure 5.7 shows the D_{1-5}/D_{1-10} proportion with 95% comparison intervals for all groups, plotted in general chronological order from earlier to more recent. Sample size, particularly small numbers for D_{1-10}, directly affects the size of the comparison intervals, as evidenced by the early-period subset from HK43. Although differences in the D_{1-5}/D_{1-10} proportion are not statistically significant for all the comparative samples, the general trend follows expectations of reduced juvenile mortality as populations transition from a primarily hunter-gatherer to agricultural subsistence strategy (Sellen and Mace, 1999). While the D_{1-5}/D_{1-10} proportion does decrease from the early to late periods at HK43, this difference is not statistically significant at the $p = 0.05$ level. On the other hand, the difference in the D_{1-5}/D_{1-10} values between HK43 and Naga-ed-Dêr approaches significance. Although these two samples may not be directly comparable—evidence suggests that Naga-ed-Dêr represents individuals from all segments of society, not only the lower-class members as suspected for HK43—they represent two coeval populations of similar cultural traditions, only separated by about 200 km.

In addition to the juvenile death rate, the D_{1-5}/D_{1-10} proportion is also correlated, though not quite as strongly, to the crude birth rate. As such, the observed decrease in this proportion from the early to late periods at HK43 could reflect a decrease in juvenile mortality or, alternatively, a decrease in the birth rate (Buikstra et al., 1986). Further analysis of the birth rate using two separate measures (see below) suggests decreasing juvenile mortality as a more likely explanation.

5.2.2 Fertility and Population Growth

Fertility (measured by the birth rate) and population growth rate were investigated using two measures—the ratio of immature skeletons (${}_{15}P_5$) and the D_{30+}/D_{5+} proportion. While the D_{30+}/D_{5+} proportion is used as a relative measure of fertility (through its correlation with the birth rate), Bocquet-Appel (2002) provides regression equations to estimate the birth rate and growth rate using the ${}_{15}P_5$ value. These formulae include a standard error of 0.00304 and 0.00534 for the birth rate and growth rate, respectively. Table 5.5 lists the calculated ${}_{15}P_5$ values for HK43 and the same comparative samples listed above.

HK43 exhibits the highest birth rate and growth rate of the samples compared. Using the values above, one may calculate the death rate, d, by rearranging and solving a basic formula from demography, $r = b - d$. Doing so yields a death rate for the early- and late-period subsets from HK43 of 0.0366 and 0.0383, respectively (0.0377 for the total sample). These estimates are slightly higher than the previously accepted death rate (0.0350) at Hierakonpolis during the Predynastic (Hoffman, 1987). Thus, over the period of cemetery use, both fertility and mortality may have increased. Though based upon paleodemographic estimates using the values for ${}_{15}P_5$, a greater increase in fertility allowed for

Table 5.5: Calculated ${}_{15}P_5$ values and paleodemographic estimates for HK43 and comparative samples.

Sample	n_{5-19}	$N_{\text{total}}{}^a$	${}_{15}P_5$	Birth rate (b)	Growth rate (r)
HK43 (early)	28	126	0.2222	0.0493	0.0073
HK43 (late)	67	247	0.2713	0.0517	0.0134
HK43 (total)	95	373	0.2547	0.0491	0.0114
Naga-ed-Dêr	95	705	0.1348	0.0295	-0.0057
Çatal Hüyük	58	254	0.2283	0.0449	0.0081
Taforalt	23.5	102.3	0.2298	0.0451	0.0083

[a]Minus small children (0-4 years old)

positive population growth. Strikingly, even the lowest estimated value for population growth rate for HK43—0.0073 (0.73%) for the early-period subset—is well above previous estimates from 0.08% to 0.18% for the Egyptian Predynastic (Butzer, 1976; Hassan, 1993).

Looking at the paleodemographic estimates using the ${}_{15}P_5$ values for the comparative samples, Taforalt, Çatal Hüyük, and the early-period subset from HK43 have growth rates around that often assumed for prehistoric populations (Paine, 2000). Again, HK43 sharply contrasts with the sample from Naga-ed-Dêr, which exhibits a low birth rate and negative growth rate (-0.57%). These figures yield a death rate at Naga-ed-Dêr of 0.0352. Thus, it appears that a difference in fertility, more so than mortality, accounts for the difference in estimated growth rates for these samples.

Finally, D_{30+}/D_{5+} proportions were calculated for HK43 and the comparative samples (Table 5.6). As with the ${}_{15}P_5$ ratio, the the D_{30+}/D_{5+} proportion attempts to control for underenumeration of infants by excluding individuals under 5 yeas of age. In a regression analysis using model life tables, (Buikstra et al., 1986:533) showed that this proportion has a strong, negative correlation with the birth rate and, slightly less so, with the death rate. Rather than use the D_{30+}/D_{5+} values in a regression equation to predict birth and death rates, the authors suggested comparing the D_{30+}/D_{5+} values directly, as a relative measure of fertility.

Decreases in the D_{30+}/D_{5+} likely reflects an increase in the birth rate, as this proportion is highly sensitive to changes in fertility (McCaa, 1998). Figure 2.8 plots the calculated D_{30+}/D_{5+} values for HK43 and the comparative samples, showing them in general chronological order. Though the overlap of the comparison intervals suggests that none of the samples are significantly different from one another, it should be noted that the comparison intervals are meant to be conservative, since

Table 5.6: Values calculated for the D_{30+}/D_{5+} proportion for HK43 and comparative samples.

Sample	D_{30+}	D_{5+}	D_{30+}/D_{5+}	95% comparison interval
Early	58	126	0.4603	0.3681–0.5525
Late	109	247	0.4413	0.3754–0.5072
Total	167	373	0.4477	0.3941–0.5013
Naga-ed-Dêr	348.5	705	0.4943	0.4553–0.5333
Çatal Hüyük	119	254	0.4685	0.4035–0.5335
Taforalt	57.1	102.3	0.5588	0.4564–0.6611

paleodemographic samples are usually small (McCaa, 2002). Assuming that this proportion does, in fact, reflect relative changes in birth rate, then these results are consistent with those from of the ${}_{15}P_5$ ratio. The Epipaleolithic sample from Taforalt exhibits the highest D_{30+}/D_{5+} value, suggesting the lowest birth rate among these samples, and the calculated values exhibit a general decrease across time. Again, these results suggest that HK43 exhibited higher birth rates than the comparative samples, and show a similar distinction between HK43 and the contemporaneous Egyptian sample from Naga-ed-Dêr.

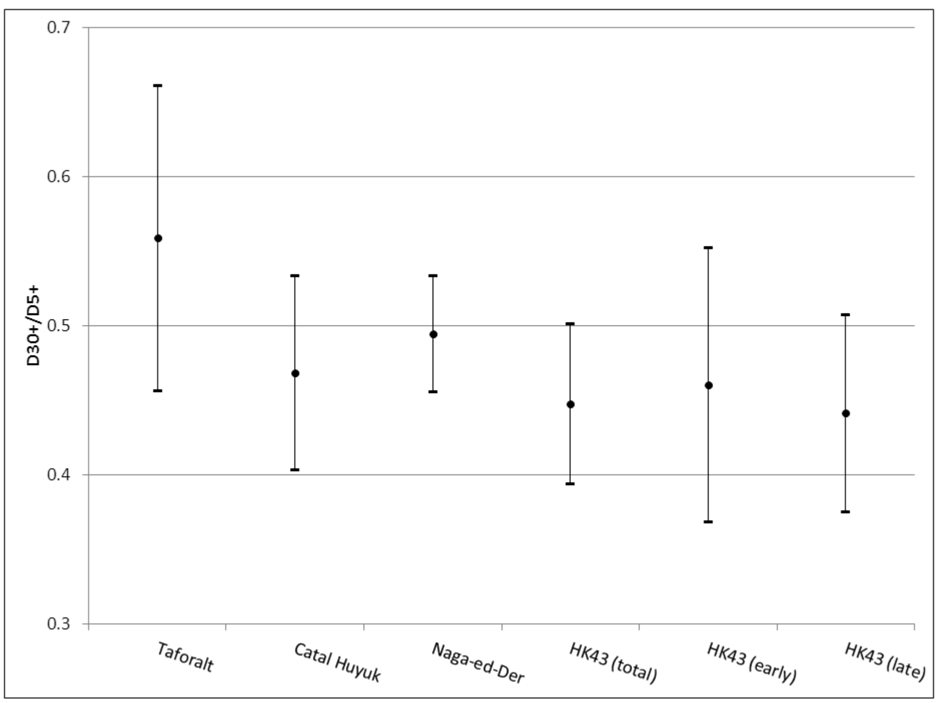


Figure 5.8: D_{30+}/D_{5+} proportion for HK43 and comparative samples.

5.2.3 Discussion

Early reports on the HK43 skeletal assemblage noted the high proportion of prime-age adults (20–35 years of age) and relatively young mean age-at-death. These results were initially interpreted as reflective of a population under strain (Rose, 2003), which contradicts the expectation that the laboring-class population at Hierakonpolis had enough biological capital to support a growing population center from which the Egyptian state eventually emerged. As Sattenspiel and Harpending (1983) pointed out over 25 year ago, though, if a population is not stationary, mean age-at-death does not accurately reflect mortality, and the age-at-death distribution tells us more about fertility than mortality. This demographic fact served as the rationale for using established, aggregate measures to gain information on fertility and, indirectly, mortality.

The results above are consistent with archaeological data that suggest that the population at Hierakonpolis increased throughout the Predynastic period. If this included an increase in the number of nonagricultural workers (i.e., craft specialists), then one would expect the number of agricultural workers to have similarly increased (Midant-Reynes, 2000b). The basic mathematics of demography provide that a population closed to migration will exhibit positive growth rate whenever the birth rate is higher than the death rate. A decrease in the spatial extent of settlement area toward the end of the Naqada II period indicate that people began aggregating closer to the floodplain (Harlan, 1985). This may have included a certain degree of immigration of individuals from smaller, outlying villages. At the same time, though, individuals were likely emigrating from the site, part of the Upper Egyptian cultural expansion during the Naqada II. Thus, even though it is unlikely that the population at Hierakonpolis was truly closed to migration, net migration may have been close to zero. If so, the above results for HK43 may be interpreted in terms of mortality and fertility alone and offer some insight into interaction of these demographic processes. In other words, were the estimated growth rates for the population represented by HK43 the result of improvements in mortality or fertility (or both)?

As mentioned above, the overall death rate, calculated from estimates of the birth rate and growth rate from the ${}_{15}P_5$ ratio, increases from the early to late period for HK43. This makes it unlikely that a decrease in overall mortality accounts for the increase in population growth. Estimates of birth rate, based on the ${}_{15}P_5$ ratio, increase from the early to late period, and this is supported by an associated decrease in the D_{30+}/D_{5+} proportion. A decrease in the D_{1-5}/D_{1-10} proportion from the early to late period for HK43 suggests that an improvement in juvenile mortality may have been a significant factor contributing to the growth rate of the population represented by HK43. An analysis of paleopathological lesions related to childhood provide additional evidence that the non-elite population at Hierakonpolis suffered a low degree of physiological stress (Kumar, 2009). Even if age-specific fertility levels remained constant over time, increases in the number of individuals reaching sexual maturity can have large effects on population growth rate and life expectancy (Pennington, 1996). These results are consistent with those from studies of contemporary, ethnographic populations. Lower rates of juvenile mortality have been found to be associated with permanent settlement and a decreased reliance on extracted food resources, such as foraging and hunting (Sellen and Mace, 1999).

An advantage of using the above aggregate measures to infer demographic characteristics is that these methods avoid some problems common to paleodemography, namely underrepresentation of certain age groups (*e.g.*, infants or the very old) and systematic bias in age estimation. On the other hand, by using these crude measures, other bits of information (age-specific patterns) are ignored. The final piece of this paleodemographic analysis uses parametric hazard models to explore these age-specific patterns, specifically those related to mortality. This will allow for the assessment of any possible changes in adult mortality, particularly during the child-bearing years, that may have contributed to the estimated increases in birth rate and population growth rate.

5.3 Adult Mortality

The following section presents results of the hazard model analysis for HK43 and a number of comparative samples. As mentioned previously, parametric hazard models have become more popular in modeling adult mortality in paleodemographic analyses. A Gompertz mortality model was fit to the original HK43 data—individuals assigned into age categories using the "traditional" approach. In all tables and figures, the two Gompertz parameters are written as α_3 and β_3, conforming to the notation of adult, age-dependent component of mortality in the five-parameter Siler hazard model. Because the Gompertz model describes adult mortality, convention dictates that the following analyses include only individuals assigned to the categories for 15 years of age and older.

5.3.1 Hazard Analysis of Raw Data

The raw data for HK43 can be treated as interval-censored, since in the traditional approach to paleodemographic analysis, individuals are assigned to an age category based upon observation of skeletal morphology. The total HK43 sample included 328 individuals assigned to one of the four age categories representing ages 15 years and older. Table 5.7 lists the estimated Gompertz parameters, α_3 and β_3, for the HK43 sample (including the early- and late-period subsets), as well as a number of comparative samples. "Paleo" represents a model based upon a series of published, paleodemographic life tables (O'Connor, 1995). "H-G" and "F-H" represent an average of contemporary hunter-gatherers and forager-horticulturalists, respectively (Gurven and Kaplan, 2007). "CDW-W1" represents the Coale-Demeny Model–West Level 1 (female) life table (Coale and Demeny, 1983).

Table 5.7: Estimated Gompertz parameters for HK43 and comparative samples (> 15 years of age).

