From the Womb to the Tumulus:

Stress, Growth, and Diet at the Qinifab School Site

by

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ABSTRACT

This dissertation examines the interrelationships between stress, frailty, growth, mortality, and diet at the Qinifab School site, Sudan, using a combination of osteological, paleopathological, and biogeochemical methods. The skeletal sample, from the fourth cataract region of Nubia, is comprised of 100 individuals from a Late Meroitic to Christian period (~250-1400 CE) cemetery. Standard osteological methods were used to estimate age and sex, and measurements were taken to assess body dimensions. Preadults were aged by dental and skeletal development, producing two independent ages to categorize individuals as developmentally "normal" or "delayed." Data were collected on nonspecific indicators of stress, including linear enamel hypoplasias (LEHs), porotic hyperostosis (PH), and cribra orbitalia (CO). In preadults, these were compared to World Health Organization (WHO) growth standards to identify individuals who experienced stunting or wasting. For all ages, evidence of stress was compared with age at death and growth/body size. Finally, stable carbon and nitrogen isotope analyses were conducted on bone collagen and carbonate samples from a representative sample of 60 individuals, of which 46 collagen samples and all carbonates had acceptable preservation.

"Delayed" preadults generally showed reduced body size relative to "normal" individuals, they were more likely to be stunted, and their growth trajectories were less similar to WHO standards. However, childhood stress had little impact on adult body size. CO occurred at higher frequencies in preadults and individuals with mixed/active lesions died at younger ages. PH rarely developed before age 6 but was present in most individuals over that age. Individuals with earlier formed LEHs tended to experience more stress overall and die younger. Active/mixed CO was associated with stunting in preadults and reduced brachial index in adults.

A greater proportion of individuals in the Christian period were affected by CO compared to the Post-Meroitic. A temporal shift also occurred in diet between the Post-Meroitic and Christian periods based upon the $\delta^{13}\mathrm{C}_{\mathrm{COLL}}$ and $\delta^{15}\mathrm{N}_{\mathrm{COLL}}$ values. Lower $\delta^{15}\mathrm{N}$ and the greater difference in $\delta^{13}\mathrm{C}_{\mathrm{AP\text{-}COLL}}$ suggest a shift toward intensified agriculture and decreased use of animal products and a potential dietary etiology for the increase in CO.

DEDICATION

To the three most important women in my life: Mom, Nana, and Katie

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CHAPTER 1

INTRODUCTION

Physiological stress experienced in early life can have lasting effects on an individual. Some of these effects may become manifest in the individual's skeleton, long outlasting the causative event. This project combines osteological, paleopathological and biogeochemical methods to examine the interrelationships between early life stress, growth, mortality, and diet in an ancient Nubian skeletal sample. Concepts from the developmental origins of health and disease hypothesis (DOHaD) and the osteological paradox, specifically hidden heterogeneity of risk and selective mortality, are explored. The primary objective is to examine the ways in which stress experienced in early life may affect later health outcomes, and how early life stress is correlated with temporal, demographic, and dietary factors.

The DOHaD hypothesis argues that physiological stress early in an individual's life history may have negative consequences in adulthood (Barker, 2004; 2007). Hidden heterogeneity in risks, an aspect of the osteological paradox (Wood et al., 1992) refers to the assumption that there is unknown variation in underlying frailty present in a population, while selective mortality refers to the fact that individuals in a cemetery sample are non-survivors and thus not representative of the living population. Integrating these factors with the DOHaD hypothesis, one may argue that lesions representing childhood stress can serve as a quantifiable source of heterogeneous frailty in a population. Because some of these lesions are retained in the adult skeleton, they can also be used to compare survivors and non-survivors of childhood, thus allowing for consideration of selective mortality.

The sample is from the Qinifab School site (UCSB 03-01 and UCSB 03-02), located in Sudan between the fourth and fifth Nile cataracts, on the north bank of the Nile near the westernmost end of Mograt Island, west of Abu Hamed. It is a multicomponent site, excavated from 2007-2009, which contains a Late Meroitic-Christian period cemetery dated from c. 250-1400 CE, a timespan that encompasses significant political change for the Nubian region (Baker, 2008, 2014,). The skeletal remains in the collection bear evidence of physiological stress (Norris et al., 2015; Norris and Baker, 2014, 2015,) and interpersonal violence (Baker, 2008, 2014, 2016).

Chapter 2 examines the impact of stress on preadults in the collection by examining several lines of evidence for impaired growth. World Health Organization (WHO) standards used to assess growth impairment in living children were incorporated in order to estimate which preadults in the collection would be considered stunted (low height-for-age) or wasted (low weight-for-height). Delayed skeletal development was assessed by comparing skeletal age to dental age, which is less affected by environmental stressors. These measures of impaired growth can be considered evidence of early life stress. Regression formulae are used to model the growth trajectories of Qinifab School preadults to WHO standards and other sites, and to compare individuals with and without evidence of impaired growth.

Chapter 3 also examines the relationship between preadult stress and growth, this time incorporating adult body size dimensions and mortality (age at death).

Paleopathological data were collected on nonspecific indicators of stress, some of which form in early life but are retained in the adult skeleton: cribra orbitalia, porotic hyperostosis, and linear enamel hypoplasia. In order to examine the effects of stress in early life with later outcomes, these data are compared with measurements of growth in adults and preadults, incorporating body size dimensions and the evidence for growth faltering identified in the first paper. The effects on mortality and cumulative stress are also examined. This study hypothesizes that, in accordance with the DOHaD hypothesis, more stress in early life results in worse health outcomes in adulthood, and also assesses whether nonspecific indicators of stress are indicators of underlying frailty.

Chapter 4 examines temporal change in diet at the Qinifab School site and the effects of dietary change on childhood stress, using a combination of biogeochemical and paleopathological methods. Ribs were sampled from 60 individuals in the collection for stable isotope analyses: carbon from both bone collagen and carbonate, and nitrogen from bone collagen. Temporal changes in diet between the Post-Meroitic and Christian period were analyzed and compared to temporal changes the frequency and expression of porotic hyperostosis and cribra orbitalia, which are associated with nutritional deficiency. Isotopic variation is considered along demographic lines, and the data are compared with other sites in Sudan to better understand the broader regional context of diet in ancient Nubia.

CHAPTER 2

SLOW GROWING IN ANCIENT NUBIA: STRESS, GROWTH, AND DEVELOPMENT AT THE QINIFAB SCHOOL SITE

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Abstract

The interrelationships of development, growth, and stress are examined in an ancient Nubian skeletal collection. Developmental delay, stunting, wasting, and the presence of non-specific skeletal indicators of stress are identified and compared. Preadults (n=32) from the Qinifab School site, a late Meroitic-Christian period site in the fourth cataract region of Sudan, were aged by dental and skeletal development to produce two independent ages to categorize individuals as developmentally "normal" or "delayed." Individual stature, body mass, and BMI estimates were calculated. Stature and BMI estimates were compared to World Health Organization (WHO) growth standards to identify individuals who experienced stunting or wasting. Models derived from regression formulae were used to compare stature estimates to WHO standards and two other Nubian samples, and to compare body mass estimates to WHO standards. Stature models were used to estimate growth velocity. Differences were evaluated using paired-samples t-tests. Preadults with delayed growth generally also show reduced stature and body size relative to "normal." Growth in "normal" individuals is more similar to WHO standards than in "delayed" individuals. Associations were found between stunting and delayed development, but not between wasting and stunting or wasting and delayed development. Adult stature decreased slightly between the Post-Meroitic and Christian periods but is not statistically significant. Similarities with patterns in modern clinical studies were found. Comparisons of growth trajectories and adult stature estimates among ancient Nubian sites suggest that preadults at al-Qinifab appear better off than those at Wadi Halfa and Kulubnarti.

Introduction

Growth and development have long been analyzed in biological anthropology as a means of assessing health and nutritional status in living populations, to estimate age and evaluate stress in ancient ones, and for studying the evolution of juvenility in our species. Relative long bone growth, adult stature, and evidence of growth retardation have often been used as non-specific indicators of stress (Bogin & Varela-Silva, 2010; Himes, 2004; Hoppa & Fitzgerald, 1999; Pinhasi, 2007). For example, a decline in stature over time in a given population might be interpreted as an increase in stress and/or a decrease in the accessibility, quantity and quality of necessary resources (DeWitte & Hughes-Morey, 2012; Mummert, Esche, Robinson, & Armelagos, 2011; Vercellotti et al., 2014). Growth has potential to be extremely informative about the social and environmental conditions of lives in the past. Nevertheless, there are certain problems inherent in any attempt to reconstruct growth patterns from skeletal samples. One issue is that the data are necessarily cross-sectional, rather than longitudinal, meaning that individual variation in growth will be masked. A second issue is that of mortality bias: all of the children in a cemetery are by definition those who failed to survive to adulthood (Wood, Milner, Harpending, & Weiss, 1992). These individuals, therefore, cannot be assumed to represent “normal” growth in their population.

“Growth” refers to increases in size that progress throughout an individual’s development (Bogin, 1999; Himes, 2004; Scheuer & Black, 2000). “Development” can be defined broadly as the progression from an immature to a mature state, and the changes that happen to an individual as a result. These changes are morphological, functional, and hormonal, among others (Bogin, 1999; Himes, 2004). The development of bones can be divided into three phases: initial ossification, appearance of distinct morphology, and fusion with another center of ossification (Baker et al., 2005; Scheuer & Black, 2000; White, Black, & Folkens, 2011). The clavicle begins to ossify *in utero* at 5-6 weeks gestation, the starting point to this 20-year process of bone development and growth (Baker et al., 2005; Scheuer & Black, 2000).

Human growth literature typically defines between four and five stages of human growth: infant, child, (juvenile), adolescent, and adult (Bogin, 1997, 1999; Cameron, 2012; Molinari & Gasser, 2004; Pinhasi, 2007). Some classifications also include a neonatal period of birth to one month (e.g., Bogin, 1999). Infancy is characterized by rapid growth that decelerates at a fast rate over time and is usually said to end with the cessation of lactation, around 2.5-3 years (Bogin, 1999; Molinari & Gasser, 2004; Pinhasi, 2007). Alternatively, Cameron (2012) suggests the infancy period lasts until the age of five, based on the typical human velocity curve. Growth slows to a moderate rate during childhood (usually described as 3-7 years), slowing even further during the juvenile period (7-10 years for females and 7-12 years for males), which ends with the start of puberty (Bogin, 1999; Pinhasi, 2007). A growth spurt typically occurs during the adolescent period (10-19 years in females and 12-21 years in males), approximately five to eight years after puberty begins (Bogin, 1999; Cameron, 2012; Molinari & Gasser, 2004; Pinhasi, 2007). Once terminal stature is attained, the individual enters the adult stage, at least as far as growth is concerned.

Estimating age for preadult skeletons is based, in order of reliability, on dental development, skeletal development, and bone growth, particularly long bone diaphysis length (Baker et al., 2005; Hoppa & Fitzgerald, 1999; Scheuer & Black, 2000). Dental development and eruption patterns are considered more accurate because bone growth and development are more likely to be affected by environmental stressors such as malnutrition or disease (Cardoso, 2007; Conceição & Cardoso, 2011; Hoppa & Fitzgerald, 1999). Studies by the World Health Organization (WHO) indicate that differences in ethnicity and genetics are of minimal import compared to environmental factors in influencing growth and development, and WHO growth standards help assess malnutrition in children worldwide (World Health Organization & United Nations Childrens Fund, 2009). Two of the most important factors evaluated are “stunting” and “wasting,” low height-for-age, and low weight-for-height, respectively (Waterflow, 1974). Although these conditions are both products of malnutrition, and both are associated with higher risk of mortality, they do not always co-occur, and the relationship between them is not always well-understood (Briend, Khara, & Dolan, 2015).

The interrelationships of development, growth, and morbidity are examined in an ancient Nubian sample from al-Qinifab, Sudan, currently housed at the Bioarchaeology of Nubia Expedition Laboratory (BONE) at Arizona State University (ASU). Previous work on this collection has shown that numerous preadults display delayed skeletal relative to dental development, and suggested a relationship between this delay and the presence of certain stress indicators (Norris, Dahlstedt, & Baker, 2015) This study uses standard measurements and published formulae to reconstruct stature, body mass, and body mass index (BMI), which are then compared to standards from the World Health Organization and to other Nubian samples. These calculations are also used to identify individuals in the collection as “stunted” and/or “wasted.” This study has three objectives: 1) to assess whether individuals with delayed skeletal development also experienced reduced body size dimensions, including stunting and wasting, 2) to assess whether individuals with normal development are more likely to match the WHO growth standards than individuals with delayed development, and 3) to compare growth trajectories and adult stature to other Nubian samples to better contextualize the results.

Growth in Ancient and Modern Sudan

Bioarchaeologists use a variety of data associated with growth and development in assessing stress within and between populations. Analyses of stress and growth have been a fruitful area of research on ancient Nubian skeletal collections (Armelagos, Huss-Ashmore, & Martin, 1982; Armelagos et al., 1972; Buzon, 2014; Buzon & Judd, 2008; Hummert, 1983; Huss-Ashmore, 1981; Judd, 2014; Prendergast Moore, Thorp, & Van Gerven, 1986; Sheridan & Van Gerven, 1997). For example, comparisons of long-bone growth between preadults from Meroitic-Christian period (350 BCE-1400 CE) Wadi Halfa and modern American boys showed that growth rates were slower and overall stature was smaller among the ancient Nubians (Armelagos et al., 1972). The American children experienced growth acceleration for the first few years of life, followed by a period of deceleration and then a second period of acceleration that peaked with the adolescent growth spurt (Armelagos et al., 1972). The Nubian children, by contrast, experienced a steady deceleration of growth from the first to the seventh year of life, with a complete cessation of growth around age six, followed by two periods of catch-up growth experienced in later childhood (Armelagos et al., 1972). This pattern was interpreted as being indicative of periods of increased stress, a conclusion also supported by follow-up work conducted by Huss-Ashmore (Huss-Ashmore, 1981). Hummert and Van Gerven (1983) compared these measurements to those of early Christian period individuals from Kulubnarti and found a similar pattern of growth in early childhood, although the Kulubnarti individuals experienced an adolescent growth spurt that started and ended earlier, and which resulted in shorter diaphyseal lengths in individuals of 14-15 years of age.

Clinical studies conducted on infants and children in modern Sudan have more directly examined the relationship between growth and disease stress. Zumrawi and colleagues (1987) examined the effects of symptoms of infection on weight gain in more than 400 infants in Khartoum during their first year of life, and found that episodes of diarrhea produced a deficit of 32 g per day ill, and 16.4 g for a cough/cold. In their reanalysis of these data, Brush and colleagues (1997) found not only that weight gain falters during illness, but there was also a correlation between illness experienced in the first 6 months and impaired weight gain in the second 6 months. Although growth in length only faltered during the period of illness, catch-up growth generally did not occur within the subsequent 6 months. However, no association was found between early slow growth and later susceptibility to disease. In a study on Sudanese children under 5 years, Kossman and colleagues (2000) found significant associations between infection and height/weight gain over a 6-month period. Even among “normally nourished” children, the risk of stunting was significantly greater 6 months after episodes of diarrhea and/or fever. The observed difference in height between stunted and non-stunted children was also found to increase with age (Kossmann, Nestel, Herrera, El-Amin, & Fawzi, 2000).

Biocultural Context of the Qinifab School Site

Nubia is a cultural and geographical region located predominantly in northern Sudan, extending from the first cataract at Aswan, Egypt, to roughly the sixth cataract located north of Khartoum, although sources vary somewhat on the exact span (Bianchi, 2004; Edwards, 2004; Lacovara, 2012; O’Connor, 1993). Following a period of Egyptian hegemony and colonization lasting from around 1500-1069 BCE, a new center of power developed, located first at Napata (1000-350 BCE), then farther south at Meroe (350 BCE-350 CE; Edwards, 2004; Fisher, 2012; Welsby, 1996). The period following the decline of the Meroitic empire is referred to as the Post-Meroitic (350-550 CE) in Upper Nubia, that portion south of the second cataract near the border with modern Egypt. This period was followed by the Medieval or Christian period (550-1400 CE), during which the kingdoms of Makuria, Alwa (Alodia), and Nobadia converted to Christianity (Edwards, 2004; Fisher, 2012; Welsby, 2002). Nobadia and Makuria later coalesced into a single kingdom (Edwards, 2004).

The Qinifab School site (UCSB 03-01 and UCSB 03-02) is located between the fourth and fifth Nile Cataracts, on the right (north) bank of the Nile near the westernmost end of Mograt Island (Fig. 1). A concession in this area was first granted to the University of California, Santa Barbara (UCSB), in 2003 as part of the Merowe Dam Archaeological Salvage Project (MDASP), for what became a joint archaeological venture between UCSB and ASU (Baker, 2008, 2014; Herbst & Smith, 2014; S. T. Smith & Herbst, 2005). A new concession in this area was granted to ASU in 2009. Prior to the initiation of the MDASP in 1996 (Ahmed, 2003), the fourth cataract region had received "almost no sustained archaeological attention" due to assumptions that settlements in the area were sparse (Emberling, 2012, p. 72). Continuing archaeological work has proved otherwise. More than 200 sites have been identified within the ASU concession alone, including numerous cemeteries and the remnants of a fort (Baker, 2016, pp. 191–193; Baker & Schellinger, 2017).

The Qinifab School site is a multicomponent site consisting of a late Neolithic to Kerma period settlement on which a late Meroitic to Christian period cemetery (~250-1400 CE) was placed (Baker, 2014; Herbst & Smith, 2014). Excavated between 2007 and 2009, this non-elite cemetery contained 37 stone tumuli, 30 smaller superstructures consisting of rock cairns, and 36 subsurface shafts (Baker, 2008, 2014). Variability in grave structures was found both between and within the time periods represented (Baker, 2014). Following the course of the river, the site is located between the Kushite power centers of Napata and Meroe, and in the frontier zone between the later Christian kingdoms of Makuria and Alwa (Zurawski, 2014). The Post-Meroitic was associated with low Nile levels, decreased political centralization, increased cultural regionalization, and an intensification of agriculture leading to a shift in diet (Edwards, 2004; White &

Schwarcz, 1994; White, Longstaffe, & Law, 2004). Evidence of interpersonal violence is evident across all time periods at the Qinifab School site, including the presence of archery equipment in late and Post-Meroitic graves, an adult male from the Post-Meroitic with an iron arrow point embedded in his sternum, and cranial depression fractures on multiple individuals from the Christian period (Baker, 2008, 2014, p. 853).

In addition to the fluctuations of power in the region and evidence for strife, the preadults of Qinifab may have been affected by malnutrition and disease. Diarrheal diseases were likely among the most dangerous for young children, caused by conditions such as dysentery and typhoid fever, an assortment of viruses, and bacterial contamination (Brahin & Fleming, 1982). Endemic diseases in the Nile Valley, in both past and present, include malaria (Bianucci et al., 2008; Giha et al., 2005; Lalremruata et al., 2013; Miller et al., 1994; Smith-Guzmán, 2015) and schistosomiasis (Adamson, 1973; Alvrus, 2006; Barakat, 2013; Hibbs, Secor, Van Gerven, & Armelagos, 2011; Miller et al., 1992). Skeletal changes associated with tuberculosis have been identified in remains from both Egyptian (e.g., Baker, 1997; Buikstra, Baker, & Cook, 1993; Dabernat & Crubézy, 2010), and Nubian populations (e.g., Bourke, 1971; Morse, Brothwell, & Ucko, 1964). The Nile Valley is also conducive to a host of helminths, such as hookworm, tape worm, and round worm, and other parasitic infections such as onchocerciasis and leishmaniasis (Bañuls, Hide, & Prugnolle, 2007; Hotez et al., 2004; Perrin, Herbreteau, Hugot, & Morand, 2010; Webber, 1996).

Materials and Methods

The Qinifab School Site

A total of 100 individuals is available for analysis in the Qinifab School site collection, including 33 preadults, of which 32 were examined for this study (one perinate stillborn individual was excluded). Four categories are used for analysis, based on those commonly used in the human growth literature (e.g., Bogin, 1997, 1999; Pinhasi, 2007): 0-3 years, 3-7 years, 7-12 years, and 12-19 years. The terms typically associated with these stages (infant, child, etc.), will be avoided here, however, due to the cultural variability with which they are used (Halcrow & Tayles, 2008). Likewise, the term "preadult" is used to designate individuals under the age of 20, although it is recognized that, in life, several of these individuals may have been considered culturally "adults." "Preadult" is used here only to indicate that they were still undergoing growth and development. Overall site demographics are illustrated in Figure 2. It should be noted that most of the preadults (62.5%) in the collection are from the Christian period, and generally well-preserved.

Methods

Age and sex estimations have been made for this collection using standard osteological methods (Buikstra & Ubelaker, 1994). Sex estimations were not made for individuals less than 15 years of age at death. Supplemental information regarding dental development and eruption (Hillson, 1997; Moorrees, Fanning, & Hunt, 1963b, 1963a; Schour & Massler, 1941; B. H. Smith, 1991; Ubelaker, 1989) and ossification and epiphyseal fusion (Baker et al., 2005; Brothwell, 1981; Scheuer & Black, 2000; Steele & Bramblett, 1988) was used to narrow estimated age ranges for preadults. Each age range was independently averaged to produce a single dental age and a single skeletal age estimate. A difference of approximately one year or more between these estimates was used to classify each individual as having either "normal" bone development relative to dental age or "delayed" development.

Length measurements were taken for all adequately preserved long bones using standard methods (Buikstra and Ubelaker, 1994). Additionally, maximum breadth of the distal femoral metaphysis was measured in individuals with unfused epiphyses, and the maximum diameter of the femur head was measured in individuals older than seven years. These measurements were used to compute estimates of stature (cm), body size (kg), and BMI, using the published formulae shown in Table 1 (Keys, Karvonen, Kimura, & Taylor, 1972; Raxter et al., 2008; Schug, Gupta, Cowgill, Sciulli, & Blatt, 2013). Stature and BMI measurements were compared with the WHO standards to classify individuals as stunted and/or wasted. Individuals whose stature was two standard deviations below the median for their age were considered "stunted," while those whose BMI was two standard deviations below the median were considered "wasted." Individuals of indeterminate sex were all compared to the female standards, in which BMI is slightly lower, so as not to overestimate the number of wasted individuals. BMI was used because WHO standards are not available for direct weight-for-height comparisons for the full range of ages examined.

IBM SPSS Statistics 25 was used to produce cubic regression formulae for stature and body mass of "normal" and "delayed" preadults separately. For comparison, cubic regression formulae were also produced for the WHO's growth standards (World Health Organization & United Nations Childrens Fund, 2009), and for two Nubian sites based on published data (Armelagos et al., 1972; Hummert, 1983; Hummert & Van Gerven, 1983). These formulae were used to produce growth models that were compared using paired samples t-tests. The models were also compared to scatterplots displaying normal vs. stunted individuals. Regression formulae were also used to model body mass for the Qinifab sample and the WHO standards up to age 10 years (standards were not available beyond this age). Comparisons between these models were tested using paired samples t-tests. Regression models were again produced for comparing body mass for stature between normal and wasted individuals and compared with scatterplots displaying normal versus delayed individuals. Scatterplots displaying BMI of normal versus wasted and normal versus delayed individuals were also produced and compared to the WHO standards. Stature growth velocities (centimeters of growth per year) were calculated for the Qinifab sample, the WHO standards, and the other Nubian samples based on the regression models, then compared using Pearson's correlation coefficient.

Finally, adult stature was calculated using Raxter et al.'s (2008) equations for maximum femur length. Comparisons between time periods were tested using independent samples t-tests. Stature estimates were also compared to published data from other Nubian sites (Buzon, 2006; Hummert & Van Gerven, 1983; Raxter, 2011; Vagn Nielson, 1970).

Results

Raw data are included for each individual in Appendix A. Frequencies of delayed development, wasting, and stunting, are listed in Table 2. Stature estimates for preadults are graphed by age in Figure 3. Individuals with normal skeletal development and those with delayed development are indicated with different symbols, and cubic regression formulae were generated to model the growth of each group separately. These cubic regression models are shown again in Figure 4, this time differentiating normal from stunted individuals. Growth delay and stunting were compared using a chi-square test, and the association was found to be significant (p=0.037). The crosstabulation is shown in Table 3. Body mass estimates for delayed and stunted individuals are shown by age in Figure 5, along with cubic regression lines for each. These same estimates are shown by stature in Figure 6, with markers differentiating normal from wasted individuals, along with quadratic regression lines for each. These same regression models are shown again in Figure 7 with comparisons to normal versus delayed individuals. Figure 7 shows less overlap between the delayed and wasted individuals than there was between delayed and stunted individuals (Figure 4). This observation is confirmed by a chi-square test, which did not yield a statistically significant association between them. A chi-square test was also run to examine the association between stunted and wasted individuals also proved not to be statistically significant. The crosstabulations for these tests are shown in Tables 4 and 5.