Sample	*n*	α_3	β_3
HK43 (early)	118	0.0362	0.0394
HK43 (late)	210	0.0311	0.0446
HK43 (total)	328	0.0311	0.0446
Paleo (O'Connor, 1995)	simulated	0.0175	0.0665
H-G (Gurven and Kaplan, 2007)	simulated	0.0158	-0.0011
F-H (Gurven and Kaplan, 2007)	simulated	0.0118	0.0201
CDM-W1 (Jones, 2007b)	simulated	0.0158	0.0221

For the Paleo, H-G, and F-H simulated samples, published Siler hazard parameters were used to simulate age-at-death distributions; then, the Gompertz hazard model was fit to the portion of each distribution 15 years of age and older. The Coale and Demeny model life tables were accessed in electronic form using functions in the *demogR* package (Jones, 2007a), available in R. The d_x values from the West Level 1 (female) life table were multiplied by a radix of 1000 to produce an age-at-death distribution; then, the Gompertz hazard model was fit to ages 15 years and older.

Figure 5.9 shows the survival curves from the estimated Gompertz parameters for HK43 and the comparative samples. Treated separately, survival curves for the early- and late-period subsets of the HK43 sample hardly differ. The survival curves for HK43 are not unlike those typical of paleodemographic samples, as seen in the similarity to the paleodemographic model. As illustrated, the survival curves for HK43 and the paleodemographic model sharply contrast with survivorship of the Coale-Demeny model and the ethnographic samples. This highlights a common pattern among paleodemographic samples—the apparent paucity of individuals surviving into old age. Possible explanations for this pattern are considered in the discussion below.

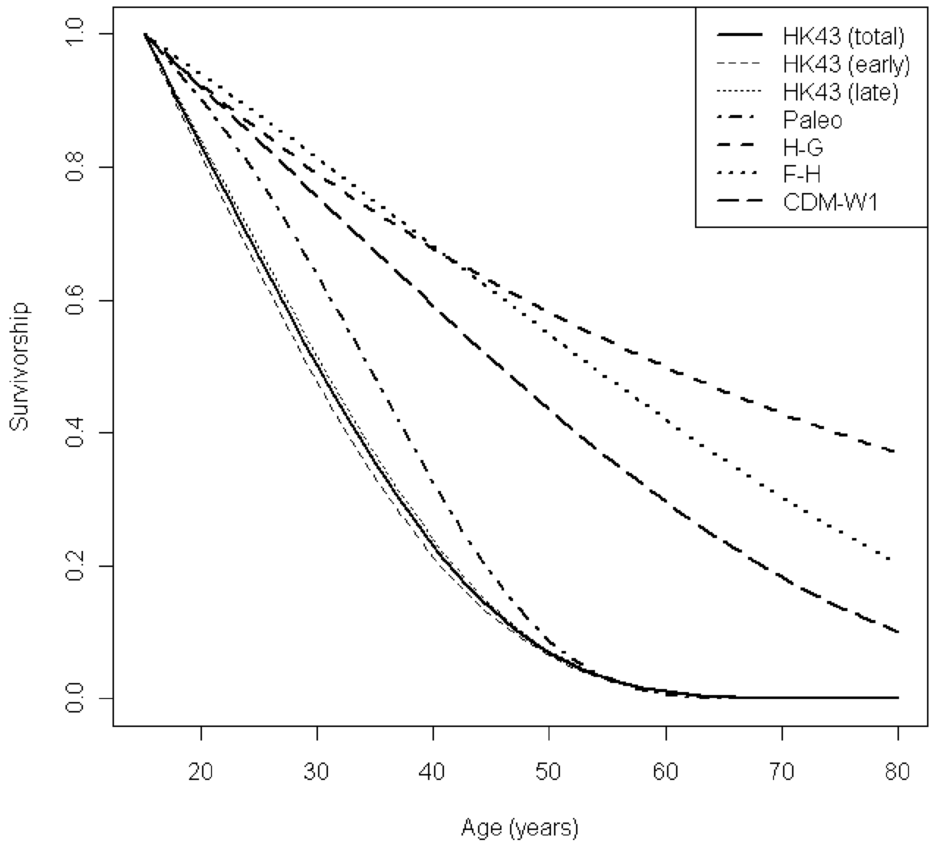


Figure 5.9: Survival curves for the HK43 sample aged 15 years and older, including the sample divided into early and late periods.

As mentioned previously, other than age, sex is the most commonly investigated covariate of mortality. Since an analysis of the aggregate measures above suggest a relatively high growth rate, particularly for a preindustrial population, and an increasing birth rate over time for HK43, it is conceivable that sex differences in the mortality experience may have played a role. Particularly, mortality effects on the sex ratio could have had significant impacts on the ease with which individuals could find mates (Early and Peters, 1990, 2000).

A total of 257 individuals from HK43 were available for this analysis, meeting the criteria of having been assigned an estimation for sex and age (15 years of age and older). Table 5.8 lists the estimated

Gompertz parameters for males, females, and both sexes combined.

Table 5.8: Estimated Gompertz parameters for HK43 males, females, and both sexes combined.

Sample	n	α_3	β_3
Males	103	0.0283	0.0604
Females	154	0.0198	0.0605
Both sexes	257	0.0234	0.0584

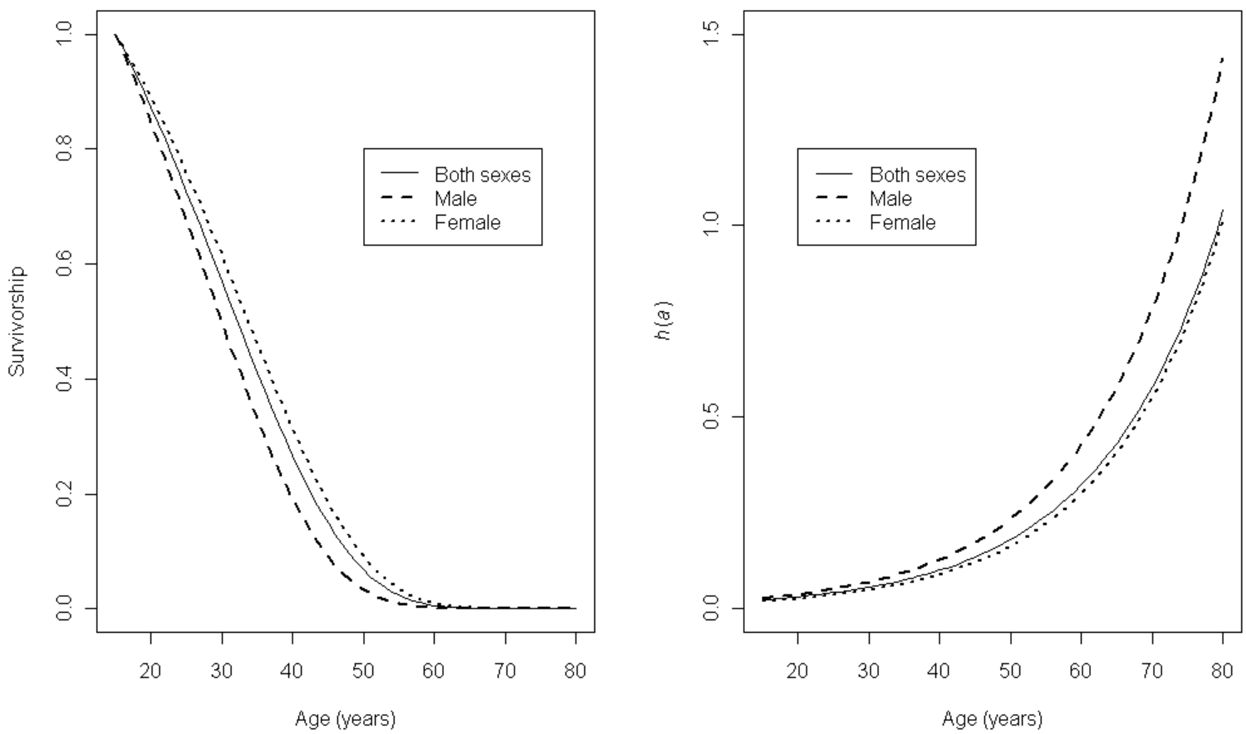


Figure 5.10: Gompertz survival (left) and hazard (right) curves for the HK43 sample—both sexes, as well as males and females plotted separately.

Figure 5.10 presents two ways of visualizing the mortality experience for males and females, ages 15 and older. The left panel shows the survival curves, while the right panel shows the curve of the hazard function (force of mortality). The hazard curves are particularly useful in illustrating the estimated Gompertz parameters for each group. Both males and females exhibit roughly the same increase in mortality with advancing age (the β_3 parameter), though males clearly exhibit a higher level of mortality (the α_3 parameter). These results suggest that throughout adulthood, males experienced a higher mortality regime than females.

To examine whether the mortality experience for males and females changed over the period of cemetery use, the male and female samples were separated by time period (early versus late). The Gompertz model was fit to these data; parameter estimates are presented in Table 5.9. Compared to their early-period counterparts, results suggest that late-period males experienced an increase in the overall level of mortality, as well as the rate at which mortality increases with advancing age. On the other hand, females exhibited a more complex change in their mortality experience. Compared to the early period, late-period females experienced a decrease in the overall level of mortality, but this was accompanied by a higher rate of mortality increase with advancing age.

Table 5.9: Estimated Gompertz parameters for HK43 males and females by time period.

Sample	*n*	α_3	β_3
Males (early)	39	0.0280	0.0583
Males (late)	78	0.0285	0.0620
Females (early)	50	0.0264	0.0523
Females (late)	104	0.0169	0.0654

Figure 5.11 illustrates these changing mortality experiences for the males and females of HK43. Though late-period males experienced higher mortality at all ages than early-period males, the hazard curves are barely distinguishable up to about 30 years of age, at which point the effect of the higher β_3 value for late-period males becomes more pronounced. Early- and late-period males exhibited a mortality rate doubling time (MRD) of about 11 and 12 years, respectively.[1]

Compared to males, early- and late-period females differed to a greater degree in both the initial mortality rate (the α_3 parameter) and the rate at which mortality increased with age. Females of the late period experienced lower mortality than their early-period counterparts until about 50 years of age, after which they experienced higher mortality. Early- and late-period females experienced an MRD of 13 versus about 11 years, respectively.

It should be noted that, even though the β_3 parameter was higher for females of the late period, their

[1]MRD is calculated as $\log(2)/\beta_3$ (Konigsberg and Herrmann, 2006:302).

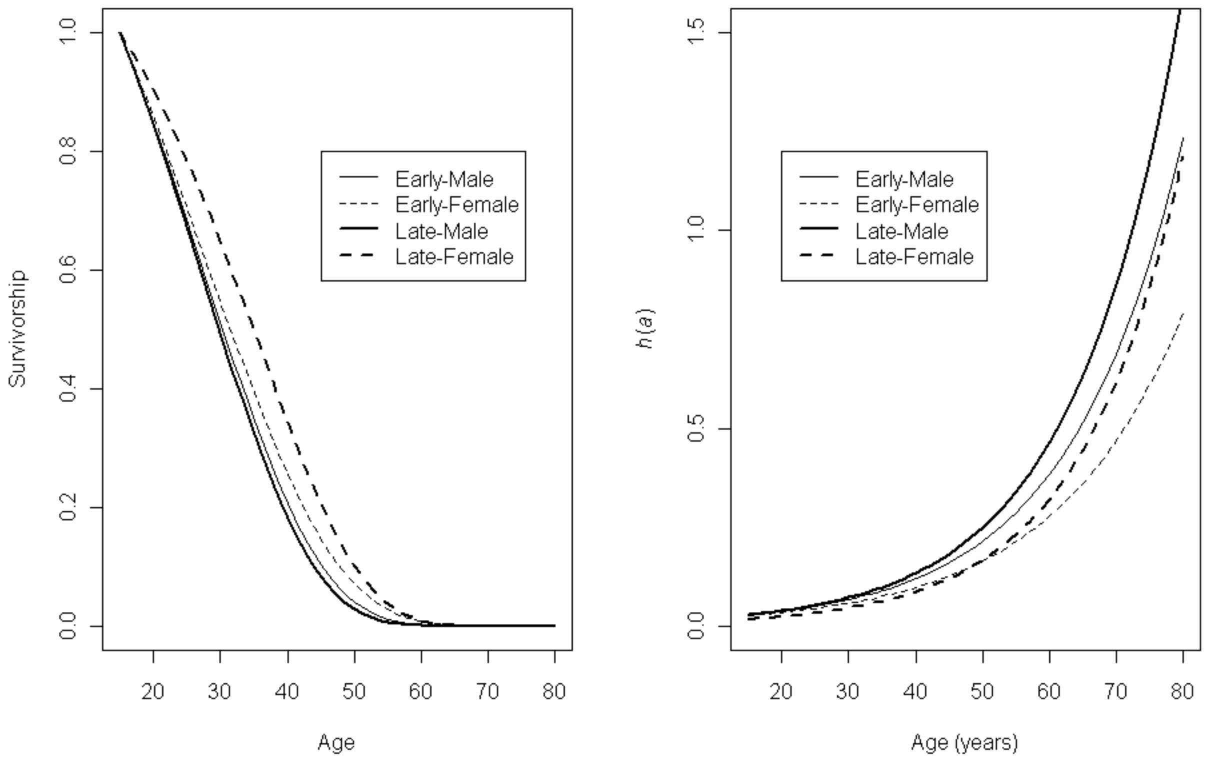


Figure 5.11: Gompertz survival (left) and hazard (right) curves for HK43 males and females, plotted separately for early and late periods.

mortality rate did not surpass that of early-period females until *after* the end of the female reproductive period (typically set at 45 or 50 years of age). This result may, in part, explain the apparent increase in the birth rate and growth rate estimated from the aggregate measures above. If late-period females did, in fact, experience an improvement in mortality throughout the reproductive years, a likely result would have been an increase in the birth rate.

For comparison, a Gompertz mortality model was fit to published paleodemographic data from two coeval, Upper Egyptian sites: Naga-ed-Dêr and Naqada. Cemeteries from these sites are included because they likely represent populations associated with what are thought to be two other Upper Egyptian polities that competed with Hierakonpolis for power and influence during the Predynastic period (Savage, 1997). As described above, cemetery N7000 from Naga-ed-Dêr represents a large, Predynastic cemetery, and the paleodemographic data have been previously reported by Podzorski (1990) and summarized by Mortensen (1991). The "unclassified" adults from Naga-ed-Dêr were assigned into an age category based on the proportions of age-classified individuals reported by

Podzorski (1990:72). The cemeteries at Naqada, originally excavated by Flinders Petrie in 1894 and 1895, represent the first graves recognized to date to the Predynastic period. Individual age estimates at Naqada were based primarily on field observations, as the recovery of crania suitable for craniometric analysis was a primary concern (e.g., Fawcett and Lee, 1902). Paleodemographic data for Naqada were taken from Mortensen (1991).

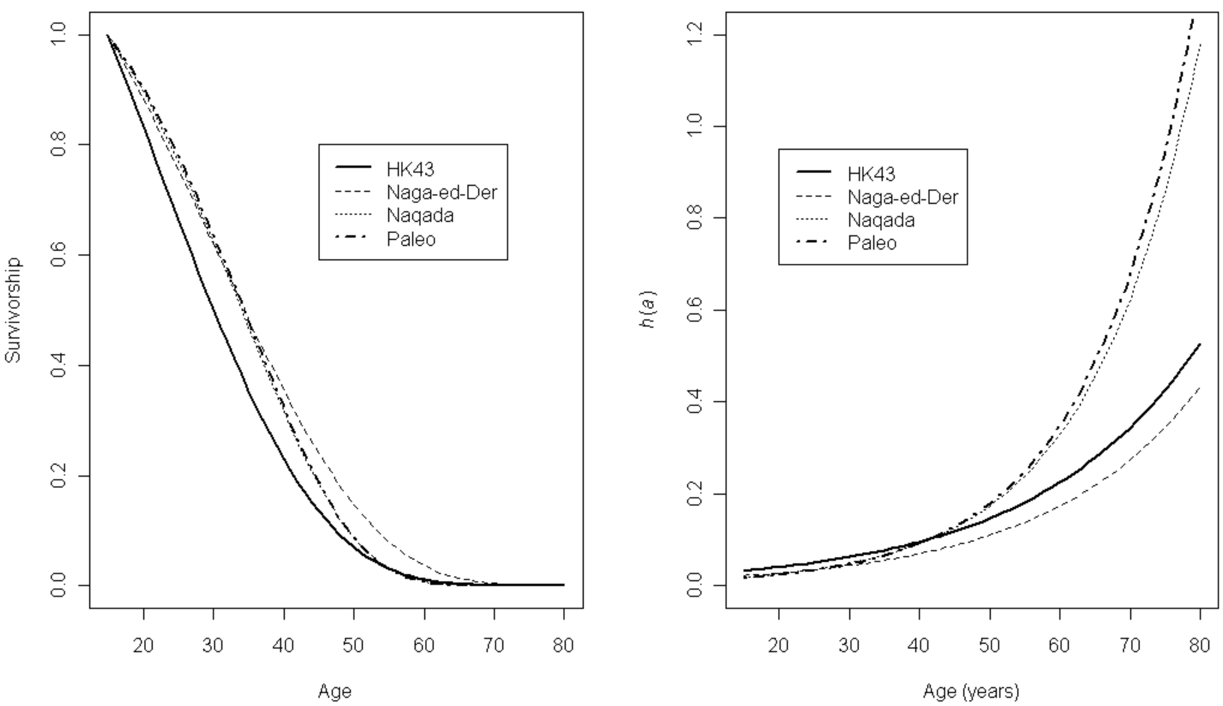


Figure 5.12: Gompertz survival (left) and hazard (right) curves for HK43, Naga-ed-Dêr, Naqada, and a paleodemographic model.

Survival and hazard curves for HK43 (total sample), Naga-ed-Dêr, Naqada, and O'Connor's paleodemographic model appear in Figure 5.12. The shape of the hazard curve for Naga-ed-Dêr ($\alpha_3 = 0.0221$, $\beta_3 = 0.0458$) is similar to HK43, though HK43 has a higher overall level of mortality. Hazard parameters for Naqada ($\alpha_3 = 0.0187$, $\beta_3 = 0.0638$) produce curves more similar to the paleodemographic model. These results should be interpreted cautiously, as observers and methods of age estimation for samples vary, and anthropological methods for estimating age from skeletal remains have improved, especially since the initial assessments of the Naqada remains. On the other hand, if the results closely reflect historical reality, they have implications, discussed below, for our understanding of developments in Upper Egypt during the middle to late fourth millennium BC.

5.3.2 Transition Analysis Results

The final analysis in this study included the application of recent methods—a combination of transition analysis and parametric hazard models—to estimate an age-at-death distribution for HK43. This approach follows the "Rostock Manifesto" (Hoppa and Vaupel, 2002b:2), which uses probability of observing a specific stage/phase of a skeletal age indicator, c, conditional on age ($\Pr(c \mid a)$) in a known-age reference sample and the probability of observing a specific stage/phase of that same age-indicator a target sample ($\Pr(c)$) to estimate $\Pr(a)$ in the target sample. $\Pr(a)$ approximates $f(a)$, the age-at-death distribution of interest. As mentioned previously, because of the mathematical relationship among the age-at-death distribution (probability density function), hazard function, and survival function, once $f(a)$ is estimated, the mortality and survival functions can be calculated.

As described in Chapter 4, the first step was to estimate $\Pr(c \mid a)$ for the pubic symphysis and auricular surface in the reference sample. This was done using restricted cumulative probit regression with age measured on a log scale. Table 5.10 provides the results of the restricted cumulative probit regression for both skeletal age indicators. The original scores for the pubic symphysis and auricular surface were collapsed as described in Chapter 4. The log-likelihood values indicate how well each model fits to the data, with the better-fitting model having a higher (less negative) value. The results show that the regression model for the pubic symphysis fits slightly better than that for the auricular surface. This contrasts with a previous analysis that reported a better fit with the auricular surface (Batey, 2009). Each study used the same reference sample, but the previous analysis used a different combination of collapsing stages for each skeletal age indicator. This suggests that the performance of the restricted cumulative probit regression model depends, at least in part, to how skeletal age indicator stages are collapsed. Figures 5.13 and 5.14 illustrate how the parametric regression models fit to the non-parametric kernel densities for the collapsed stages for pubic symphysis and auricular surface, respectively.

The next step in this analysis used the above information on $\Pr(c \mid a)$ in the reference sample with the Gompertz mortality model in order to estimate the age-at-death distribution for subsets of the HK43 sample with observations for either the pubic symphysis or auricular surface. As with the analysis using the interval-censored raw data from the HK43 database, once the hazard parameters were

Table 5.10: Transition analysis results for collapsed scoring schemes of the pubic symphysis and auricular surface; age measured on the log scale.

Pubic symphysis		Auricular surface	
Transition	Log age	Transition	Log age
1/2	3.2516	1/2	3.3289
2/3	3.4846	2/3	3.8202
SD	0.3841	3/4	4.3324
		SD	0.3899
ln L	-413.5705	ln L	-782.4826

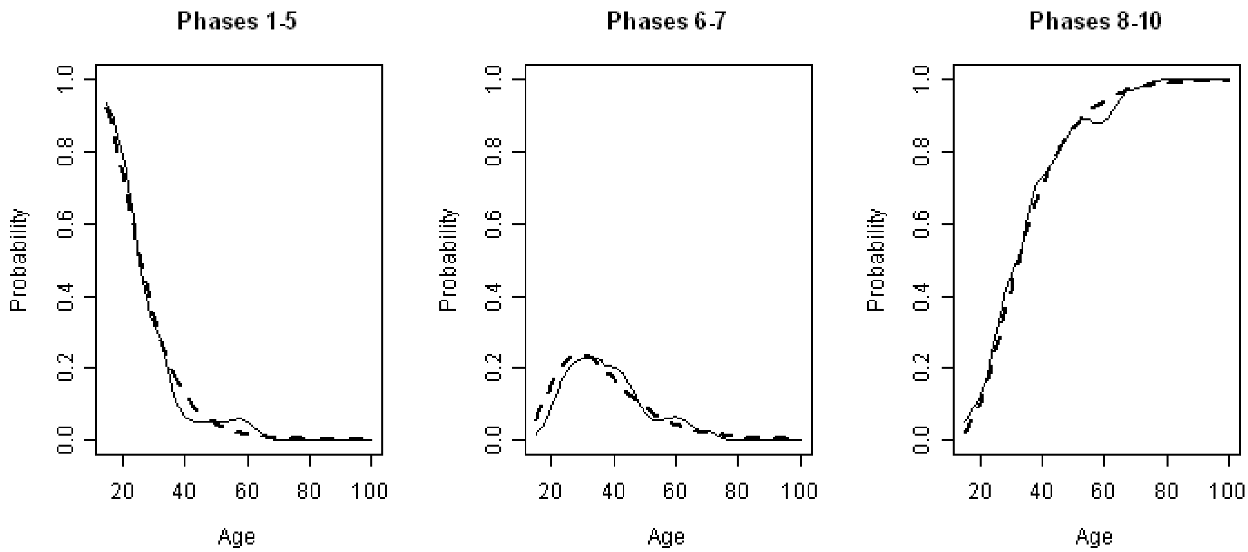


Figure 5.13: Restricted cumulative probit regression (dashed lines), with age measured on a log-scale, plotted against kernel densities (solid lines) for the collapsed, 3-phase scheme of the Todd (1920) scoring system for the pubic symphysis.

estimated, the age-at-death distribution, survival function, and hazard function were readily produced. Table 5.11 lists the estimated Gompertz parameters that describe the age-at-death distribution that most likely produced the observed distribution of phases for each age indicator. To evaluate the performance of the model for each skeletal age indicator, the table includes a likelihood ratio chi-square statistic and probability. Along with parameters estimated using transition analysis, Table 5.11 also includes Gompertz parameters estimated from the raw, interval-censored data.

The chi-square values indicate that the restricted cumulative probit regression with the Gompertz model do a slightly better job of recovering the observed stage counts for the pubic symphysis than

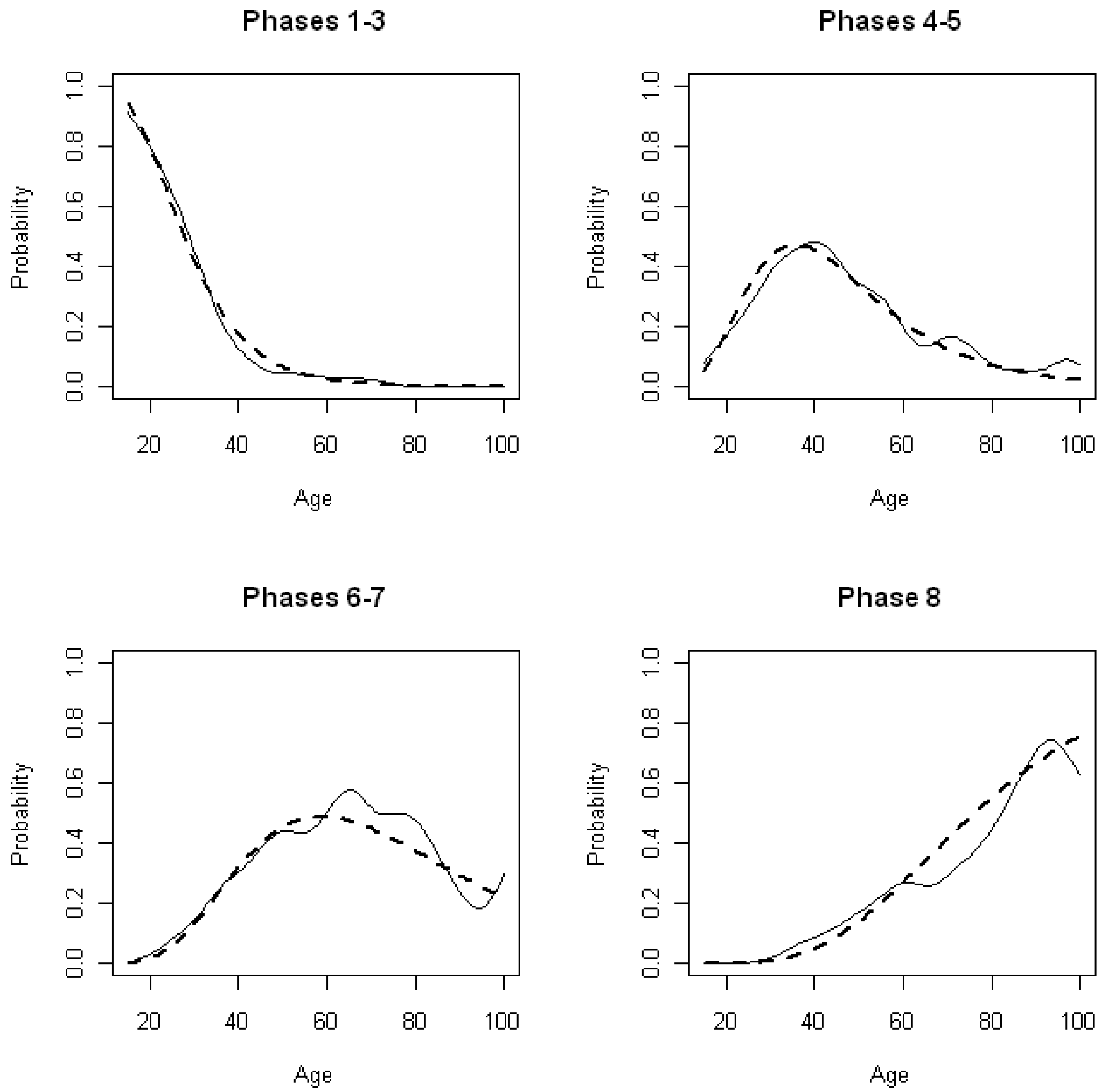


Figure 5.14: Restricted cumulative probit regression (dashed lines), with age measured on a log-scale, plotted against kernel densities (solid lines) for the collapsed, 4-phase scheme of the Lovejoy et al. (1985b) scoring system for the auricular surface.