The modeled growth trajectories for stature were then compared to cubic regression formulae generated based on the WHO growth standards, and published average measurements from two other ancient Nubian samples, Kulubnarti and Wadi Halfa (Armelagos et al., 1972; Hummert, 1983; Hummert & Van Gerven, 1983). These comparisons are shown in Figure 8. Differences between the models were evaluated using a paired samples t-test. All differences were found to be statistically significant

(Table 6). When broken down by age group (Table 7), however, some statistical similarities emerged. In the 0-3 years age group, the Qinifab normal model showed no statistically significant difference with either Kulubnarti or Wadi Halfa, while the Qinifab delayed model showed no difference with Wadi Halfa only. In the 3-7 years group, no statistically significant difference was found between the Qinifab delayed model and Kulubnarti or Wadi Halfa. In the 7-12 years age group, only the difference between the Qinifab normal model and the WHO standards is not statistically significant, which is also true in those age 12-19 years. In this group (reduced to 12-16 years due to data availability in the Kulubnarti sample), there is also no statistical difference between the Qinifab delayed model and Kulubnarti.

Cubic regression models for body mass were also compared among the WHO dataset, and the “normal” and “delayed” Qinifab data (Fig. 9). Because the WHO data do not extend beyond 10 years of age, the models also stop at this point. Paired t-tests show that differences among all three are statistically significant (Table 8). In the 0-3 years category, however, the differences between the “normal” and “delayed” Qinifab models were not statistically significant (Table 9), whereas in the age categories of 3-7 and 7-12 years the differences between the WHO and “normal” Qinifab models were not statistically significant (Table 9).

Figure 10 compares BMI by age between normal and wasted Qinifab individuals, with a quadratic regression line representing WHO standards. While most Qinifab individuals are below the WHO line, only five qualify as “wasted.” In Figure 11, the markers instead indicate normal versus delayed individuals. Observing both Figure 10 and Figure 11, it is obvious that there is some overlap between wasted and delayed individuals; however, the majority of delayed individuals did not also experience wasting.

Figure 12 shows a comparison of stature growth velocity (defined as centimeters of growth per year) reconstructed from the previously shown regression models. Similarities between these models were tested using Pearson correlation coefficients (Table 10). The most highly correlated pair are the normal Qinifab individuals and the WHO standards, while the weakest correlation is between the former and Kulubnarti.

Finally, Table 11 shows the mean stature for males and females from the Post-Meroitic and Christian period, along with the means for the site as a whole. The Meroitic period has not been given separately due to small sample size, though it is included in the total site calculation. The overall stature median, standard deviation, and range for males and females are represented in Figure 13. Comparisons between the Qinifab School site and other samples are shown in Table 12. Although for comparative purposes the mean statures for the Post-Meroitic and Christian periods are given in addition to the mean for the whole sample, the difference between time periods was not found to be statistically significant.

Discussion

Growth Reconstructed

Mortality bias or selective mortality is a well-acknowledged problem in bioarchaeology, especially when it comes to studying preadults (Wood et al., 1992). Individuals who died as children cannot be assumed to be representative of children in the living population. None of the so-called “normal” preadults in this study should be assumed representative of “normal” growth and development among the living population of children who once inhabited al-Qinifab (Saunders & Hoppa, 1993). Furthermore, any reconstruction of growth patterns is necessarily cross-sectional, and cannot be assumed to represent the growth pattern of any single individual in life. Nevertheless, the differences in these growth patterns between individuals with normal skeletal development and those with developmental delays are still informative and warrant further exploration. In this section, therefore, we present a hypothetical picture of growth at al-Qinifab in the Post-Meroitic to early Christian period, based on the models presented.

Preadults with “normal” skeletal development still started off life smaller on average than the WHO standards in both stature (Fig. 8, Table 7) and body mass (Fig. 9, Table 9). In those first few critical years, however, they grew at the same rate (Fig. 12, Table 11). Between roughly 3 and 7 years of age, Qinifab preadults began to catch up in body mass and by 7-12 years they caught up in stature as well. Their growth rate, though declining steadily as expected in the pre-pubescent years, was higher than that of the WHO standards, allowing the observed “catch up” in body size. By puberty, the expected adolescent growth spurt is evident in the WHO standards. This spurt did not occur for the “normal” Qinifab preadults, whose growth rate continued its steady decline (Table 11). Nevertheless, the outcome in stature was more or less the same (Table 7), as was their BMI (Fig. 11).

The “delayed” Qinifab preadults also started off smaller than the WHO standards and slightly smaller than their normal Qinifab peers in stature, though not in body mass. On average, however, their growth velocity was similar in those first three years, apart from an aberrant decrease between 1 and 2 years. The delayed group remained smaller than both the normal Qinifab group and the WHO standards throughout their development, reaching a peak mean difference in stature (19.2 cm and 18.8 cm respectively) between 7 and 12 years of age. Their growth velocity up to this point was also much slower. Around puberty, however, their growth rate took a steep upturn, exceeding the velocity of both the normal group and the WHO standards. Subsequently, although they remained smaller in stature, they did manage to reduce the mean distance to 12.9 cm and 15.1 cm respectively between the ages of 12 and 19 years.

Stature models for the other two Nubian sites are more similar throughout to that of the delayed Qinifab preadults, while the model for the normal Qinifab preadults is more similar to the WHO standards. It should be noted that the published data are limited to averages, so the models here must be interpreted with more caution. The first category of development (0-3 years) is the only period in which the normal Qinifab stature model is more similar to the other Nubian sites than it is to the WHO standards. This finding may indicate that the average birth weight in ancient Nubia was lower than that of the modern samples from which the WHO data derive. However, even the Qinifab preadults with normal skeletal development still died in childhood, so their presumed low birth weight may not represent the average for preadults who survived. Mortality rates for those under age 5 are a common statistic used to evaluate health across modern populations because this period is a particularly critical one when young children are especially susceptible to the effects of nutritional and disease stress. This age range is typically the period during which weaning occurs, and with it the so-called “weanling’s dilemma,” in which non-milk foods increase exposure to pathogens, but lack of them falters growth (Katzenberg, Herring, & Saunders, 1996). The data here suggest that, in these early critical years, the infant and weanling diet was able to sustain growth *rates* close to the standards for both normal and delayed individuals at Qinifab, but not at the same size.

Growth Reconsidered

There is some overlap among the categories of delayed development, stunting, and wasting. The pair with the most overlap, delayed development and stunting, is also the only one for which the association is statistically significant. Even so, there are individuals who are delayed but not stunted, stunted but not delayed, and most of those in either category are not also wasted. In fact, there are only two individuals (UCSB 03-01 B64 and B79) who had the ultimate misfortune of suffering from stunting, wasting, and delayed development, although all three conditions are caused by similar factors.

In the 1970s, Taha (1978) conducted a study on over a thousand Sudanese children in the Gezira, south of Khartoum. The mean height and weight measurements for these children are remarkably similar to those of the “normally” developing preadults from the Qinifab School site. Taha (1978) found that less than half of the children in his study were well-nourished. Returning to the subject of mortality bias, it should be re-emphasized that the preadults from the Qinifab School site, especially those under the age of 5, were likely to have been malnourished or ill when they died, even if their skeletal measurements indicate “normalcy.” One reason that there may be a much greater number of preadults with stunting as opposed to wasting is that wasting is typically considered the result of acute malnutrition, whereas stunting is more typically associated with chronic malnutrition (Waterflow, 1974); Briend (2015), however, cautions that this assertion is somewhat misleading since, if left untreated, wasting can last several months. From a bioarchaeological perspective, an acute condition leading to wasting is likely to kill the child too quickly for the consequences to manifest in their skeletal measurements. It is more likely that a prolonged episode of wasting would be detectable and, at least in this sample, this pattern seems to have been more unusual than the chronic but more moderate malnutrition that tends to be responsible for stunting (Briend et al., 2015; Victora, 1992; Waterflow, 1974).

Growing Pains in Context

The next point that must be considered is the meaning behind the variation noted in development at al-Qinifab compared to other sites. The data demonstrate that there is a difference in both stature growth trajectory and velocity between the normal Qinifab preadults and those with delayed development. This distinction between normal and delayed is not made in the data from Wadi Halfa or Kulubnarti, so direct comparison is not possible. However, certain inferences can be made based on the data that are available.

Research has shown that the populations from Wadi Halfa and Kulubnarti were genetically similar (Greene, 1982; Van Gerven, 1982), so it is unlikely that hereditary factors explain the differences observed at these two sites (Hummert & Van Gerven, 1983). In both growth trajectory and velocity, Kulubnarti is more similar to the delayed Qinifab preadults than those deemed to have normal development, whereas Wadi Halfa is intermediate. In Figure 14, the normal and delayed Qinifab preadults are combined into a single model. Again, Kulubnarti's preadults are shorter through most of their growth trajectory than either Qinifab or the intermediate Wadi Halfa. This observation may suggest that a proportionately greater number of the Kulubnarti preadults were developmentally delayed compared to Qinifab and Wadi Halfa, and that proportionately more preadults at Wadi Halfa were delayed compared to Qinifab.

Kulubnarti is located in a region known as the *Batn el Hajar,* where the alluvial floodplain that sustains the riverine settlements of the Nile Valley is limited and discontinuous. It has been suggested that the villages there were somewhat politically isolated as well (Adams, 1977; Armelagos & Van Gerven, 2017; Edwards, 2004). It would not be surprising, therefore, if the preadults of Kulubnarti were affected by a greater degree of stress than in comparable populations. Agricultural prospects were somewhat better at Wadi Halfa, although it was only after the introduction of the *saqia* waterwheel in the late Meroitic that the area was likely able to achieve subsistence farming (Edwards, 2004). Although there is limited evidence available from settlement sites of this time span in the ASU concession, in other areas of the fourth cataract region there seems to have been less reliance on the *saqia,* and more reliance on irrigation techniques that require more rainfall than the region experiences today, suggesting a lusher climate in the past (Żurawski, 2014, p. 150). Aridification in Nubia has proceeded southward over time (Edwards, 2004), so it is possible that the climate was more favorable farther south at al-Qinifab during the time periods under scrutiny than it was at either Wadi Halfa or Kulubnarti. In the area around al-Qinifab, however, the end of the Meroitic period through the Christian period was marked by construction of a string of forts and increasing evidence of interpersonal violence (Baker, 2008, 2014; Baker & Schellinger, 2017; Żurawski, 2014). This evidence suggests that the fourth cataract region was an area of conflict that may be expected to have increased physiological stressors among its inhabitants. Clearly, environmental and cultural factors affecting growth and development the second and fourth cataract regions differed and merit further exploration.

Another way to examine the context of growth at the Qinifab School site is to compare adult stature with that at other sites. Table 12 compares adult stature between Qinifab and other Nubian sites, in addition to an ancient Egyptian, a modern Egyptian, and a modern Sudanese sample. Stature at al-Qinifab is on the taller end of this spectrum, not surpassed by any of the contemporaneous samples. The difference is modest, ranging from 1.3-2.6 centimeters. If stature could be taken as a simple indicator of overall health, the individuals at the Qinifab School site would have been among the healthiest in ancient Nubia. However, it would not be wise to oversimplify the data to this extent. Terminal stature is determined by hereditary factors as well as environmental ones. Raxter (2011) noted that for every time period examined (with the exception of the New Kingdom period of Egyptian colonization of Nubia), Nubians were consistently taller than their northern neighbors in Egypt. This difference holds for the modern Sudanese and Egyptian samples (Raxter, 2011). Furthermore, the other sub-Saharan African populations compared also tended to be taller than Egyptians, excluding “pygmy” groups. This pattern is significant because the Qinifab School site is located farther south than any of the other sites compared, so it is not inconceivable that the differences observed both in growth trajectories and adult stature are influenced by genetic factors rather than (or in addition to) differences in preadult stress.

Although the complex relationship between hereditary and environmental factors makes it difficult to assess stature variation, it does not appear that the adults of the Qinifab School site were significantly affected by the stunting observed in some of the preadults. Presumably, stunted children tended either to die young or experience catch-up growth. However, studies of growth in the past are always hindered by the fact that we cannot reconstruct the growth trajectories of those who lived to adulthood; we can only observe the ultimate outcome of their development. Nor can we predict whether a stunted child who died young would have experienced catch-up growth had they but lived a few years longer.

Conclusion

The two hypotheses tested in this study–that individuals with delayed skeletal development also experienced reduced body size dimensions, and that individuals with normal development are more likely to match the WHO growth standards than individuals with delayed development–were broadly supported. However, only a relationship between stunting and delayed development could be demonstrated statistically, and no such relationship was demonstrated between stunting and wasting or wasting and delayed development. Comparative data suggest that the preadults of el-Qinifab may have been somewhat better off than their peers at Wadi Halfa and Kulubnarti. There is nothing to suggest that adults in the sample were affected by the stunting observed in some children. On the contrary, adult stature was among the tallest observed in ancient Nubian collections. However, questions about the biological distance between these populations may be pertinent. The results suggest that further research is needed to elucidate differences more fully in the biocultural context that may account for these observations.