Table 5.11: Estimates for Gompertz hazard parameters for subsets of HK43 sample with skeletal age indicator data—T = Transition, S = Summary.

Age indicator	α_3	β_3	χ^2	*p*-value
Pubic symphysis (T)	0.1054	0.0143	1.5526E-05	0.9969
Pubic symphysis (S)	0.0258	0.0496		
Auricular surface (T)	0.0592	0.0113	2.0698	0.1502
Auricular surface (S)	0.0162	0.0656		

for the auricular surface. Figure 5.15 compares the age-at-death distributions produced from the hazard parameters estimated using the transition analysis approach with that produced using hazard parameters estimated from the raw data ("summary" method). For both subsets of individuals, the transition analysis approach yields an age-at-death distribution younger than that originally estimated. A two-sided Komolgorov-Smirnov test was used to test for significant differences between distributions using each method. Age-at-distributions for the auricular surface were not significantly different, but those for the pubic symphysis were ($p = 0.041$).

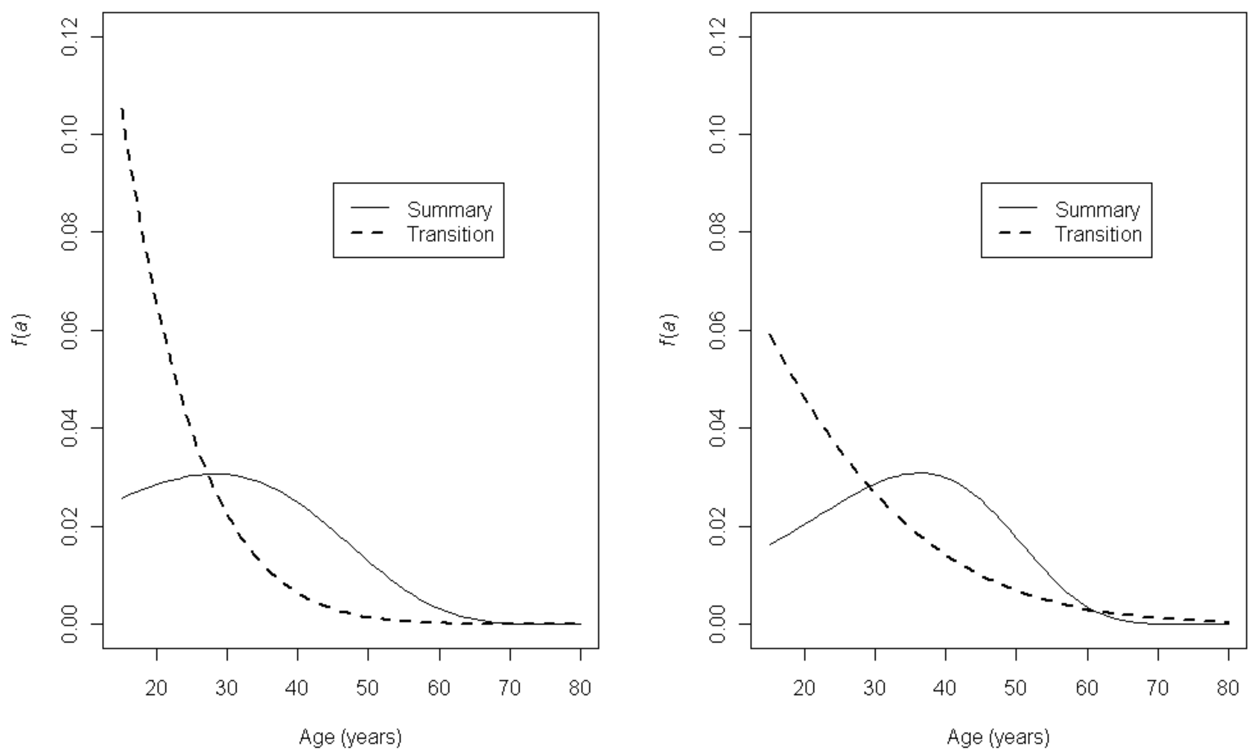


Figure 5.15: Age-at-death distributions for HK43 adults with pubic symphysis scores (left, $n = 139$) and auricular scores (right, $n = 176$), based on hazard parameters estimated using traditional summary-age methods and transition analysis.

In order to evaluate the impact of the revised age-at-death distributions for individuals subjected to transition analysis, the distribution for the pubic symphysis was used to apportion individuals into the four traditional age categories. The 139 individuals with scores for the pubic symphysis were added to the remaining sample with no scores for the pubic symphysis. (Virtually the same revised age-at-death distribution resulted from using the distribution from the auricular surface sample.) Table 5.12

shows the frequency and percent of individuals within each age category for the raw data and for the total sample after apportioning individuals using the age-at-death distribution estimated by transition analysis and the Gompertz hazard model. The age category most significantly affected was the 15–20-year group, which nearly doubled in size. Following that, the old-adult group (50+ years of age) fell by 50%. The young-adult group (20–35 years of age) was least affected, with the revised data consisting of only nine fewer individuals.

Table 5.12: HK43 individuals in adult age categories ($N = 328$)—summary-age compared with distribution revised by transition analysis.

	Summary		Transition	
Age category	*n*	%	*n*	%
15–20	50	15.2	97	29.6
20–35	166	50.6	157	47.9
35–50	88	26.8	62	18.9
50+	24	7.3	12	3.7

The revised age-category counts in Table 5.12 were used to estimate Gompertz hazard parameters. The resulting parameters were used to draw the age-at-death distribution, survival curve, and hazard curve for the revised counts (Figures 5.16 and 5.17). When compared to the the raw data, the revised data produced an age-at-death distribution younger than originally estimated. The revised data had the effect of lowering survival at all ages until about 55 years of age, when the two curves intersect. The effect of the revised data is more apparent in the curves for hazard function. The initial mortality rate is higher for the revised data, but the shape of the curve (determined by the β_3 parameter) is much flatter. After about 40 years of age, the revised data exhibit a lower mortality rate than the estimated using the raw data.

5.3.3 Discussion

The results presented above offer additional insight into our current understanding population dynamics during Egypt's Predynastic period. The use of parametric hazard models to study adult mortality allows for the direct comparison of biologically meaningful parameters within and between populations. As often reported for prehistoric populations, the mortality experience for HK43 departs from that observed in stable, model populations and ethnographic populations, as well as that recorded

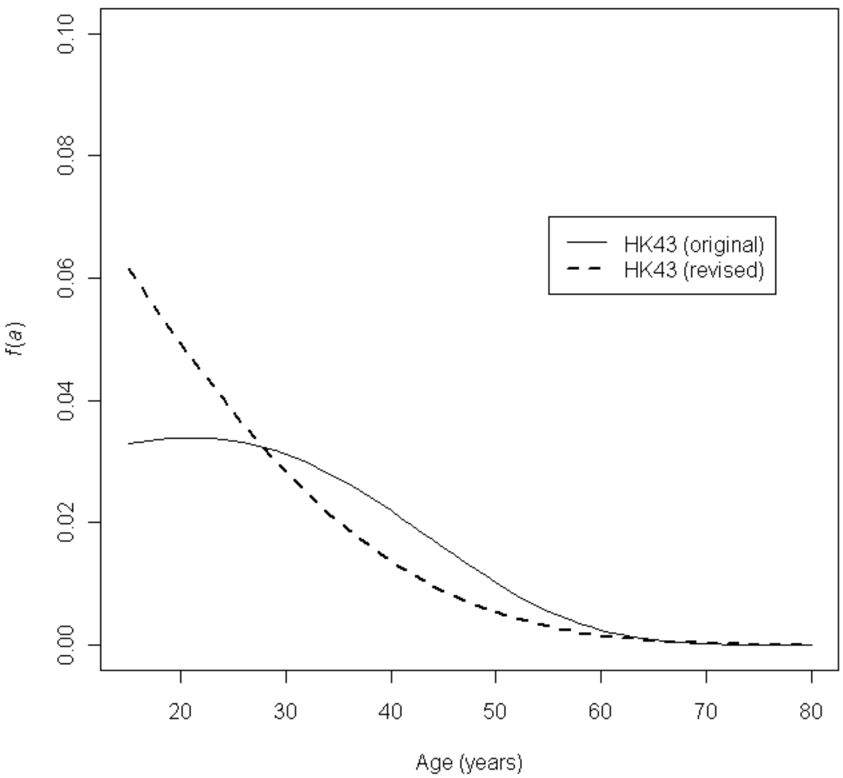


Figure 5.16: Adult age-at-death distributions for HK43 based on Gompertz parameter estimates from raw data (solid line) and data adjusted with transition analysis (dashed line).

for many historical populations. This is true even after the adjustment of the entire age-at-death distribution by taking into account the age-at-death distribution for individuals included in transition analysis with the skeletal age-indicator data.

Compared to the distributions of adult deaths in historical and modern ethnographic populations, HK43 consists of an abundance of young adults and too few old adults. Similar results were reported for the Predynastic skeletal assemblages from Upper Egyptian sites at Asyut and Gebelen; this combined sample was characterized by a "huge peak in the 20–30 year class and the very small number of individuals aged more than 40" (Masali and Chiarelli, 1972:163). When adjusted for a positive, non-zero growth rate (for example, those in Table 5.5), slightly corrects this pattern by decreasing the proportion of individuals between 15 and about 35 years of age, while increasing the proportion of those over 35 years of age. However, the age-at-death distribution for HK43, while similar to other paleodemographic samples, remains quite distinct from those of historical and modern, ethnographic populations.

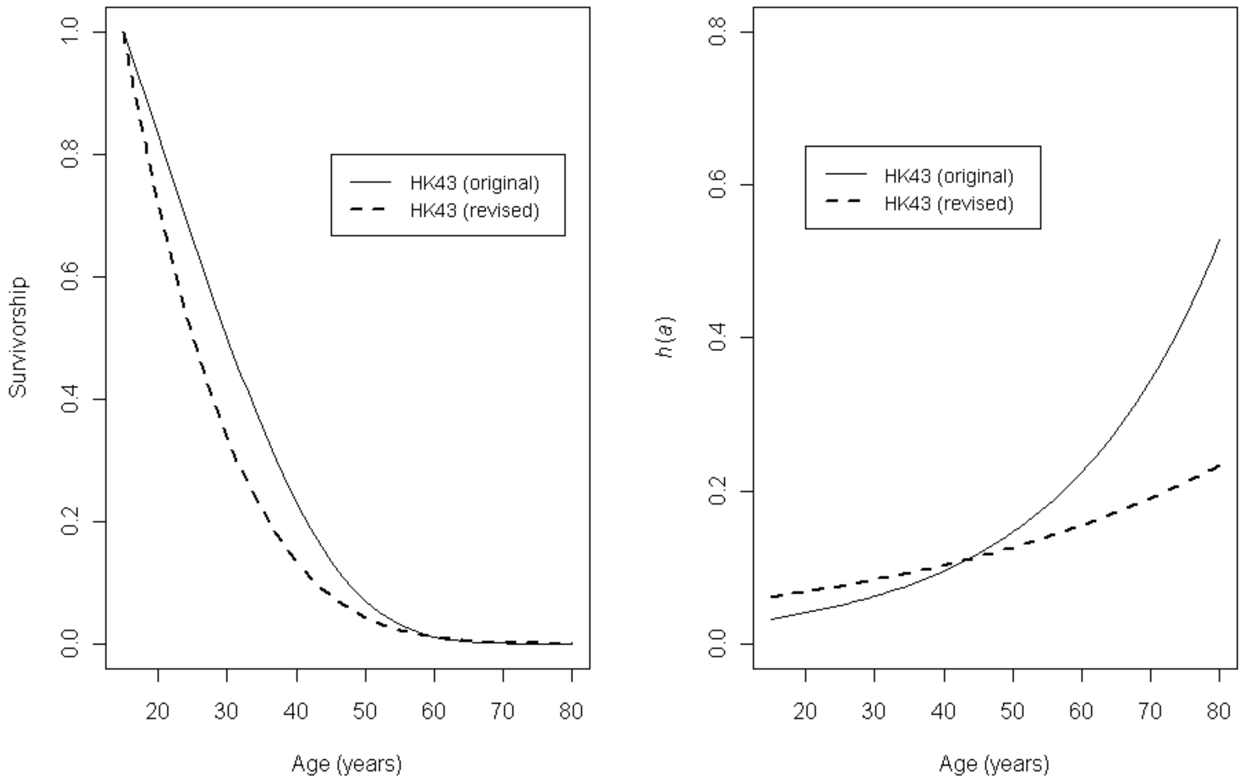


Figure 5.17: Survival curves (left) and hazard curves (right) for the original and revised HK43 data.

In their survey of mortality patterns among modern ethnographic populations, Gurven and Kaplan (2007) found that the modal age of death among adults is in the seventh decade of life. From the estimated Gompertz parameters for their hunter-gatherer and forager-horticulturalist samples, the proportion of deaths between 60 and 70 years is 7.5% and 12.8%, respectively. The CDM-W1 (female) model also has 12.8% in that age rage. In contrast, this proportion for the Paleo model and HK43 (raw and revised data) ranges from 0.8% to 1.2%. So then, where are all the older individuals? The simplest explanation is that, in prehistory, very few individuals lived into older adulthood. This was the argument originally made by Lovejoy and colleagues (1977) in their analysis of the Libben site.

The complex interaction of changing fertility and mortality may also contribute to the young age-at-death distribution of HK43. Depending on the initial level of mortality, changes in mortality will have contradictory effects on a population's age structure. At high initial levels, a decrease in mortality generally makes a population younger by increasing the population growth rate (more individuals survive to reproduce). If mortality is already low, a decrease in mortality tends to make a population older, as the effect of more individuals surviving to advanced ages becomes stronger. Assuming that the non-elite population at Hierakonpolis was experiencing relatively high mortality to begin with, small improvements during the period of cemetery use may have contributed to the young age-at-death distribution vis-à-vis a younger living age distribution.

With respect to the first hypothesis outlined in Chapter 1, these results illustrate that the application of more recent statistical methods, such as those outlined in Hoppa and Vaupel (2002a), by themselves, will not solve a constant issue of paleodemographic studies—the peculiar age structure of archaeological cemetery samples. This stems, in part, from the fact the current age indicators commonly observed in order to estimate age (or an age-at-death distribution) do not clearly identify the very old. The search for better osteological indicators of advanced age is an area of active research among biological anthropologists. Recent studies using known-age reference samples of skeletons have shown promise that there are, in fact, a number of indicator of old age that have yet to be studied (Milner and Weise, personal communication).

Another possibility—unfortunately, one of great concern for our understanding of cultural and individual meanings associated with mortuary behavior—is that the very old (as well as the very young) may not have successfully passed through the cultural filter to make it into the cemetery. As mentioned previously, there is sufficient reason to assume that HK43 is a fairly representative sample, at least for the time period represented. Preservation of the skeletal remains is good and associated material culture suggests that the excavated burials represent a more-or-less bounded time period. Further, surveys of the surrounding area do not point to separate cemeteries serving primarily the very old or young, such as Adaïma's eastern cemetery that dates to the very end of the Naqada III period, which represents the First and Second Dynasties (Coqueugniot et al., 1998). If one assumes, then, that selection bias played a limited role in the observed age-at-death distribution, one may consider the implications of the results for the remaining hypotheses.

One factor hypothesized to have contributed to an increase in birth rate and population growth rate was a decrease in female mortality, specifically among those of reproductive age. Hazard analysis for early- and late-period subsets of females support this interpretation. Life expectancy at the beginning of the reproductive period (e_{15}) increases from 17.5 to 20.1 for the early- and late-period samples, respectively. In other words, late-period females that survived to at least 15 years of age lived about

2.5 years longer, on average, than their early-period counterparts. These results contrast with previous research that has interpreted Egyptian paleodemographic data as reflective of high death rates among females due to maternal mortality (Masali and Chiarelli, 1972; Masali, 1980). Risk related to childbirth has been offered as an explanation for changes in female mortality elsewhere. For example, Eshed and colleagues (2004) interpreted a decrease in the mean age-at-death between Natufian and Neolithic females as an increase in mortality that resulted from stresses of an increasing birth rate. At HK43, though, the experience appear to have been the opposite—an improvement in mortality for reproductive-age females may have actually contributed to an increase in the birth rate.

Hazard analysis results also suggest that males and females of HK43 had a different mortality experience during the period of cemetery use. Males experienced higher mortality than females across the entire adult lifespan. This pattern has long been recognized in human populations and can be attributed to biological and behavioral factors (Lopez and Ruzicka, 1983; Gage, 1989). In some populations, female mortality during the peak of the reproductive period has been observed to be slightly higher than male mortality, a phenomenon considered to be associated with childbirth. Mortality differences between males and females typically peak during early adulthood, when males begin participating in higher-risk behavior associated with competition for resources, social status, and mates (Kruger and Nesse, 2006). At the same time, these general patterns exhibit variation by age, level of mortality, and cause of death (Lopez and Ruzicka, 1983; Gage, 1991).

The results of previous bioarchaeological investigations may provide additional information regarding the differences in mortality between males and females at HK43. First, with respect to behavior related to physical activity, males at HK43 exhibited significantly higher degrees of expression in muscle markings (Zabecki, 2009). This is to be expected since, to some degree, the larger size of males contributes to larger muscle markings. At the same time, Zabecki (2009) concluded that the observed degree of difference in muscle markings between males and females at HK43 suggests that sex-related differences in activity pattern were present. Further, HK43 males exhibited higher frequencies of fractures on the hands and feet, suggesting that males may have been engaged in activities at high-risk for injury (Kumar, 2009). Non-elite females at Hierakonpolis may have also benefited from greater amounts of protein than their male counterparts. Greene and colleagues (2005) found significantly higher degrees of calculus (mineralized plaque) for males in the upper-anterior and upper-posterior dentition for young- and old-adults, respectively. The authors interpreted these results reflect a difference in diet, rather than behavior.

When separated into early- and late-period subsets, the mortality experience for males and females at HK43 changed in contrasting ways. Under the assumption, however unlikely, of a stationary population, the estimated Gompertz parameters suggest that e_{15} for late-period males was lower than their early-period counterparts—15.6 versus 16.2 years, respectively. As mentioned above, females that survived to 15 years of age *gained* over two years in life expectancy during the late period. Thus, in contrast to females, mortality seems to have increased for males over time. This suggests that the restructuring of the socioeconomic environment during the Naqada I-II transition at Hierakonpolis had a differential impact on male and female mortality. Though actual life expectancy may be underestimated—if, as suggested, the population represented by HK43 was growing—the pattern suggested by the results still holds true. The results are even more intriguing when considering previous bioarchaeological studies that have found little difference between males and females with respect to diet, physical stress, and pathological conditions (cf., Greene, 2006; Zabecki, 2009; and Kumar, 2009, respectively).

A consideration of the comparative data from Naqada and Naga-ed-Dêr places the analysis of HK43 within a regional perspective. The popular interpretation of the Upper Egypt during the mid-to-late fourth millennium BC is that three polities, often referred to as chiefdoms (Hoffman, 1982; Hassan, 1988), centered at Naqada, This (near Abydos), and Hierakonpolis merged into an Upper Egyptian proto-kingdom that expanded northward to eventually overtake Lower Egypt (Trigger et al., 1983). The comparative data, then, represent populations from the major sociopolitical, cultural, and population centers associated with two of these Upper Egyptian polities—Naqada for the Naqada polity and Naga-ed-Dêr for the Thinite (This) polity. Thus, along with HK43, one may investigate the demographic experience of those most directly by inter-polity competition for control over all of what the Nile Valley could offer (e.g., arable land, human capital, access to travel and trade networks to the north and south, etc.).

If Hierakonpolis did, in fact, eventually absorb the other two Upper Egyptian polities of Naqada and This, one would expect that the non-elite population—those shouldering the burden of expansion—may have had a demographic advantage over its rivals. To a degree, the results support this hypothesis.

When compared to Naqada, Hierakonpolis had a higher initial mortality rate (the α_3 parameter), but after about 40 years of age, age-specific mortality rates at Naqada begin to increase dramatically over those at Hierakonpolis. In contrast, HK43 had higher initial mortality rate than Naga-ed-Dêr, but its β_3 parameter was only slightly lower, giving the hazard curves for these two samples roughly the same shape. Thus, HK43 exhibited higher adult mortality rates than Naga-ed-Dêr. These results are consistent with those of the aggregate age measures; the death rate calculated for HK43 was higher than Naga-ed-Dêr (0.0377 versus 0.0352, respectively). At the same time, the success of a population is not determined by mortality alone. If the nonelites at Hierakonpolis did experience higher overall levels of mortality than those at Naga-ed-Dêr, then a higher birth rate for the former may have been a key advantage, particularly with regards to the availability of human capital.

Chapter 6 Conclusion

6.1 Summary and Conclusions

The overarching goal of this study was to reconstruct population dynamics of the Predynastic, nonelites at Hierakonpolis through an analysis of the age-at-death distribution of HK43. Toward this goal, this study incorporated a number of different analyses. The objective of the first analysis was to reassess previously reported results of an analysis of dental attrition as a method of age estimation for HK43 and its potential to provide an population-specific reference sample that could be later used with more recent paleodemographic methods (i.e., transition analysis and maximum likelihood estimation of hazard model parameters). The objective of the second analysis was to analyze aggregate measures of the age-at-death distribution for HK43 in order to investigate juvenile mortality, birth rate, and population growth rate. The final goal was to use parametric mortality (hazard) models to investigate adult mortality at HK43. This included fitting these models to raw, interval-censored data and the application of a transition-analysis approach in estimating an age-at-death distribution from observed, skeletal age-indicator data.

A brief summary of the major findings and conclusions drawn from the results are presented below, followed by a consideration of the significance and implications of the results. This chapter ends with suggestions for future research.

1) Estimation of age-at-death using dental attrition did not result in an older age-at-death distribution, as has been previously reported. In her Master's thesis, Huard (2006) used a modified version of the Miles method to estimate age-at-death for a subset of the HK43 skeletal assemblage with observations of dental attrition and found that those age estimates produced an older and more realistic demographic profile. This contrasts with the results of the current study, in which age estimates based on dental attrition produced a similar, if not slightly younger, age-at-death distribution than that based on a summary approach using multiple skeletal age indicators. Similarly, O'Connor (1995) found that age estimates from dental attrition produced age-at-death distributions slightly younger than those from summary techniques using other age indicators, such as cranial sutures, the pubic symphysis, and the auricular surface.

Further, the results suggest that previously reported ages-at-death estimated from dental attrition were too high. This overestimation was primarily an effect of the particular method used to calculate the yearly attrition rate for each tooth. Age estimates using the Mean6 method developed for this study were in closer agreement to independent estimates of developmental age than those calculated with the SD6 method. Application of these two methods to another population, particularly one with individuals of known age, would be useful.

At least for the HK43 skeletal assemblage, there appear to be limitations to using dental attrition for developing a population-specific reference sample, due to the lack of any individuals with dental attrition data and an estimated age of over 50 years. This same issue was noted by O'Connor (1995). Thus, the highly skewed (i.e., young) age-at-death distribution of the sample of individuals with dental attrition data precluded the use of these results in developing a population-specific sample to be used with transition analysis.

2) The nonelites at Hierakonpolis exhibited relatively high rates of population growth, and the growth rate appears to have increased during the period of cemetery use at HK43. Estimates of fertility (i.e., birth rate) and population growth rate using aggregate age measures support existing archaeological evidence for population growth at Hierakonpolis during the Naqada I and II periods. Results suggest that fertility increased during the period of cemetery use. Both measures, the ${}_{15}P_5$ ratio and the D_{30+}/D_{5+} proportion, are consistent with an increasing birth rate. There is evidence (see below) that improvements in mortality rates for juveniles and reproductive-age females may have contributed to an increase in the population growth rate. If one accepts these higher estimates for population growth—1.14% annually during the period of cemetery use—previous estimates of population size for the Predynastic at Hierakonpolis may be too high.

3) Improvements in juvenile mortality may have contributed to an increase in the population

growth rate. Results of the analysis of the D_{1-5}/D_{1-10} proportion between the early- and late-period subsets of the HK43 skeletal assemblage suggest that juvenile mortality improved, perhaps due to increasing survival rates among young children. Though a decrease in D_{1-5}/D_{1-10} values could also reflect a decrease in fertility, separate analysis of the birth rate using the ${}_{15}P_5$ ratio and D_{30+}/D_{5+} proportion does not support this interpretation. These results have some support from studies that have documented improvements in juvenile mortality in contemporary, ethnographic populations transitioning from mobile, foraging systems to those characterized by lower mobility and increased reliance on agriculture. An increase in the number of juveniles surviving to adulthood (i.e., reproductive age) would have had a positive affect on the birth rate, leading to population growth (Pennington, 1996).

4) During the period of cemetery use, mortality for males appears to have increased, while female mortality seems to have improved, specifically among reproductive-age females. For the entire period of cemetery use, and when the sample was divided into early- and late-period subsets, males exhibited higher mortality rates than females. In this respect, HK43 is more like contemporary populations, rather than prehistoric ones. Paleodemographic studies commonly find that higher rates in females than males. The converse is true for many contemporary, ethnographic and national populations. It seems, then, that males and females may have had a different demographic response to cultural changes during the Naqada II period. The reason for this disparity is unclear, though, other bioarchaeological evidence suggests that slight differences in diet and physical activity may have played a role. One possible scenario is that, during parts of the year when agricultural activities were at a minimum (i.e., the annual innundation of the floodplain), males increasingly participated in nonagricultural activities related to territorial and administrative expansion (Allen, 1997).