Author Contributions

ALN and BJB: study design, data collection. ALN: data analysis and interpretation, drafting and editing of manuscript, AD: data acquisition and analysis. BJB: collection curation, manuscript revisions. All authors reviewed and approved the final manuscript.

Tables and Figures

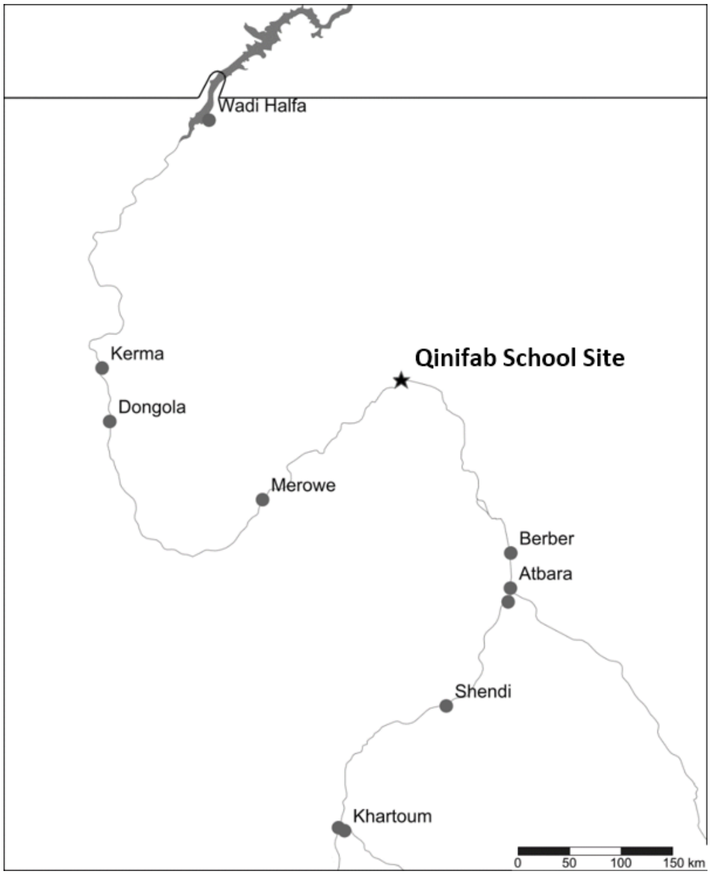

Figure 1 Location of the Qinifab School site

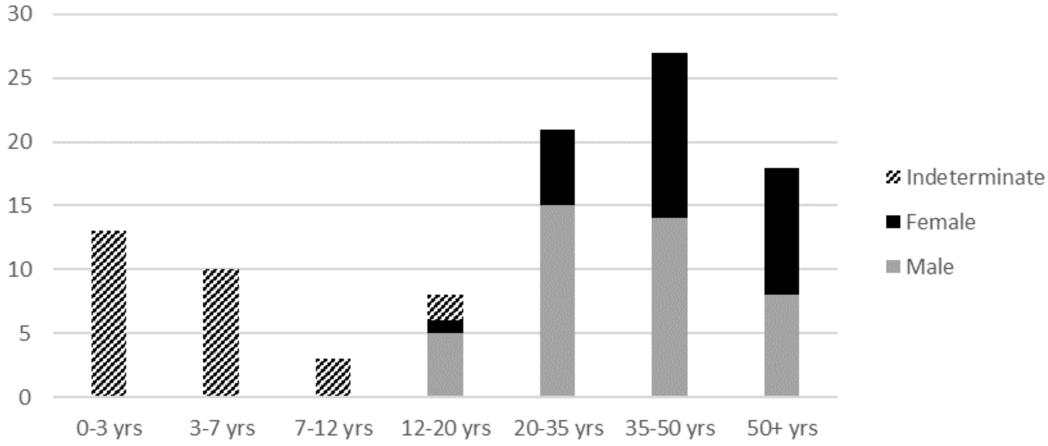

Figure 2 Qinifab School site demographics by age and sex

Table 1 Calculations and formulae

Calculation	Measurement	Formula	Source
Stature (0-12 years)	Femur diaphyseal length (FDL)	Stature = 31.0390 + 0.3221*FDL	Schug et al., 2013
Stature (14-19)*	Maximum femur length (FML)	Stature = 2.340(FML) + 56.99 (males)	Raxter et al., 2008
		Stature = 2.257(FML) + 63.93 (females)	
Body Mass (0-7 years)	Femur metaphyseal breadth (FMB)	ln{body mass} = 13.0615 - 7.3338*ln{FMB} + 1.2058*ln{FMB}^{2}	Schug et al., 2013
Body Mass (7-18 years)	Maximum femur head diameter (FHD)	ln{body mass} = 11.5770 - 6.2969*ln{FMB} + 1.1297*ln{FMB}^{2}	Schug et al., 2013
Body mass index (BMI)	Stature and body mass	BMI = Body mass / stature^2	Keys, 1972
*For two individuals of indeterminate sex, the female equation was used			

Table 2 Frequency of delayed development, stunting, and wasting

Affliction	Number affected	Number observable	Frequency
Delayed skeletal development	11	32	34.4%
Stunting	13	30	43.3%
Wasting	5	28	17.9%

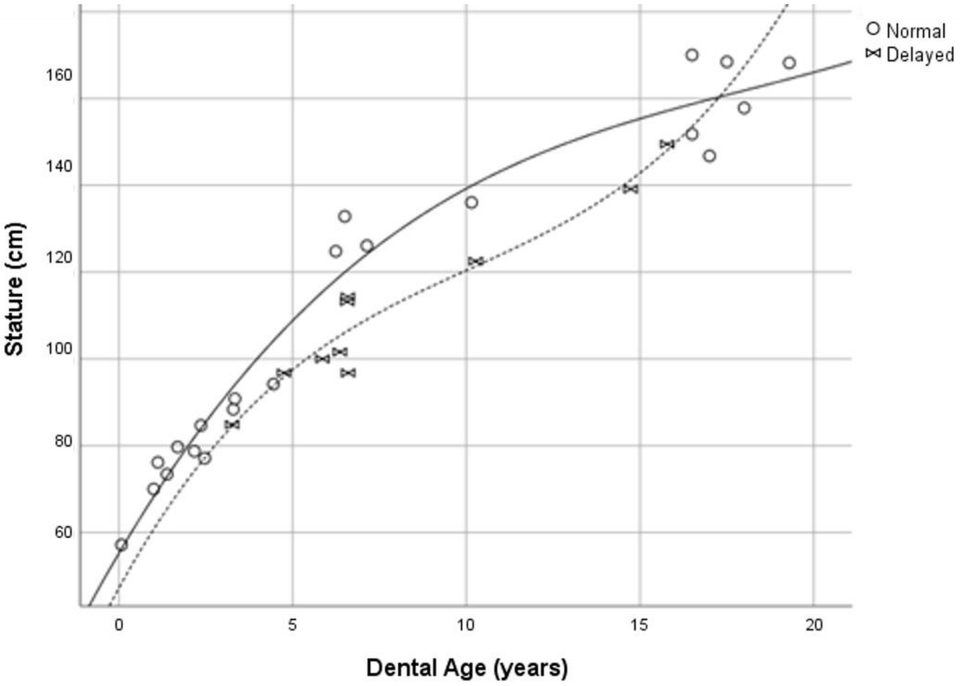

Figure 3 Stature (cm) estimations for "normal" and "delayed" Qinifab preadults

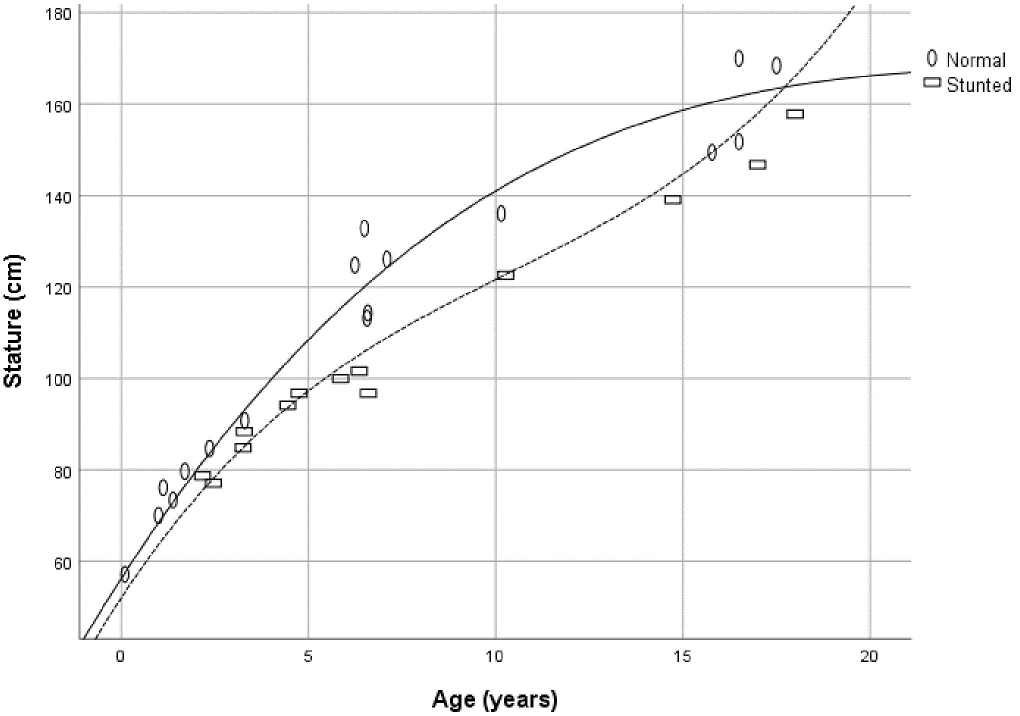

Figure 4 Normal vs. stunted individuals by age and stature, compared with regression lines for normal vs. delayed individuals from Fig. 3

Table 3 Crosstabulation: Delayed x Stunted

		Stunted		
		.00	1.00	Total
Delayed	.00	14	6	20
	1.00	3	7	10
Total		17	13	30

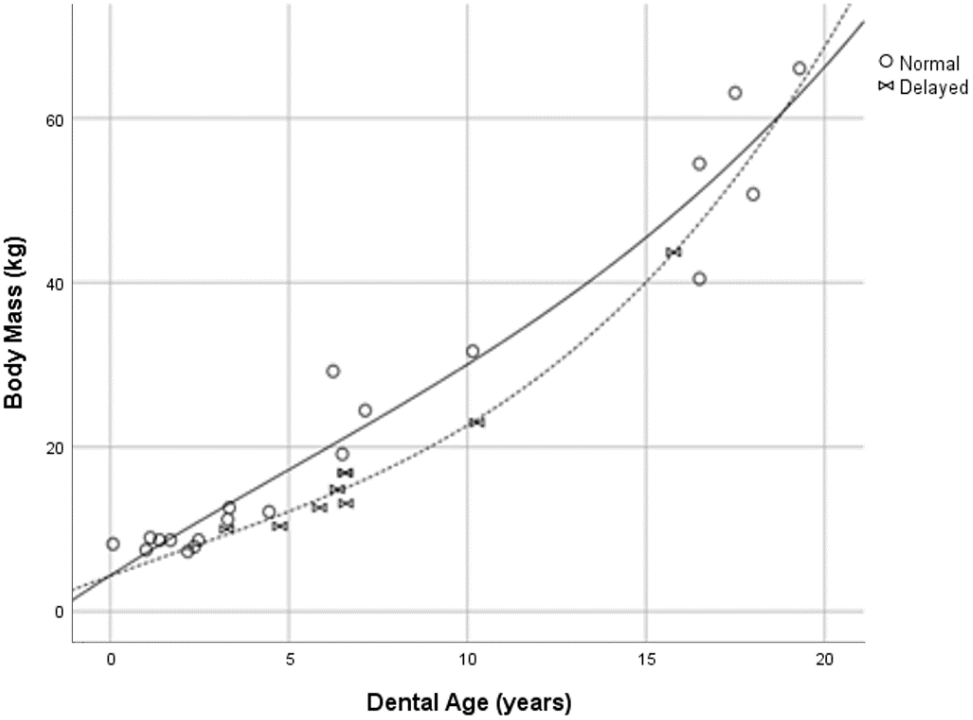

Figure 5 Normal vs delayed individuals by body mass (kg) and age (years)