With respect to females, it seems that the observed improvement in mortality was concentrated on those of reproductive age. Like improvements in juvenile mortality, an improvement in mortality rates for females in the child-bearing years would have most likely increased the birth rate (more females surviving each year) and total fertility rate (more females surviving to older ages). Of course, just because more females may have been living and living longer, potentially to reproduce, does not mean that they did. On the other hand, models and empirical evidence from behavioral ecology suggest that there would have been advantages to having more children since they become producers (not just consumers) at a much younger age in agricultural systems than in mobile, foraging systems (Shennan, 2009). Thus, as the population at Hierakonpolis became increasingly reliant on agriculture as part of the overall subsistence strategy, the cost (time and energy) of raising a child would have decreased, perhaps influencing individual choices related birth control.

5) Hierakonpolis enjoyed a demographic advantage—partially in mortality, but even more so in the birth rate and population growth rate—over competing centers in Upper Egypt. The nonelites at Hierakonpolis may have experienced both higher and lower mortality rates than some of their neighbors. The comparison of estimated hazard parameters suggests that the nonelites at Hierakonpolis experienced a mortality regime between that of Naqada and Naga-ed-Dêr. It seems that the main demographic advantage came from a much higher birth rate at Hierakonpolis. This higher birth rate more than compensated for the observed disparity in mortality between Hierakonpolis and Naga-ed-Dêr. In fact, the results suggest that, due to a low birth rate, the population at Naga-ed-Dêr may have been experiencing a decline. Unfortunately, the quality of the data for Naqada were not sufficient to estimate birth rate and population growth rate. A demographic advantage of a higher population growth rate may have given Hierakonpolis an edge in biological capital, a social surplus that may could be mobilized by elites for nonagricultural activities related to expansion.

6) The application more-recent paleodemographic methods, like those outlined in Hoppa and Vaupel (2002a), did not significantly alter the age-at-death distribution for the HK43 skeletal assemblage. Contrary to results reported elsewhere, when the age-at-death distribution for the total HK43 sample was revised by combining the subset of individuals reassessed using transition analysis with those without age-indicator data, it still looked like many published age-at-death profiles. The highest proportion of individuals remained in the young-adult age category (20–35 years), while the proportion of old adults decreased (and remained the lowest). Surprisingly, the second largest age category changed from the middle-adult group (30–50 years) to older adolescents (15–20 years). Thus the adult age-at-death distribution appears to have been even younger than originally thought.

The younger, revised age-at-death distribution may result from a number of reasons. First, ages for older adolescents, middle adults and old adults may have been systematically overestimated. Systematic biases in age estimation are a well known occurrence. Typically this is seen in the overaging of young adults and underaging of old adults, which has been blamed, at least in part, for the high proportion of individuals in these age groups commonly seen in paleodemographic age profiles. Another issue is the poor performance of commonly used skeletal age indicators in identifying the very old. Many skeletal age indicators, including the pubic symphysis and auricular surface, exhibit clear morphological changes that can be used to assign an individual to an age other than "50+ years." Finding new morphological features on the human skeleton that can help identify the very old is another area that is crucial for the improvement of paleodemography. In fact, a number of researchers are actively working to do just that (e.g., Weise et al., 2012).

6.2 Significance and Implications

This study represents a significant contribution to the study of Predynastic Egypt. As mentioned previously, both the prehistoric and historic periods of Egypt have been a popular research foci for scholars across a number of disciplines, including anthropology. However, the study of human population dynamics in Egypt's past has received relatively little attention, with the exception of studies of Egyptian demography during the Roman period (e.g., Bagnall and Frier, 1994; Scheidel, 2001). Though the demographic studies of Roman Egypt are certainly interesting to a wide array of scholars, including anthropologists, these data represent an Egyptian population that lived over 3000 years after the formation of the Egyptian state. By taking the study of human skeletal remains "out of the appendix" (Buikstra, 1991), this research has extended the study of Egyptian demography back in time and offered a means to better understand the complex relationships among human population dynamics, behavior, and the environment in small-scale populations.

The conclusions above have a number of implications on current understanding of the demographic patterns associated with Predynastic period at Hierakonpolis. As discussed in Chapter 2, previous estimates of population size in the Hierakonpolis region vary widely—from about 1500 to nearly 11,000 people for any one point in time (Hoffman, 1982; Harlan, 1985). These estimates are based upon settlement data and burial counts for the entire Hierakonpolis concession and, also, include the main Predynastic sequence that lasts about 700 years. Hoffman (1987) favored higher estimates, arguing that a relatively large population and high population density were prerequisites for the success of

Hierakonpolis emerging as a early capital of a unified Upper Egypt.

Hoffman's (1982) population estimates assume a relatively large initial population size (about 1000 individuals). Further, assumptions of a low population growth rate (about 0.1% to 0.5% per year) are based on all of Egypt (Butzer, 1976; Hoffman, 1987; Hassan, 1993) and the entire Predynastic, including the Badarian period. There is little reason, though, why these long-term growth rates for all of Egypt should necessarily apply to the 200–300 year period for the local, nonelite population represented by HK43 since aggregate measures of regional or larger populations may mask demographic variability at the local level (Early and Peters, 2000). If the estimated rates of population growth based upon the ${}_{15}P_5$ values for HK43 reflect reality, the nonelite and total population at Hierakonpolis may have been smaller than originally thought, perhaps in the low- to mid-hundreds. Thus, the results of this study support lower estimates for the population at Hierakonpolis (e.g., Harlan, 1985; Mortensen, 1991).

With the above interpretation of these results, particularly those for population size and growth rates, one may reflect on recent interpretations of the bioarchaeological evidence from Hierakonpolis. These have operated within a theoretical framework borrowed from economic historians (e.g., Artzrouni and Komlos, 1985; Steinmann and Komlos, 1988; Komlos and Nefedov, 2002), based on Kuznets' (1966) general observation that sustained periods of economic growth are often accompanied by sustained population growth. Looking at the population of Hierakonpolis in these terms invokes two main theories that have been applied to questions of preindustrial population growth—Malthusian and Boserupian dynamics. The former regime describes the regulation of populations by resource (i.e., food) limitation, while the latter describes population expansion and adaptation through technological innovation. In reality, it is likely that prehistoric populations experienced cycles of these two systems—limitation and expansion (Lee, 1986; Wood, 1998).

The proposition of these recent interpretations is that, during the Naqada II period (including the period of cemetery use at HK43), the nonelite population at Hierakonpolis had accumulated enough capital (both in terms of agricultural production and human capital) to escape a Malthusian trap, in which the population would have been limited by nutritional resources. It was this feature that allowed Hierakonpolis to play such an important role in the centuries prior to unification. As previously mentioned, there is ample evidence of both increases in economic output (agricultural and nonagricultural production) and population growth at the Hierakonpolis throughout the Predynastic, particularly during the Naqada II period.

While the results of this study could support this interpretation, an alternative interpretation is that, at least for this population during this time period, there was relatively little threat of falling into a Malthusian trap. Under the assumption that population density in the Nile Valley was low and population size at Hierakonpolis was on the order of hundreds, not thousands, the growing population could have effectively raised agricultural yield by working the land longer, working more intensely, working more plots of land, or any combination of these. Because the process and timing of agricultural production (planting, growing, and harvest), especially in Upper Egypt, was controlled by the annual flooding of the Nile, the most effective method for the nonelites at Hierakonpolis to increase crop yield would have been to work more plots of land. Additionally, Allen (1997) has argued that a shift to a more agriculturally-intensive subsistence strategy likely increased the output per worker, probably by working more land that required more work time. Again, the seasonality of agriculture characteristic of the Nile Valley would have allowed farmers to be used as a labor source for nonagricultural activities. The control of labor resources, not land, may have been more important to the increasingly influential class of elites at Hierakonpolis.

The results of this study offer additional support for the consensus interpretation that, during the Naqada II–III transition, Hierakonpolis played a pivotal role as a regional center for population, as well as political and economic power. With a growing population of agricultural workers that could be used for nonagricultural activities during certain parts of the year, Hierakonpolis had an advantage over competing polities at Naqada and This. With improvements in mortality for juveniles and reproductive-age females, an increasing birth rate would have given Hierakonpolis what was, perhaps, its most decisive advantage—a labor surplus that resulted from the accumulation of human capital during the Naqada II period.

6.3 Future Research

As a result of working on this project, it is my opinion that the field of biological anthropology (and all its specializations) needs to embrace opportunities to conduct and publish research in open-source environments. Many open-source applications are available for general or specific problems. An advantage of R, for example, is its flexibility as a programming environment, which is part of the reason there are so many user-contributed packages for performing an increasing array of statistical analyses. The source code for these packages is free to be modified, if one wants to tailor a procedure to a specific problem. Further, many R packages have been built to integrate other open-source systems developed for specific research areas, such as agent-based modeling and GIS applications (e.g., NetLogo and GRASS, respectively). Lastly, scholarly journals within the field could benefit by accepting manuscripts written using LaTex. Not only is LaTex a powerful typesetting system, but it can be used with Sweave (Leisch, 2002), a tool that allows for the embedding of R code within LaTex documents. This allows one to create dynamic documents that may be updated automatically, if data change. Further, this approach to report-writing would truly foster collaboration and reproducible research.

The current study suggests a number of different research directions. From a practical perspective, there is a clear need to make the current methodological approaches to paleodemographic analysis more accessible to others, both within and outside of the discipline. Methodological advances in the last decade have offered solutions to some of the issues that have plagued paleodemography since its inception. The incorporation of transition analysis, or similar approaches to model age-related changes in skeletal morphology, and parametric hazard models for modeling mortality have largely addressed the issue of age-mimicry. In some cases, the use of these methods to re-analyze previously studied skeletal assemblages has produced age-at-death distributions and demographic parameters that are more consistent with those observed or estimated for contemporary, ethnographic populations (Konigsberg and Herrmann, 2006). On the other hand, this study has shown that the use of these methods, alone, may not have similar results for all samples. Thus, alternative explanations for the peculiar age profiles of archaeologically-derived skeletal assemblages remain to be explored.

One issue affecting the application of a transition analysis approach is the number of phases/stages in the scoring system for a particular age indicator. As this study illustrates, all phases within a previously published scoring system may not actually do a good job at discriminating age. Following the approach of others (e.g., Herrmann and Konigsberg, 2002; Konigsberg and Herrmann, 2006), this study used a trial-and-error approach—a visual inspection of the kernel density distributions—to determine the best way to collapse phases for the pubic symphysis and auricular surface. Recently, Konigsberg and Frankenberg (2012) have suggested that there are a number of available goodness-of-fit tests that may aid in this process.

If anything, this study illustrates that long-standing debates within paleodemography have yet to be fully resolved. One issue that continues to affect our interpretations in paleodemographic studies is sample representativeness. As noted, the creation of a skeletal sample for study is a complex process that includes multiple filters affecting the probability of death, burial, recovery, and analysis. While some progress has been made toward identifying selective mortality and heterogeneity in the risk of death using a combination of paleodemographic and paleopathological data, less attention has been directed at developing formal models for the cultural and taphonomic processes affecting the composition of skeletal assemblages (cf. Hoppa, 1996, 1999). In order to improve in this respect, paleodemography desperately needs some sort of theoretically-grounded model of the processes that determine the probability of observing a mortality event (i.e., an individual observed as part of a skeletal assemblage). Thus, it is likely that more-sophisticated simulation studies will become increasingly important in developing theoretical models and testable hypotheses about the interacting forces (e.g., demographic, epidemiological, taphonomic, etc.) that produce the skeletal assemblages studied by bioarchaeologists.

The last major shake-up within the field paleodemography is now a decade old. While the methodological approaches advocated for in the Rostock Manifesto are finally beginning to appear more frequently, paleodemography is ripe for another major step. The direction of this step is unclear, though I feel that it may include an increasingly important role of nonstable demographic theory (e.g., Bonneuil, 2005; Paine and Boldsen, 2006; Gage, 2010) and life history theory (e.g., Ahlström, 2011; Roksandic and Armstrong). Additionally, population projection methods, commonly applied to nonhuman species in the field of conservation biology, may offer an additional approaches for tackling problems that arise in paleodemographic studies. Some of these methods have already shown promise for developing theoretical models that may be used to investigate complex systems of population dynamics, cultural, and environment (Lee and Tuljapurkar, 2008; Puleston and Tuljapurkar, 2008; Lee et al., 2009).

Finally, I am optimistic for further investigations of the population dynamics of prehistoric and historic Egypt. This study illustrated that paleodemographic data, especially from relatively large, well-preserved samples, have the potential to refine or change previous interpretations of the demographic experience associated with a population on the cusp of major sociopolitical shift. This study and those like it provide an argument for the reanalysis of previously excavated, curated skeletal assemblages and the incorporation, when feasible, of bioarchaeological contributions to future excavations. Further, though historical demography and osteological paleodemography often suffer from some of the same issues relating to data quality, these two approaches can also complement each other. If used in conjunction with documentary sources (e.g., tax lists, censuses, epigraphic inscriptions, etc.), the study of human skeletal remains may help to fill in the 3000-year gap in our knowledge of the Egyptian demographic experience.

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Appendix A: HK43 Data

The following list provides summary of the variables in the table below.