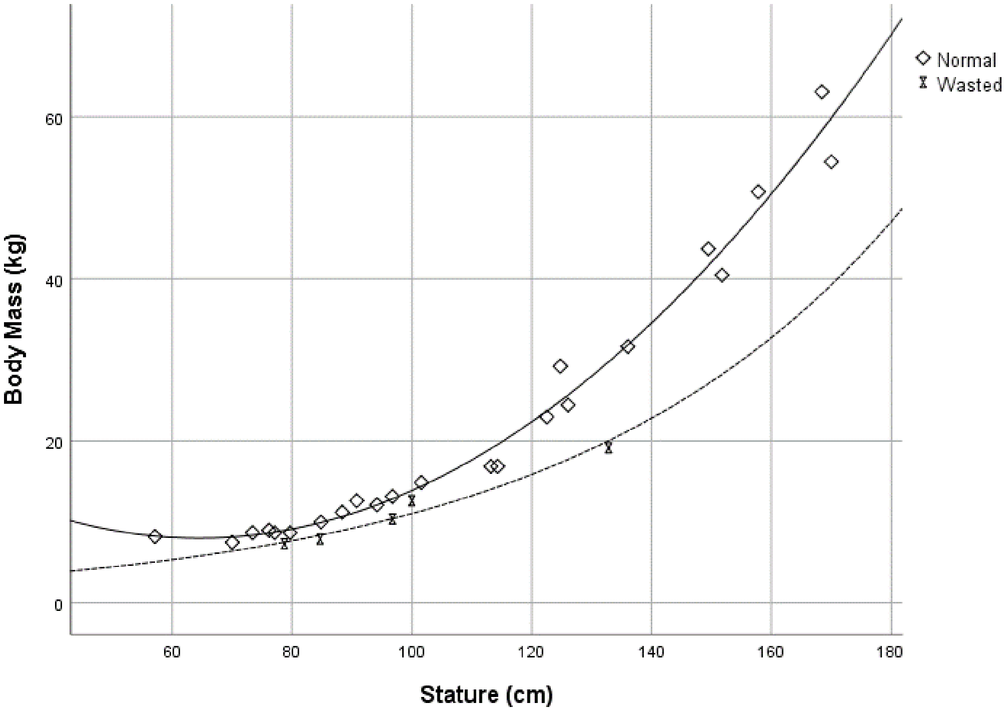

Figure 6 Normal vs wasted individuals by body mass (kg) and stature (cm)

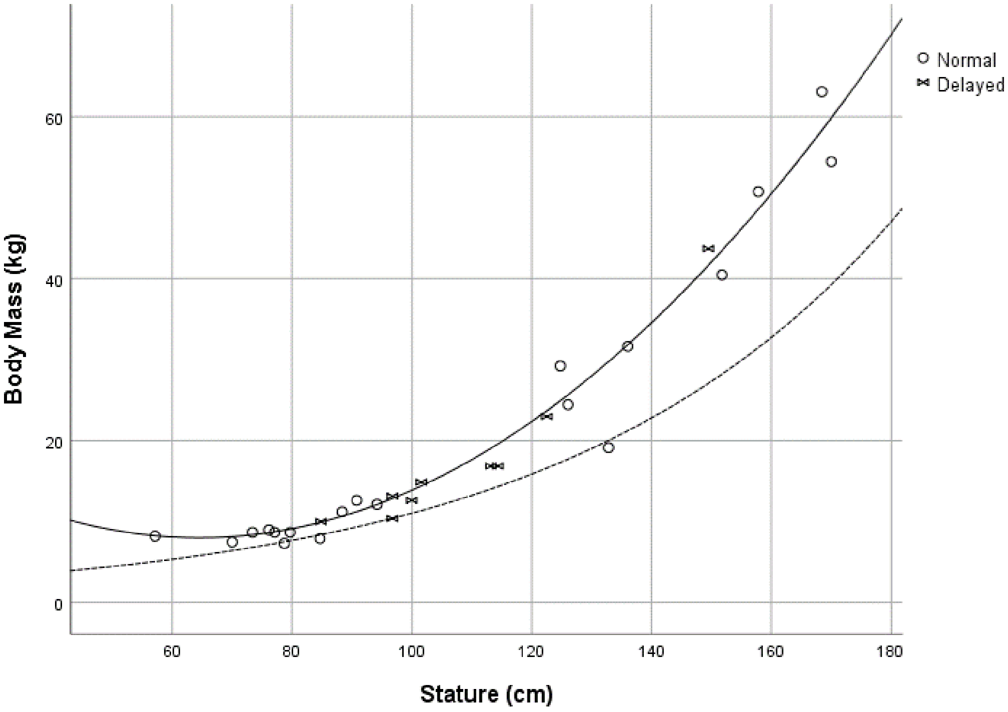

Figure 7 Normal vs delayed individuals by body mass and stature, with regression lines from Fig. 6 representing normal vs wasted individuals

Table 4 Crosstabulation: Delayed x Wasted

		Wasted		
		.00	1.00	Total
Delayed	.00	16	3	19
	1.00	7	2	9
Total		23	5	28

Table 5 Crosstabulation: Stunted x Wasted

		Wasted		
		.00	1.00	Total
Stunted	.00	15	2	17
	1.00	8	3	11
Total		23	5	28

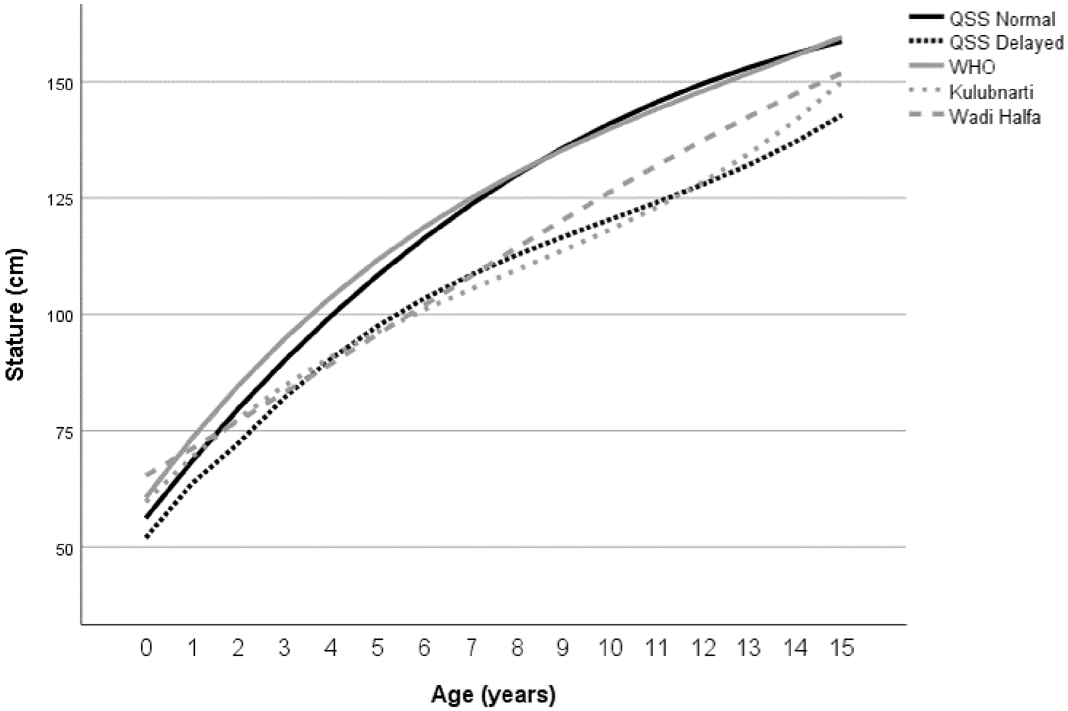

Figure 8 Comparison of stature estimates

Table 6 Paired samples t-tests comparing stature regression models between samples

0-19 Years								
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig.
				Lower	Upper			
QSS* Normal - QSS Delayed	12.692	7.173	1.646	9.235	16.149	7.713	18.0	0.000
QSS Normal - WHO	-2.261	2.994	0.687	-3.704	-0.818	-3.292	18.0	0.004
QSS Delayed - WHO	-14.953	4.228	0.970	-16.991	-12.916	-15.416	18.0	0.000
QSS Normal - Kulubnarti	9.521	12.003	2.754	3.736	15.306	3.457	18.0	0.003
QSS Delayed - Kulubnarti	-3.172	5.828	1.337	-5.980	-0.363	-2.372	18.0	0.029
QSS Normal - Wadi Halfa	8.287	6.893	1.581	4.965	11.609	5.241	18.0	0.000
QSS Delayed - Wadi Halfa	-4.405	5.051	1.159	-6.840	-1.971	-3.802	18.0	0.001
*QSS = Qinifab School Site								

Table 7 Paired samples t-tests for stature regression models by age group

	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig.
				Lower	Upper			
0-3 Years								
QSS Normal - QSS Delayed	6.097	1.866	0.933	3.127	9.066	6.533	3.0	0.007
QSS Normal - WHO	-4.733	0.251	0.125	-5.132	-4.334	-37.731	3.0	0.000
QSS Delayed - WHO	-10.829	1.975	0.987	-13.971	-7.687	-10.968	3.0	0.002
QSS Normal - Kulubnarti	0.773	3.853	1.927	-5.358	6.904	0.401	3.0	**0.715**
QSS Delayed - Kulubnarti	-5.324	2.131	1.065	-8.715	-1.933	-4.997	3.0	0.015
QSS Normal - Wadi Halfa	-0.582	6.934	3.467	-11.617	10.452	-0.168	3.0	**0.877**
QSS Delayed - Wadi Halfa	-6.679	5.183	2.591	-14.926	1.568	-2.577	3.0	**0.082**
3-7 Years								
QSS Normal - QSS Delayed	11.222	2.865	1.281	7.665	14.779	8.759	4.000	0.001
QSS Normal - WHO	-3.150	1.310	0.586	-4.777	-1.523	-5.376	4.000	0.006
QSS Delayed - WHO	-14.372	1.555	0.695	-16.302	-12.441	-20.668	4.000	0.000
QSS Normal - Kulubnarti	11.980	5.062	2.264	5.694	18.266	5.292	4.000	0.006
QSS Delayed - Kulubnarti	0.758	2.261	1.011	-2.050	3.566	0.750	4.000	**0.495**
QSS Normal - Wadi Halfa	11.927	3.407	1.524	7.696	16.158	7.827	4.000	0.001
QSS Delayed - Wadi Halfa	0.705	1.142	0.511	-0.713	2.124	1.380	4.000	**0.240**
7-12 Years								
QSS Normal - QSS Delayed	19.213	2.620	1.069	16.463	21.962	17.965	5.000	0.000
QSS Normal - WHO	0.453	1.175	0.480	-0.779	1.686	0.946	5.000	**0.388**
QSS Delayed - WHO	-18.759	1.445	0.590	-20.276	-17.243	-31.797	5.000	0.000
QSS Normal - Kulubnarti	21.198	1.738	0.709	19.375	23.022	29.883	5.000	0.000
QSS Delayed - Kulubnarti	1.986	1.444	0.590	0.470	3.501	3.368	5.000	0.020
QSS Normal - Wadi Halfa	14.508	1.350	0.551	13.091	15.925	26.317	5.000	0.000
QSS Delayed - Wadi Halfa	-4.705	3.744	1.528	-8.634	-0.776	-3.078	5.000	0.028
12-19 Years								
QSS Normal - QSS Delayed	12.877	9.286	3.510	4.289	21.465	3.669	6.000	0.010
QSS Normal - WHO	-2.210	4.000	1.512	-5.909	1.489	-1.462	6.000	**0.194**
QSS Delayed - WHO	-15.087	5.286	1.998	-19.975	-10.198	-7.552	6.000	0.000
QSS Normal - Kulubnarti	15.691	5.481	2.740	6.970	24.412	5.726	3.000	0.011
QSS Delayed - Kulubnarti	-3.666	2.898	1.449	-8.277	0.946	-2.530	3.000	**0.085**
QSS Normal - Wadi Halfa	6.795	3.954	1.495	3.138	10.452	4.546	6.000	0.004
QSS Delayed - Wadi Halfa	-6.082	5.636	2.130	-11.294	-0.869	-2.855	6.000	0.029

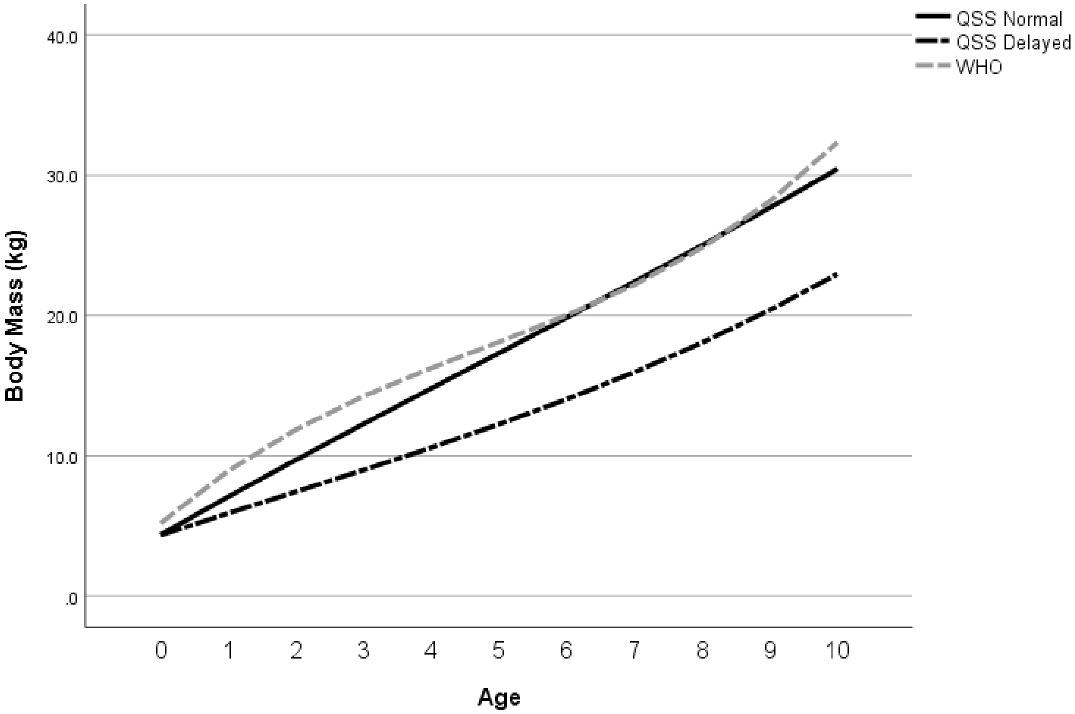

Figure 9 Comparison of body mass estimates to WHO standards

Table 8 Paired samples t-test for body mass regression models

	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig.
				Lower	Upper			
QSS Normal - QSS Delay	4.55	2.57	0.77	2.82	6.27	5.873	10	0.000
WHO - QSS Normal	1.02	0.89	0.27	0.42	1.62	3.792	10	0.004
WHO - QSS Delay	5.57	2.27	0.68	4.04	7.09	8.143	10	0.000

Table 9 Paired samples t-tests for body mass regression models by age group

	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig.
				Lower	Upper			
0-3 Years								
QSS Normal - QSS Delay	1.69	1.40	.70	-.53	3.91	2.422	3	**.094**
WHO - QSS Normal	-1.70	.60	.30	-2.66	-.75	-5.684	3	.011
WHO - QSS Delay	-3.40	1.92	.96	-6.45	-.34	-3.535	3	.038
3-7 Years								
QSS Normal - QSS Delay	4.97	1.26	.56	3.41	6.53	8.848	4	.001
WHO - QSS Normal	-.84	.90	.40	-1.95	.28	-2.086	4	**.105**
WHO - QSS Delay	-5.80	.37	.16	-6.26	-5.35	-35.431	4	.000
7-10 Years								
QSS Normal - QSS Delay	7.04	.46	.23	6.31	7.77	30.646	3	.000
WHO - QSS Normal	-.49	.98	.49	-2.06	1.07	-.999	3	**.392**
WHO - QSS Delay	-7.53	1.39	.69	-9.74	-5.33	-10.875	3	.002

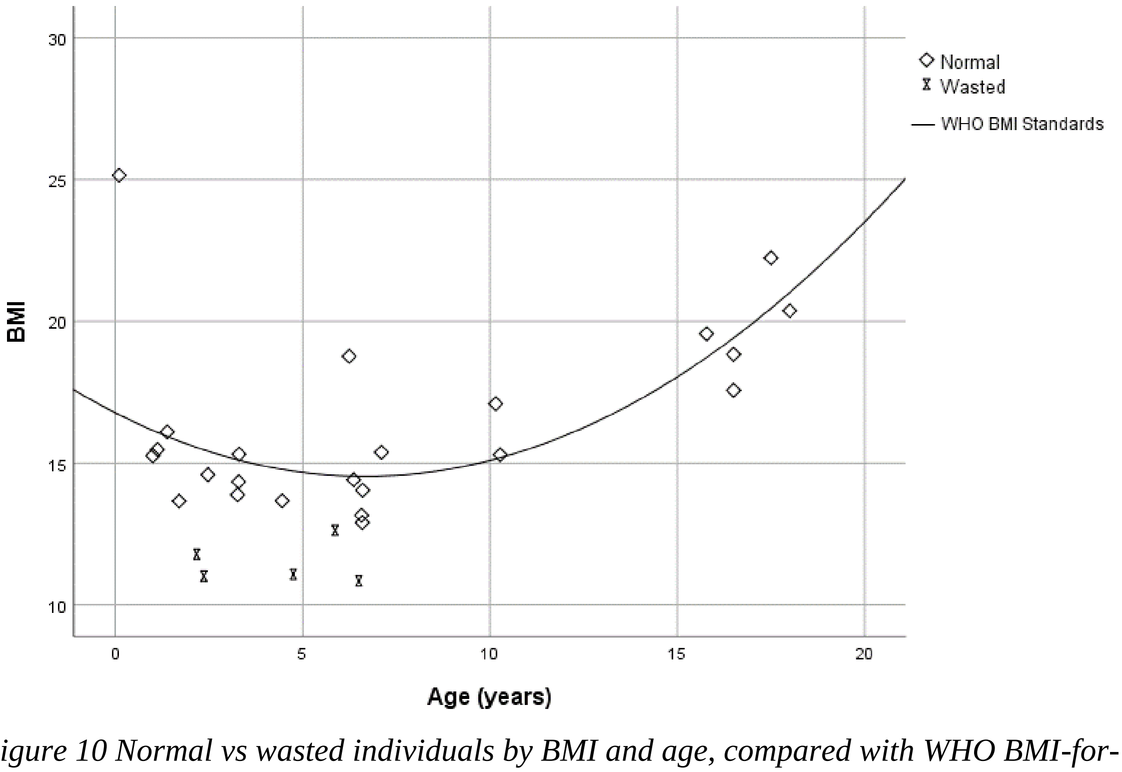

Figure 10 Normal vs wasted individuals by BMI and age, compared with WHO BMI-for-age standards

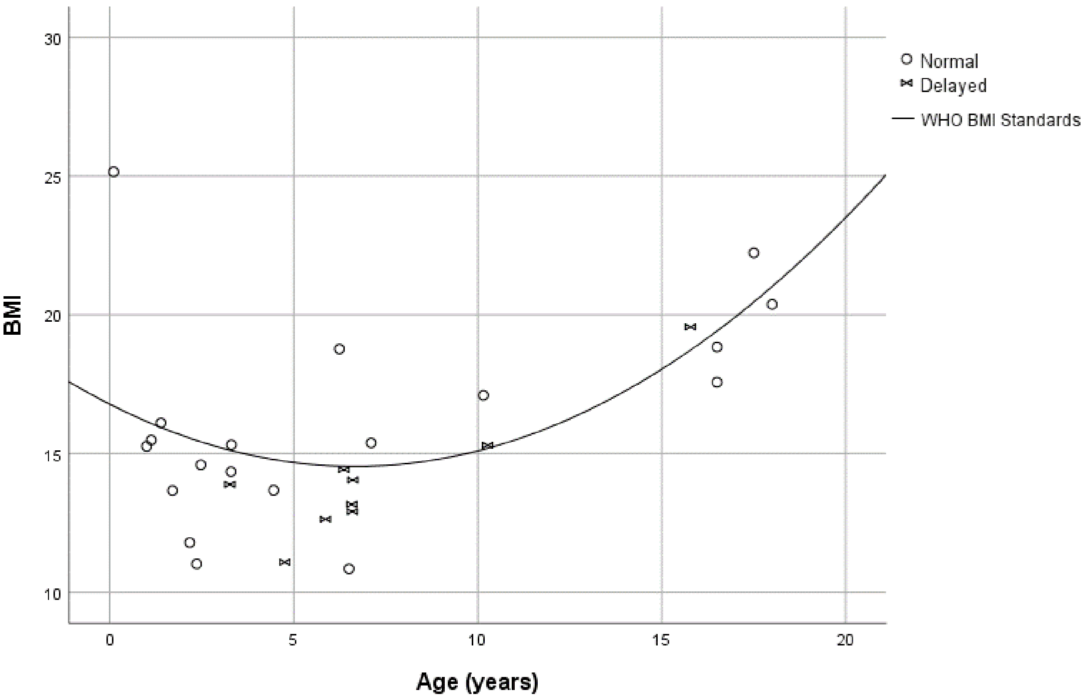

Figure 11 Normal vs delayed individuals by BMI and age, compared with WHO BMI-for-age standards

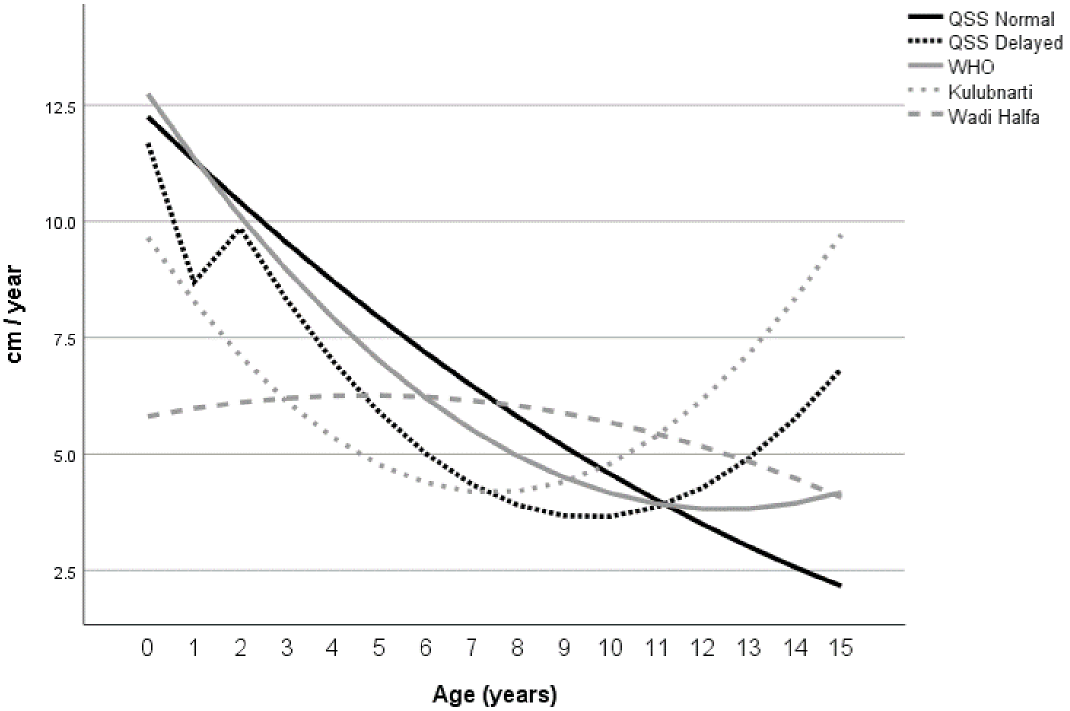

Figure 12 Comparison of stature growth velocity

Table 10 Correlations for stature growth velocity

	N	Correlation	Sig.
Normal vs. WHO	18	0.925	**0.000**
Normal vs. Wadi Halfa	18	0.776	**0.000**
Delayed vs. WHO	18	0.750	**0.000**
Delayed vs. Kulubnarti	16	0.683	**0.004**
Normal vs. Delayed	18	0.457	0.057
Normal vs. Kulubnarti	16	0.106	0.697
Delayed vs. Wadi Halfa	18	-0.190	0.451