1. burial = Burial number
2. date = Preliminary assignment of relative chronology for burial
   - 0 = Early
   - 1 = Late
3. age = Age category originally assigned in HK43 database
   - 0 = Undetermined
   - 1 = 0–5 years
   - 2 = 5–10 years
   - 3 = 10–15 years
   - 4 = 15–20 years
   - 5 = 20–35 years
   - 6 = 35–50 years
   - 7 = 50+ years
4. sex = Estimated sex ("probable" males/females treated as males/females)
   - 0 = Undetermined
   - 1 = Male
   - 2 = Female
   - 3 = Ambiguous
5. pube = Recorded score for pubic symphysis (Todd, 1920)
6. auric = Recorded score for the auricular surface (Lovejoy et al., 1985b)
7. age.devo = Age estimate based upon developmental criteria
8. nm1–xm3 = Total attrition score (left side; if missing, right side substituted)
9. base = Potentially included in baseline sample of juveniles (aged 6–25 years)
   - 0 = No
   - 1 = Yes

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
1	348	1	2	0			7.17	14	4		13	4		1
2	46	1	2	0			7.50	10			10			1
3	225	1	2	0			9.50	10			4			1
4	272	1	2	0			9.25	6	4		6	4		1
5	210	1	2	0			8.25	5			5			1
6	165	1	2	0			6.50	5			4			1
7	351	1	2	0			9.17	4			4			1
8	299	1	2	0			8.25	4			4			1
9	353	1	2	0			6.50	4			4			1
10	39	0	2	0			6.50	4			4			1
11	238	1	2	0			8.00							1
12	142	0	2	3			7.75							1
13	211	1	2	0			7.00							1
14	259	1	2	0			7.00							1
15	374	1	2	0			7.00							1
16	223	1	3	0			13.17	14	8		17	9		1
17	279	1	3	0			14.50	16	8		13	7		1
18	287	1	3	0			14.00	12	10	4	11	6	4	1
19	185	1	3	0			13.25	18	4		13	4		1
20	21	0	3	0			14.50	16	4		17	4		1
21	280	1	3	0			13.00				14	6		1
22	339	1	3	0			14.33	14	6		14	6		1
23	358A	1	3	0			10.50	12	4					1
24	200	1	3	0			11.50	11	4					1
25	121	0	3	0			13.00	11	4		10	4		1
26	198	1	3	0			12.50	7	4		10	3		1
27	420	1	3	0			14.00							1
28	301	1	3	0			13.00							1
29	369	1	3	0			13.00							1
30	436	1	3	0			13.00							1
31	443	1	3	0			12.25							1
32	358B	1	3	0			12.00							1
33	384	1	3	0			12.00							1

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
34	107	0	3	0			11.50							1
35	416	1	3	0			11.50							1
36	459	1	3	0			11.50							1
37	126A	0	3	0			11.00							1
38	158	0	4	2			19.50	17	12	11	17	12	8	1
39	149	0	4	0	1		19.50	17	10		15	12		1
40	195	1	4	2	1	1	19.00	20	10	4	19	8	4	1
41	48	0	4	1			17.00				20	10	4	1
42	78	0	4	0			15.00	18	8	4	17	12	4	1
43	97	0	4	1	1	1	19.75	17	12	4	17	6	4	1
44	206.1.2	1	4	0			16.50	16	8	4				1
45	182	1	4	1	1		18.50				18	10	4	1
46	31	0	4	0			14.33	16			13	4		1
47	184	1	4	0			18.00		8	4	21	8	4	1
48	199	1	4	0			17.50				16	8	4	1
49	20	0	4	1	1		16.67	14	6	4	15	6	4	1
50	302.1	1	4	3			16.50		8	4	14	8	4	1
51	306	1	4	0	2		20.00							1
52	385	1	4	0			20.00							1
53	26	0	4	2	1	1	19.50							1
54	187	1	4	1			19.00							1
55	405	1	4	2			19.00							1
56	407	1	4	2	1	1	19.00							1
57	446	1	4	1			19.00							1
58	419	1	4	0			18.50							1
59	429	1	4	0			18.50							1
60	155	0	4	1			18.00							1
61	267	1	4	0			18.00							1
62	148	0	4	2			17.83							1
63	261	1	4	3			17.50							1
64	318B	1	4	0			17.50							1
65	440	1	4	1			17.50							1
66	82	0	4	2	1		17.50							1

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
67	403	1	4	1			17.00							1
68	41	0	4	0	1		17.00							1
69	410	1	4	0			17.00							1
70	449	1	4	1			17.00							1
71	49	0	4	2			17.00							1
72	169.1	1	4	1			16.50							1
73	366	1	4	0			16.50							1
74	464	1	4	1			16.50							1
75	154B	0	4	0			16.25							1
76	77C	0	4	0			16.00							1
77	110A	0	4	0			15.17							1
78	466	1	4	0			9.50							1
79	108	0	5	2			21.00	18	14	12				1
80	123A	0	5	1	2	1	21.30	22	16	12	28	21	6	1
81	367	1	5	2			22.50	23	15	10	23	15	8	1
82	102	0	5	1	2	1	24.50	23	14	11	22	15	10	1
83	90	0	5	1			21.50	19	15		26	13	12	1
84	359	1	5	2	3	5	22.50	18	14	8				1
85	140B	0	5	2	1	1	21.00	21	13	10	21	13	12	1
86	260	1	5	2	3		25.00	24	13	8	24	12	4	1
87	159	0	5	2	1	1	22.50	19	11	6				1
88	320	1	5	2			22.50	18	14	10	19	14	8	1
89	377	1	5	1	3	4	20.00	18	13	6	19	12	8	1
90	68	0	5	2	3	2	22.50	18	12	8	20	10	7	1
91	47	0	5	1		3	22.50	19	11	5				1
92	340	1	5	0			22.00	16	10	4				1
93	291	1	5	2	1		19.30	20	13	8	19	8	4	1
94	357	1	5	1	2	3	22.50	18	8		17	10		1
95	304	1	5	2	1	1	22.50	17	11	8		8		1
96	270	1	5	1			20.20	16	12	4	17	12	8	1
97	91	0	5	2			19.80	19	11	7	19	10	4	1
98	24	0	5	1	1	1	20.50	19	11	6		10	4	1
99	228	1	5	2	2	1	22.00	14	10					1

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
100	295C	1	5	1	2	2	22.80	17	11	4	18	11	4	1
101	71	0	5	2	2	1	21.00	19	12	4	18	14	4	1
102	313	1	5	2	3	5	22.50	16	10	4	17	8	4	1
103	9	0	5	2	1	1	22.00	15	11	4	17	10	4	1
104	316.2	1	5	2	2		23.50				17	12	4	1
105	84	0	5	2			22.00				20	8	4	1
106	123B	0	5	1	3	2	22.80	17	8		16	8	4	1
107	85	0	5	2	1	1	22.00	16	10	4	15	10	4	1
108	323	1	5	2	2	2	23.50	16	8	4	15	8	4	1
109	361	1	5	2	3	3	20.30	16	13	4	14	4	4	1
110	226.1	1	5	0			20.50		4		15	8		1
111	18	0	5	1			21.00	18	6		13	5	4	1
112	312	1	5	2			20.00				16	7		1
113	355	1	5	3		2	22.50				13	8	4	1
114	423.2	1	5	2	1	1	21.50	4						1
115	111	0	5	0			25.00							1
116	282	1	5	0			25.00							1
117	170	1	5	2		2	23.80							1
118	70B	0	5	2			23.80							1
119	439	1	5	2	2	1	23.50							1
120	454	1	5	1			23.00							1
121	250	1	5	2			22.50							1
122	293	1	5	2	1	1	22.50							1
123	334	1	5	0			22.50							1
124	344	1	5	1		2	22.50							1
125	441	1	5	0			22.50							1
126	5	0	5	0			22.50							1
127	70A	0	5	2	1	1	22.50							1
128	129	0	5	2	2	1	22.00							1
129	285	1	5	1	2	1	22.00							1
130	386	1	5	1	2	1	22.00							1
131	354	1	5	3			21.80							1
132	309	1	5	1	1	2	21.50							1