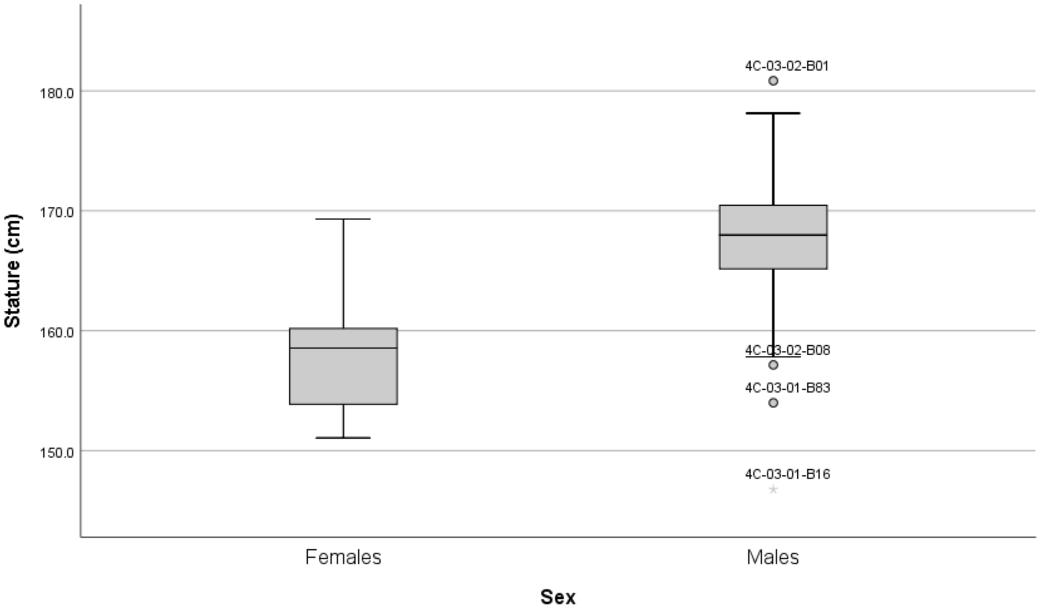

Figure 13 Adult stature by sex

Table 11 Adult stature by time period

Time Period	Dates	Female	Male
Post-Meroitic	350-550 CE	157.0	169.0
Christian	550-1400 CE	157.3	167.0
All (Late Meroitic-Christian)	0-1400 CE	157.8	167.0

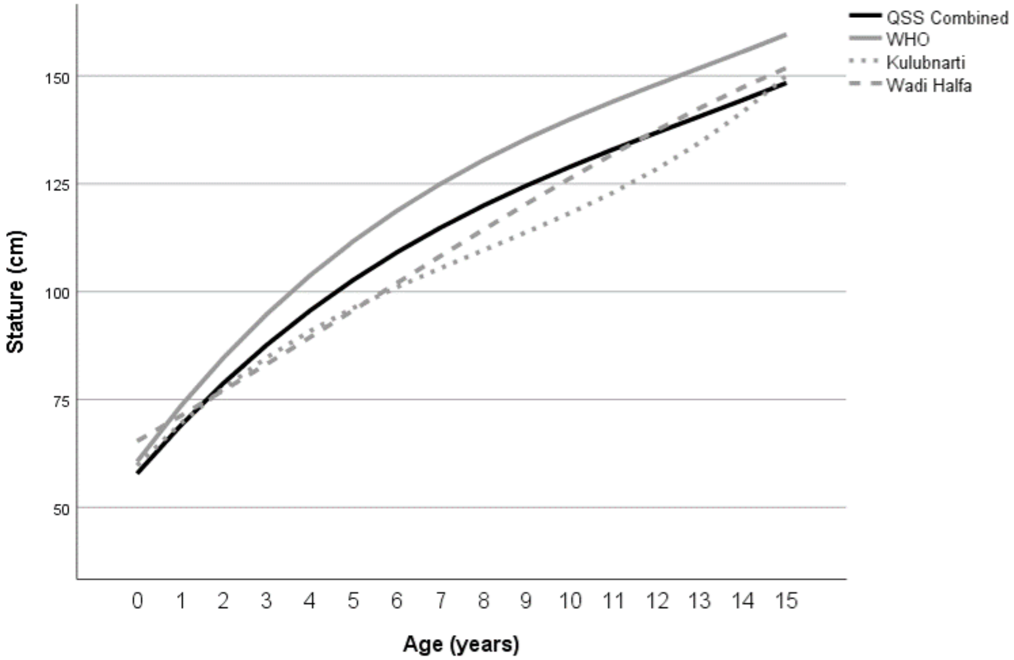

Figure 14 Stature of combined Qinifab sample compared

Table 12 Adult stature comparison

Site	Time Period	Source	Female	Male
Tombos	1569-1081 BC	Raxter, 2011	154.3	162.7
Wadi Halfa PM	AD 350-550	Vagn Nielson, 1970	154.8	164.4
Sayala	AD 350-641	Raxter, 2011	155.8	165.1
Wadi Halfa Meroitic	350 BC-AD 350	Vagn Nielson, 1970	155.0	165.5
Wadi Halfa Christian	AD 550-1400	Vagn Nielson, 1970	153.9	165.5
Kulubnarti*	AD 550-800	Hummert and VanGerven, 1983	156.3*	165.7*
Ancient Egyptians	5500 BC-AD 600	Raxter, 2011	155.2	165.8
Wadi Halfa C-Group	2000–1600 BC	Buzon, 2006	156.7	166.9
Classic Kerma	1700-1500 BC	Raxter, 2011	155.7	167.0
Qinifab School (all)	**AD 0-1400**		**157.8**	**167.0**
Qinifab School Christian	**AD 550-1400**		**157.3**	**167.0**
Modern Egypt	Modern	Raxter, 2011	160.0	167.3
Wadi Halfa Mesolithic	10,000-5000 BC	Vagn Nielson, 1970	159.4	167.9
Qinifab School PM	**AD 350-550**		**157.0**	**169.0**
Modern Sudan	Modern	Raxter, 2011	159.8	169.8
Wadi Halfa A-Group	3400-2400 BC	Vagn Nielson, 1970	156.4	171.4
Jebel Sahaba	12,000-10,000 BC	Raxter, 2011	160.0	171.7
*Calculated using Trotter and Gleser, 1952				

CHAPTER 3

SURVIVING AND THRIVING IN ANCIENT NUBIA: STRESS, FRAILTY, AND THE DEVELOPMENTAL ORIGINS OF HEALTH AND DISEASE HYPOTHESIS

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Abstract

This study investigates whether early life stress had a discernible impact on frailty, longevity, and/or growth in an ancient Nubian skeletal sample. The skeletal sample is from the fourth cataract region of Sudanese Nubia, comprised of 100 individuals from a Late Meroitic to Christian period (~250-1400 CE) cemetery. Standard osteological methods were used to estimate age and sex. Data were collected on skeletal indicators of stress formed in childhood, including linear enamel hypoplasias, porotic hyperostosis, and cribra orbitalia. In preadults, periosteal reactions and localized hypoplasia of the deciduous canine were also assessed. Four adult body size dimensions (femur length, femur head diameter, crural index, brachial index) and three types of preadult growth faltering (delayed skeletal development, stunting, wasting) were compiled. Evidence of stress was compared with age at death and growth/body size parameters. Cribra orbitalia occurred at higher frequencies in preadults and individuals with at least partially active lesions died at younger ages. Porotic hyperostosis rarely developed before age 6 but was present in nearly all individuals over that age. Individuals who experienced stress episodes earlier (based on LEH age of formation) were more likely to experience additional stress and more severe degrees of stress, and to die at

younger ages. Active/mixed CO is associated with stunting in preadults and reduced brachial index in adults. The results suggest that timing of stress events may be more critical than quantity, and that cribra orbitalia is a more reliable indicator of underlying frailty than porotic hyperostosis or enamel hypoplasias in this collection. Childhood stress had little discernible impact on adult body size.

Introduction

DOHaD and the Osteological Paradox

The very young have often faced challenges growing, surviving, and thriving in a world plagued with infectious disease, contaminated food and water sources, parasites, and inadequate access to food. It is not surprising, therefore, that some of the most documented pathological lesions on ancient bones are those that form during childhood and remain evident on adult skeletons. Stressors of childhood may have consequences for health in later life (Barker, 2007; Barker & Osmond, 1986; Gardner, Winter, & Barker, 1984), yet individuals who survive early stress and respond with skeletal lesions rather than immediate death may be more robust than those who do not form these lesions (Wood, Milner, Harpending, & Weiss, 1992). This study uses paleopathological and standard metric data to examine two concepts—the osteological paradox (Wood et al., 1992) and the Developmental Origins of Health and Disease (DOHaD) hypothesis (Barker, 2007)—to investigate the consequences of stress experienced in early life for adult health outcomes.

The DOHaD hypothesis, also called the Barker hypothesis, is based on the premise that physiological stress early in an individual's life history may have negative consequences in adulthood (Barker, 2004, 2007). The DOHaD hypothesis originates in the medical literature, inspired by analyses of mid-20th-century mortality data from England and Wales conducted by epidemiologist David Barker and his colleagues (Barker & Osmond, 1986; Gardner et al., 1984). In these studies, cardiovascular and other circulatory diseases in adulthood were correlated with stress occurring during fetal development associated with lower standards of living (Barker, 2004; 2007; Barker & Osmond, 1986; Gardner et al., 1984; Hales & Barker, 2001). In its original form, the DOHaD hypothesis posited that undernutrition *in utero* leads to permanent alteration in an individual's metabolism, such that the individual is more likely to develop coronary heart disease (Barker, 2007). Recent proponents of this idea have expanded the premise and suggested bioarchaeological applications (Amoroso, Garcia, & Cardoso, 2014; Armelagos, Goodman, Harper, & Blakey, 2009; Gowland, 2015). Armelagos and colleagues (2009) reviewed the bioarchaeological studies that can be linked to the DOHaD hypothesis, focusing on data accumulated on nonspecific stress indicators that form during an individual's earliest years, while Gowland (2015) has examined the implications of DOHaD for the life course approach in bioarchaeology.

Although DOHaD presents a relatively new challenge for bioarchaeologists, we have been grappling with the osteological paradox, first described by Wood and colleagues (1992), for over two decades (DeWitte & Stojanowski, 2015). This study will highlight two particular "conceptual problems" identified by Wood et al. (1992): selective mortality and hidden heterogeneity in risks. Selective mortality refers to the fact that all individuals of a given age in a cemetery sample are only those who died at that age and are not representative of all individuals of that age in the living population. Hidden heterogeneity in risks refers to the unknown variation in underlying frailty present in a population. Integrating these factors with the DOHaD hypothesis, one may argue that childhood stress, as represented by lesions observed on adult skeletons that are known to form during childhood, is a quantifiable source of heterogeneous frailty in a population. Wood et al. (1992) also caution that observed skeletal stress indicators actually indicate that the individual *survived* an episode of physiological stress, which could (paradoxically) mean more robust health rather than frail health. This possibility can be considered an alternative hypothesis, in opposition to the DOHaD hypothesis.

The primary objective of this study is to investigate the relationship between early life stress experiences and later health outcomes, hypothesizing that, in accordance with the DOHaD hypothesis, more stress in early life results in worse health outcomes in adulthood. In terms of the osteological paradox, are nonspecific indicators of stress indicators of underlying frailty? This problem is approached through investigation of three questions:

1) Were those who suffered systemic stress in early life (as evidenced by nonspecific indicators of stress) more susceptible to additional or more severe signs of morbidity?
2) Did those who suffered stress early in life then suffer earlier mortality?
3) Does suffering stress in early life have consequences for growth outcomes?

Ultimately, the goal of this study is to use an intra- rather than inter-population approach to better establish the interrelationships among stress, growth, and mortality. This comparative life course approach aims to highlight the complexities of human variation in health measures.

Nonspecific Indicators of Stress

This study examines three nonspecific indicators of stress to represent early life experience in both adults and preadults: linear enamel hypoplasias (LEHs), porotic hyperostosis, and cribra orbitalia. In preadults, data also were collected on localized hypoplasias of the deciduous canine (LHDC) and periosteal reactions. LEHs in permanent teeth, porotic hyperostosis, and cribra orbitalia are all lesions that form during growth and development but are retained in the adult skeleton. This persistence allows certain comparisons to be made between those who survived to adulthood and those who did not.

LEHs are defects in tooth enamel that result from a cessation of ameloblastic activity during which secretion of the enamel matrix is halted due to an episode of systemic stress (Hillson & Bond, 1997; Guatelli-Steinberg, 2001). Because tooth enamel does not regenerate or repair itself after it has formed, enamel defects occurring during growth and development create a permanent record of an episode of systemic stress occurring during the individual's prenatal, infant, or early childhood history. LHDCs are small, circumscribed pits found on the labial surface of deciduous canines. Although their etiology is somewhat ambiguous, they have been correlated with growth faltering, infectious disease, physical trauma, and potentially osteopenia (Skinner, Rodrigues, & Byra, 2014).

Porotic hyperostosis and cribra orbitalia are characterized by the appearance of porosities or pitting, often coalesced or sieve-like, on the outer table of the cranial vault and orbital roof respectively (Aufderheide & Rodriguez-Martin, 1998; Ortner, 2003). Porotic hyperostosis is produced by a process known as marrow hyperplasia, an expansion of the diploe caused by an increase in red blood cell (RBC) production as a compensatory reaction to deficiency in the hemoglobin of RBCs (Aufderheide & Rodriguez-Martin, 1998, pp. 348–350; Ortner, 2003, pp. 370–372) Although cribra orbitalia is also usually attributed to marrow hyperplasia, work by Rivera and Lahr (2017) has demonstrated that, in the absence of co-occurring porotic hyperostosis, cribra orbitalia is more often associated with thinning of the diploe, rather than the expansion characteristic of marrow hyperplasia. Both lesions are generally thought to represent a childhood condition (Stuart-Macadam, 1985, 1987).