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
133	423.1	1	5	2	1	1	21.50							1
134	460	1	5	2	1	1	21.30							1
135	431	1	5	1	1	1	21.20							1
136	11	0	5	3			21.00							1
137	127	0	5	2		1	21.00							1
138	402	1	5	2	1	2	20.80							1
139	96	0	5	1			20.80							1
140	255	1	5	2	2		20.50							1
141	411	1	5	0			20.00							1
142	444	1	5	2	1	1	19.50							1
143	37	0	5	0			18.50							1
144	148X	0	0	3				37	31		40	38	36	0
145	112	0	0	0				34	22	12	21	15	10	0
146	298A	1	0	1				18	16	6	20	14	12	0
147	268	1	0	0							20	15	12	0
148	294	1	0	2				17	14	8	18	16	12	0
149	226.2	1	0	0				14	8		19	12	11	0
150	131	0	0	0							20	9	4	0
151	110X	0	0	3										0
152	124	0	0	0										0
153	130	0	0	0										0
154	132	0	0	0										0
155	134	0	0	1										0
156	136	0	0	0										0
157	141	0	0	0										0
158	145	0	0	0										0
159	150	0	0	0										0
160	156	0	0	3										0
161	157	0	0	0										0
162	162	1	0	3										0
163	17	0	0	2										0
164	178	1	0	0										0
165	179	1	0	0										0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
166	197.1	1	0	1										0
167	205.2	1	0	3										0
168	214	1	0	1										0
169	215	1	0	0										0
170	219	1	0	0										0
171	220	1	0	0										0
172	221	1	0	0										0
173	229X	1	0	1										0
174	232.2	1	0	0										0
175	252	1	0	0										0
176	254	1	0	0										0
177	258	1	0	0										0
178	274	1	0	0										0
179	277	1	0	2										0
180	281	1	0	0										0
181	288	1	0	0										0
182	290	1	0	3										0
183	303	1	0	0										0
184	311	1	0	0										0
185	311X	1	0	0										0
186	318A	1	0	1										0
187	327	1	0	3										0
188	328	1	0	0										0
189	335	1	0	0										0
190	336A	1	0	0										0
191	336B	1	0	0										0
192	341	1	0	0										0
193	347	1	0	0										0
194	349	1	0	1										0
195	352A	1	0	0										0
196	373	1	0	0										0
197	37X	0	0	0										0
198	380	1	0	0										0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
199	381B	1	0	1										0
200	388	1	0	2										0
201	393	1	0	2										0
202	396	1	0	0										0
203	406	1	0	2										0
204	424	1	0	0										0
205	442	1	0	0										0
206	451	1	0	1										0
207	455	1	0	0										0
208	457	1	0	0										0
209	458	1	0	0										0
210	61	0	0	0										0
211	64.1	0	0	0										0
212	64.2	0	0	0										0
213	83	0	0	3										0
214	95	0	0	3										0
215	A-2 NE	0	0	1										0
216	LOC39.2	0	0	3										0
217	LOC39.3	0	0	3										0
218	LOC39.4	0	0	3										0
219	233	1	2	0			5.50	4			4			0
220	230	1	2	0			5.50							0
221	33A	0	2	0			5.50							0
222	469	1	2	0			5.50							0
223	322	1	2	0			5.00							0
224	447	1	2	0			5.00							0
225	109	0	3	0				17	6		16	8		0
226	342	1	3	0										0
227	191	1	1	0										0
228	203	1	1	0										0
229	213	1	1	0										0
230	231	1	1	0										0
231	246	1	1	0										0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
232	253	1	1	0										0
233	297	1	1	0										0
234	336C	1	1	0										0
235	352.4	1	1	0										0
236	356	1	1	0										0
237	401	1	1	0										0
238	430	1	1	0										0
239	433	1	1	0										0
240	434	1	1	0										0
241	463	1	1	0										0
242	27	0	1	0			4.00							0
243	217	1	1	0			3.50							0
244	251	1	1	0			3.50							0
245	86	0	1	0			3.50							0
246	206.3	1	1	0			2.50							0
247	236	1	1	0			2.50							0
248	324B	1	1	0			2.50							0
249	390	1	1	0			2.50							0
250	381	1	1	0			1.80							0
251	307	1	1	0			1.75							0
252	383	1	1	0			1.75							0
253	126B	0	1	0			1.50							0
254	300	1	1	0			1.50							0
255	329	1	1	0			1.50							0
256	331	1	1	0			1.50							0
257	80	0	1	0			1.50							0
258	92B	0	1	0			1.25							0
259	108B	0	1	0			1.00							0
260	30	0	1	0			1.00							0
261	171	1	1	0			0.75							0
262	425	1	1	0			0.75							0
263	426	1	1	0			0.75							0
264	43	0	1	0			0.67							0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
265	413	1	1	0			0.58							0
266	240	1	1	0			0.50							0
267	305B	1	1	0			0.50							0
268	398	1	1	0			0.47							0
269	337	1	4	0				15	8		13	8		0
270	114	0	4	0										0
271	169X	1	4	3	1									0
272	314	1	4	1										0
273	32A	0	4	0										0
274	338	1	4	0										0
275	33B	0	4	0										0
276	397	1	4	0										0
277	62	0	4	0										0
278	283B	1	5	1	5	3		32	24	29				0
279	224	1	5	1				32	29	15		26		0
280	360	1	5	1	5	4		30	22	18	34	23	21	0
281	99	0	5	2		2	26.00	28	20	14				0
282	284	1	5	2				36	18	12	32	16	10	0
283	116	0	5	2		3		35	30	18	21	19	14	0
284	169.2	1	5	2					20					0
285	177	1	5	0							32	22	18	0
286	2A	0	5	2	4				20	15				0
287	N/A	0	5	2				24	18	11	25	19		0
288	88	0	5	1	5	3	29.00	27	18	13	25	19	13	0
289	117	0	5	1		3	29.80	30	18	12	31	16	12	0
290	229.1	1	5	1	6	3		27	17	13	31	17	12	0
291	302.2	1	5	0				21	18	11				0
292	376	1	5	2		1		22	18	13	24	15	12	0
293	19	0	5	1		2		26	20	8	26	18	10	0
294	105	0	5	1	3	2		21	17	8				0
295	128	0	5	2	3			22	16		24	12		0
296	205	1	5	1	5		27.50	23	15	11	23	14	8	0
297	160	0	5	1				17	15	12		13	11	0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
298	176	1	5	2				22	15	10		13	12	0
299	119	0	5	1				27	15	10	23	13	10	0
300	36	0	5	1	2	2		23	17	12	25	15	9	0
301	196	1	5	1		2		20	14	10			12	0
302	222	1	5	2		3			12				12	0
303	249.1	1	5	2				20	14	8	22	12	8	0
304	GREENS	0	5	2				16		10				0
305	153	0	5	1				14	13	10		16	12	0
306	146	0	5	2	3	2			8		27	15		0
307	174	1	5	1									12	0
308	57	0	5	0				25	13	4	10	23		0
309	42	0	5	2	3		27.50	24	15		20	13	4	0
310	289	1	5	1		3		24	14	4			4	0
311	207.1	1	5	1		1		18	10					0
312	72	0	5	0	6	3					23	11	9	0
313	81	0	5	2	3	2	25.50	18	13	11	19	10	4	0
314	193	1	5	1		2							8	0
315	212	1	5	2	2	2		18	11	8	17	12	8	0
316	218	1	5	2	2	2			17	8	14	10		0
317	77	0	5	2		3		16	14	6	15			0
318	375	1	5	2			27.50	16	12	8	16	12	8	0
319	310	1	5	1	3	3		17	13	8	17	10	4	0
320	207.3	1	5	1		3		18	11	4	20	12	4	0
321	362	1	5	2	4	4					15	10	12	0
322	257	1	5	1							17	12	4	0
323	55	0	5	2				19	8	4	17	8	4	0
324	278	1	5	0		1							6	0
325	332	1	5	2		3		17	10	4	17	8	4	0
326	350	1	5	1							20	11	4	0
327	298B	1	5	0				16	8	4	15	8	4	0
328	271	1	5	2	3	2		16	12	4	15	8	4	0
329	453.2	1	5	2	3	3	28.80							0
330	247	1	5	2	5		28.50							0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
331	180	1	5	2	6	2	27.50							0
332	235	1	5	2	3	3	27.50							0
333	244	1	5	2	3	3	27.50							0
334	400	1	5	1	2	2	27.00							0
335	40	0	5	1		2	26.00							0
336	427	1	5	1	2	2	26.00							0
337	1	0	5	1	3	1								0
338	100	0	5	1										0
339	151A	0	5	0										0
340	151B	0	5	2										0
341	152	0	5	0										0
342	167.1	1	5	1										0
343	173	1	5	0		3								0
344	175.2	1	5	2	2	3								0
345	183	1	5	1										0
346	186.2	1	5	2	3									0
347	190	1	5	0										0
348	22	0	5	1										0
349	25	0	5	0										0
350	256	1	5	2		3								0
351	275	1	5	0										0
352	276	1	5	0										0
353	321	1	5	2	5	3								0
354	324A	1	5	1	3	3								0
355	325	1	5	1		3								0
356	34A	0	5	2										0
357	365	1	5	2	1	4								0
358	368	1	5	2	3	3								0
359	382	1	5	1										0
360	387	1	5	2		5								0
361	391	1	5	2										0
362	392	1	5	1		3								0
363	394	1	5	2	5	3								0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
364	395	1	5	2		3								0
365	4	0	5	0										0
366	404	1	5	2	5	3								0
367	415	1	5	2										0
368	422	1	5	1	4									0
369	428	1	5	2	5									0
370	432	1	5	2	3	3								0
371	437	1	5	1	4	3								0
372	438	1	5	1		3								0
373	445	1	5	2										0
374	45	1	5	2	3	1								0
375	50	0	5	1	3	3								0
376	52	0	5	1	6	4								0
377	73	0	5	1										0
378	R6D-2	0	5	2										0
379	38	0	6	1				34	36	37				0
380	202	1	6	2	9	6					34	30	24	0
381	7	0	6	2					40		36	22	12	0
382	262	1	6	2	7	5		32	16	13	40	36		0
383	237	1	6	1				31	24	22	35	30	16	0
384	186.1	1	6	2	8					20				0
385	204	1	6	2	7	4		35	24	13	35	21	17	0
386	75	0	6	0				26	21	13				0
387	32B	0	6	1				27	17	19	23	18	13	0
388	168	1	6	1				30	22	15		20	13	0
389	245	1	6	1				30	21	13	26	16	10	0
390	8	0	6	1	6	4		24	19	13	27	19	10	0
391	76	0	6	2	7	4		28	23		25	17		0
392	59	0	6	2				25	19	15	13	20	10	0
393	315	1	6	1				22	14	8	32	17	8	0
394	208	1	6	1		6		26	16		22	14	12	0
395	2NW	0	6	2		5					24	21	12	0
396	125	0	6	2		5			18	12	28	15	12	0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
397	371	1	6	2	9	5		22	16	10	22	14	10	0
398	28	0	6	2	9			21	13	11	24	14	10	0
399	265	1	6	3					18	12	24	15	12	0
400	379	1	6	2		5		18	14	14	22	15	10	0
401	229.2	1	6	2	8	5			13	12	20	22	12	0
402	120	0	6	2	7	4		18	13	12	25	15	11	0
403	333	1	6	2		5		23	16		19	16	4	0
404	241	1	6	0	1	4			14			16		0
405	296	1	6	2		5		19	16	12	19	13	8	0
406	305A	1	6	2		4					30	12	4	0
407	273	1	6	2		6		18	12	8	17	14	8	0
408	316.1	1	6	2		5		18	8					0
409	319	1	6	2		4		16	12	4	17	8	4	0
410	10	0	6	1		6								0
411	101	0	6	2	7	4								0
412	115	0	6	0										0
413	122	0	6	2		4								0
414	135	0	6	1	7	4								0
415	143	0	6	1		4								0
416	154A	0	6	0										0
417	161.1	0	6	1	8	5								0
418	164	1	6	2	10	6								0
419	166	1	6	1	9									0
420	173X	1	6	3		4								0
421	175.1	1	6	1		5								0
422	188	1	6	1										0
423	192	1	6	2	6	6								0
424	194	1	6	2	7	4								0
425	1SE	0	6	2	7	3								0
426	201	1	6	2		5								0
427	209.2	1	6	2	10	5								0
428	216	1	6	1	6	5								0
429	23	0	6	0										0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
430	243	1	6	2	6	4								0
431	263	1	6	2		4								0
432	269	1	6	1										0
433	286	1	6	1	4	5								0
434	292A	1	6	1		3								0
435	292B	1	6	2	5									0
436	2B	0	6	2	7	3								0
437	3	0	6	2										0
438	326	1	6	0										0
439	345	1	6	2		5								0
440	346	1	6	0										0
441	34B	0	6	1										0
442	370	1	6	0		3								0
443	372	1	6	1		5								0
444	399	1	6	2		5								0
445	409	1	6	1	7	4								0
446	412	1	6	1	6	5								0
447	417	1	6	1										0
448	418	1	6	2	8	5								0
449	435	1	6	2		5								0
450	44	1	6	1	9	6								0
451	448	1	6	2	6	4								0
452	453.1	1	6	2	10	5								0
453	453.3	1	6	2	6	4								0
454	456	1	6	2		4								0
455	461.1	1	6	2	10	5								0
456	461.2	1	6	2		4								0
457	462	1	6	1		5								0
458	465	1	6	2										0
459	467	1	6	2		5								0
460	468	1	6	2	9									0
461	51	0	6	0										0
462	63	0	6	2	9	6								0

	burial	date	age	sex	pube	auric	age.devo	nm1	nm2	nm3	xm1	xm2	xm3	base
463	66	0	6	0										0
464	92A	0	6	2										0
465	FENCELI	0	6	1	8	5								0
466	WEST FE	0	6	1	6									0
467	364	1	7	2		8		39	22	25	40			0
468	317	1	7	2		7		40	34	12	36	36	18	0
469	74	0	7	1	10			35	25	20		35	26	0
470	147.1	0	7	1	10	8		36	25		36	22	15	0
471	239	1	7	2		8					36	28	27	0
472	147.2	0	7	2	10	7		36	24	21	38	27	17	0
473	79	0	7	3		7		29	23	17	39	28	15	0
474	330	1	7	2		4		34	20	16				0
475	197.2	1	7	2		8			25	19	34	21	16	0
476	264	1	7	3	10	8		35	16	19	36	13	4	0
477	207.2	1	7	2	10	7		28	22	16	26	20	10	0
478	69	0	7	2	10	7		24	20	14	19	18	12	0
479	133	0	7	2		8								0
480	209.1	1	7	2	10	5								0
481	232.1	1	7	0		8								0
482	248	1	7	2		7								0
483	266	1	7	2	10	6								0
484	283A	1	7	2		8								0
485	378	1	7	2	8	6								0
486	421	1	7	1	10	7								0
487	450	1	7	2	10	6								0
488	452	1	7	1	10	7								0
489	87	0	7	0	9									0
490	G4	0	7	2	10	6								0

Appendix B: Examples of R code

The following appendix provides some examples of R code used for analysis and graphics in this dissertation. As an open-source tool for statistical computing and production of high-quality graphics, R is steadily becoming more popular among researchers in the social sciences, including anthropology. As a personal observation while at professional meetings, there seems to be an increasing number of presentations and posters that explicitly mention the use of R for statistical analysis.

In paleodemographic research, one of the biggest advocates for using R has been Lyle Konigsberg, who has made data and working examples of R code available online (https://netfiles.uiuc.edu/lylek/www/). Konigsberg and others have also made snippets of R code available in a number of publications (Konigsberg and Herrmann, 2002; Frankenberg and Konigsberg, 2006). These sources provided templates for the code used in this study. In the examples below, the R code is written in a monospaced font. In the R console, when code goes more than one line, it is denoted by the plus sign (+). So, if one were to copy and paste the code below into R, the ``+" would need to be removed before R could process the command properly.

The base download of R comes with extensive documentation (manuals). In addition, there is an active online help community with archived discussions for R users and many books covering basic statistical analysis using R (e.g., Venables and Ripley, 2002; Crawley, 2005; Verzani, 2005). While all these resources helped during this project, I found that much success came from trial and error, slightly modifying previously published code and seeing the results.

Example 1: Structuring interval-censored, paleodemographic data. Often published paleodemographic data, especially those from early studies, are presented only as counts of individuals in each age category. The following code puts the data in a structure to which hazard models can be fit.

```
hk.tot <- structure(c(15,20,35,50,20,35,50,Inf,50,166,88,
     +    24),.Dim=as.integer(c(4,3)),Dimnames=list(NULL,
     +    c("col1","col2","col3")))
```

The specific example above creates the object `hk.tot`, a matrix describing the age-at-death structure for the HK43 adult sample. The first and second columns represent the start and end years for each age category, respectively. The third column represents the number of individuals assigned to each age category.

Example 2: Fitting a Gompertz mortality (hazard) model to interval-censored data, like `hk.tot`. The following function finds maximum likelihood estimates for the two Gompertz parameters, α_3 and β_3.

```
hk.tot_Gomp <- function(x,deaths=hk.tot){
     +    a3=x[1]
     +    b3=x[2]
     +    shift<- 15 # only ages 15 and up are considered
     +    nrow<- NROW(deaths)

     +    S.t<- function(t){
     +    return(exp(a3/b3*(1-exp(b3*(t-shift)))))}

     +    d<- S.t(deaths[1:nrow,1])-S.t(deaths[1:nrow,2])
     +    obs<- deaths[,3]
     +    lnlk<- as.numeric(crossprod(obs,log(d)))
     +    return(lnlk)}

optim(c(0.01, 0.01),hk.tot_Gomp,control=list(fnscale=-1))
```

The `optim` call returns an α_3 value of 0.03286343, a β_3 value of 0.04271132, and a log-likelihood value of -386.2922. Any similar, interval-censored age data may be fit to the Gompertz model above. One just needs to change the counts of individuals in each age category as appropriate. One advantage of this approach is that the age categories need not be of equal length, and the model allows for an "unknown" age category. For example, individuals only classified as adults could be grouped into an age category from 20 to 80 (or 100, or infinity).

Example 3: Plotting the survival, hazard, or density (i.e., age-at-death distribution) functions for a set of Gompertz hazard model parameters. Once the model parameters have been estimated, the following function may be used to plot the associated curves. The function below uses the parameters estimated by `hk.tot_Gomp`.

```
hk.tot_Gomp.draw <- function (t){
     +    x=c(0.03286343, 0.04271132)
     +    a3<- x[1]
     +    b3<- x[2]
     +    shift<- 15

          S.t<- exp(a3/b3*(1-exp(b3*(t-shift))))
          h.t<- a3*exp(b3*(t-shift))
          d.t<- S.t*h.t
          return<- S.t
          #return<- h.t
          #return<- d.t
}

plot(seq(15,80,1),hk.tot_Gomp.draw(seq(15,80,1)),type='l',
     +    ylab='Survivorship',xlab='Age (years)',
     +    ylim=c(0,1.0))
```

As written, the function above plots the survival function. The `return` command controls the output: survival (`S.t`), hazard (`h.t`), or density (`d.t`) function. The hash (#) tells R to read the line as a comment, rather than an actual command. To plot the hazard function, place a hash before `return<-S.t`, remove the hash before `return<-h.t`, and rerun the code. One could make changes to the plot command, such as changing the label and limits for the y-axis (`ylab` and `ylim`, respectively).