At birth, all marrow is of the hematopoietic red type. As the individual ages, much of this is converted to yellow marrow, with some elements passing through a stage of mixed red and yellow marrow (Brickley, 2018). If a compensatory increase in RBC production is required, an element with mixed marrow may reconvert to red marrow without causing any expansion of the marrow space (Brickley, 2018; Małkiewicz & Dziedzic, 2012). However, in an element that is already in the red marrow stage, the marrow must expand to meet the RBC production demands, causing pressure atrophy in the surrounding bone, and eventually leading to the perforation of the cortex characteristic of the porous lesions of cribra orbitalia and porotic hyperostosis (Brickley, 2018). Conversion from red to yellow marrow in the skull begins in the base and the facial bones, then proceeds through the calvarium (beginning around 1-2 years), typically occurring earlier in the frontal than the parietals (Foster, Chapman, & Johnson, 2004). This conversion process is generally complete by around 15 years, making it unlikely that porotic lesions resulting from compensatory marrow expansion will form in the cranium after adolescence (Brickley, 2018). Possibly as a result of this pattern of development, the lesions in the orbits have frequently been observed to occur in younger individuals than the vault lesions (Brickley, 2018; Stuart-Macadam, 1989).

Both lesions have long been considered indicative of anemia in the bioarchaeological literature, particularly iron deficiency anemia, although this association has been debated (Mcilvaine, 2015; Stuart-Macadam, 1987; Walker, Bathurst, Richman, Gjerdrum, & Andrushko, 2009; Wapler, Crubezy, & Schultz, 2004), as has the association between the orbital and vault lesions (Brickley, 2018; Rivera & Lahr, 2017; Stuart-Macadam, 1989). Cribra orbitalia has also been linked to conditions such as Vitamin C deficiency and inflammation (Wapler et al., 2004). Whatever the ultimate etiology, both lesions can be considered evidence of stress experienced in early life that may be retained in the adult skeleton.

Finally, this study also incorporates periosteal new bone formation (periosteal reaction) occurring in preadult skeletons. Periosteal reactions are characterized by the formation of woven bone on the cortical surface resulting from inflammation of the periosteum, primarily in response to injury, metabolic insult, or infection (Weston, 2012). In spite of their diverse etiology, in bioarchaeological literature they have been most often equated with nonspecific infection, and used as nonspecific indicators of stress

(Goodman, Thomas, Swedlund, & Armelagos, 1988; Klaus, 2014; Weston, 2008, 2012). Weston (2012) has argued against this interpretation, on the grounds that the body does not produce new bone during conditions of stress. Klaus (2014:298), however, suggests that periosteal reactions can be considered “loosely analogous to enamel hypoplasias,” in that they “reflect stress and morbidity, but may often represent lesion formation in the latter phases of inflammation and subsequent recovery from disruption of normal physiology.”

Stress and Growth

In addition to exploring the relationship between nonspecific indicators of stress and longevity, this study also incorporates measures of skeletal growth. Like nonspecific stress indicators, measures of bone growth have long been used to compare “health” between different skeletal assemblages and temporal horizons (Armelagos, Huss-Ashmore, & Martin, 1982; Armelagos et al., 1972; Buikstra & Cook, 1980; Cook, 1979; Cowgill & Hager, 2007; Mummert, Esche, Robinson, & Armelagos, 2011; Pearson, 2000; Ruff, Garofalo, & Holmes, 2013; Vercellotti et al., 2014), since it is well-known that inadequate nutrition during development can lead to growth faltering and stunting (Briend, Khara, & Dolan, 2015; Scheuer & Black, 2000; Victora, 1992; World Health Organization & United Nations Childrens Fund, 2009). Malnutrition and disease are intimately interlinked. Malnutrition impairs immune system functionality and increases susceptibility to infection, putting children in particular at a higher risk of death (Cantani, 2008; Ehrhardt et al., 2006; Pelletier, Frongillo, & Habicht, 1993; Pelletier, Frongillo, Schroeder, & Habicht, 1995). Furthermore, infectious or parasitic agents can cause nutrient depletion and malabsorption prompted by episodes of diarrhea or intestinal bleeding (El Samani, Willett, & Ware, 1988; Ezeamama et al., 2008; Olivares, Walter, Hertrampf, & Pizarro, 1999). This synergistic cycle of malnutrition, disease, and impaired growth can have numerous long-term consequences, not only to adult stature, but to overall health, longevity, and economic productivity (Alderman, Hoddinott, & Kinsey, 2006; Guerrant, Oriá, Moore, Oriá, & Lima, 2008; Steckel, 1995; Victora et al., 2008). It has been frequently noted in the literature that shorter stature is often associated with earlier mortality (Gage & Zansky, 1995; Kemkes-Grottenthaler, 2005; Steckel, 1995).

Despite the established connection between systemic stress and growth faltering, the relationship between growth and nonspecific indicators of stress in the skeleton is not always clear-cut. Clinical research has demonstrated an association between growth faltering in children and occurrence of enamel defects (Masterson et al., 2017). However, results in the bioarchaeological literature have been mixed. In a study on preadult growth in ancestral Pueblo Indians, Schillaci, Nikitovic, Akins, Tripp, & Palkovich (2011) found that individuals without porotic hyperostosis suffered higher degrees of stunting. Likewise, in a collection from Roman Egypt, Wheeler (2009) observed that preadults with more stress indicators also had longer femurs. Pinhasi, Timpson, Thomas, & Slaus (2014) found that preadults with healed nonspecific indicators of stress had larger size dimensions by age than preadult with active lesions in medieval/post-medieval Croatia. Boldsen (1997) and Temple (2008) both found no relationship between adult size and enamel hypoplasia among medieval English and Jomon forager skeletons respectively, while in Rectenwald’s (2012) study on a modern Thai population, LEH presence and frequency were associated with relatively shorter distal lower limbs. In an interpopulational analysis, Vercellotti and colleagues (2014) found that tall stature was associated with both higher and lower stress at different sites. Holder, Miliauskienė, Jankauskas, & Dupras (2020) observed similarly contradictory results in a sample of Napoleonic soldiers from a mass grave in Lithuania, in which LEH variables were correlated with both negative and positive effects on stature. The factors affecting adult stature are multidimensional and multifaceted, and different stress indicators may have different implications for growth in different contexts.

Stressing Out in Ancient Nubia

Littleton (2011, p. 361) describes the bioarchaeological interest in preadult health as the “canary in the coalmine approach,” wherein “the health of children, the most vulnerable segment of society is seen as a measure of the health of the entire community." This approach has largely characterized the way in which childhood morbidity data have been used in the region of interest: Nubia and the broader Nile valley (e.g., Sandberg & Van Gerven, 2016). As in other regions, nonspecific stress indicators that form in childhood and persist in the adult skeleton traditionally have been used to compare sites, temporal horizons, sex, age groups, status, etc. (Armelagos, Van Gerven, Martin, & Huss-Ashmore, 1984; Buzon, 2006; Rudney, 1983; Sheridan & Van Gerven, 1997; Van Gerven, Hummert, Prendergast Moore, & Sandford, 1990). This approach dates back to some of the earliest examples of bioarchaeological investigations of Nubia, such as Armelagos’ (1968) dissertation examining paleopathology in sites from Wadi

Halfa. Much of this work has incorporated the biocultural model promulgated by Armelagos and his students (Baker, 1997, 2016; Baker & Judd, 2012), which uses stress indicators to explore adaptation to a particular environmental/cultural setting. Bioarchaeologists, however, have often ignored the implications of the osteological paradox in favor of the simplistic assumption that a higher frequency of stress indicators is directly indicative of general ill health in a population (DeWitte & Stojanowski, 2015).

In the Nile Valley, sources of physiological stress are many and varied, both today and in antiquity. Agents of parasitic infection are prevalent in modern Sudan, and include endemic malaria, schistosomiasis, onchocerciasis (river blindness), leishmaniasis, and helminths such as hookworm, roundworm, and pinworm (Webber, 1996). Young children would have been especially at risk from diarrheal diseases caused by viruses or bacterial infection, such as typhoid fever or dysentery (Brahin & Fleming, 1982). Periosteal new bone formation on many ribs from this sample attest to the presence of chronic respiratory infections, which is the leading cause of death for children under age five in modern Sudan (WHO, 2015).

Some of these conditions have been linked specifically to anemia, thought to be a primary cause of porotic hyperostosis and cribra orbitalia lesions. A clinical study on malaria conducted in eastern Sudan found that severe anemia was the most common complication of malaria, especially in young children (Giha et al., 2005). Severe malarial anemia has a mortality rate that can be as high as 30% among children in holoendemic areas (Perkins et al., 2011). Other parasitic infections such as schistosomiasis (genus: *Schistosoma*) and hookworm (*Ancylostoma duodenale* and *Necator americanus*) also have a well-documented association with anemia (Brooker et al., 1999; Ezeamama et al., 2008; Friedman, Kanzaria, & McGarvey, 2005; Hotez et al., 2004; Olsen, Magnussen, Oumaz, Andreassens, & Friis, 1998). The antiquity of some of these conditions has been demonstrated in skeletons and mummified tissue from Egypt and Sudan (Alvrus, 2006; Cockburn, Barraco, Reyman, & Peck, 1975; Hibbs, Secor, Van Gerven, & Armelagos, 2011; Miller et al., 1992; Smith-Guzmán, 2015a, 2015b). Smith-Guzmán's work has suggested a direct association between malaria and both porotic hyperostosis and cribra orbitalia (Smith-Guzmán, 2015a, 2015b).

High frequencies of nonspecific indicators of stress have frequently been noted at Nubian sites. Some studies on preadult health in ancient Nubia have noted a correlation between nonspecific stress indicators and early mortality (e.g., Mittler, Van Gerven, Sheridan, & Beck, 1992). Buzon (2006) reports rates of enamel hypoplasia ranging from 19-36% at sites throughout the Nile Valley. Armelagos (1968) reported rates of cribra orbitalia ranging from 10-25% in cemeteries from different temporal horizons at Wadi Halfa, and Buzon (2006) reported similar findings (11% afflicted) at Tombos. Alvrus (2006) found significantly higher rates (82%) at Semna South, while Mittler and Van Gerven (1994) report 45% at Christian-period Kulubnarti. Porotic hyperostosis frequencies are more variable. Alvrus (2006) found that a majority of observed individuals were afflicted at Semna South, but most lesions were faint pinprick porosities, and fully healed. In contrast, Carlson and colleagues (1974), working with data collected by Armelagos (1968), found that less than 5% of the individuals from several cultural horizons at Wadi Halfa displayed this lesion, while Buzon (2006) found almost no afflicted individuals at Tombos. It is possible that less-pronounced lesions may not be scored by more conservative researchers. Some caution must be advised in interpreting variation among sites due to the high degree of inter-observer error reported for these lesions, particularly in scoring degree of expression and activity (i.e., healing) status (Jacobi & Danforth, 2002).

Materials and Methods

The Qinifab School Site

The Qinifab School site, named for its location adjacent to a modern school in the village of al-Qinifab, is a multicomponent site located between the 4th and 5th Nile cataracts at the “great bend” in the river (Fig. 1). The site was excavated between 2007 and 2009, and the skeletons formerly interred there are now housed in the Bioarchaeology of Nubia Expedition (BONE) laboratory at Arizona State University. There are 100 individuals available for analysis. The cemetery component dates from ~250-1400 CE, thus spanning the end of the Meroitic (350 BCE-350 CE), the Post-Meroitic (350-550 CE), and Christian (550-1400 CE) periods of Nubian history (Baker, 2014). As the Meroitic empire declined, Nubia was increasingly characterized by regional autonomy, until the rise of three kingdoms that became the dominant polities (Edwards, 2004) and subsequently converted to Christianity (Godlewski, 2014; Obłuski, 2014). During the Christian period, the Qinifab School site existed in the borderland between two of the kingdoms that dominated the region (Makuria and Alwa). Evidence of interpersonal violence is present across all time periods at the Qinifab School site, as both skeletal trauma and archery burial accoutrements, and the nearby remains of a large fortification, demonstrate (Baker, 2008, 2014, 2016; Baker & Schellinger, 2017). In short, the people of this area lived in often turbulent times.

Methods

Standard osteological methods (Buikstra & Ubelaker, 1994; Baker, Dupras, & Tocheri., 2005) were used to estimate age and sex. Probable males (PM) have been grouped with males and probable females (PF) have been grouped with females for statistical analyses. Individuals less than 16 years were considered preadults. Age ranges were converted to single midpoint estimates to facilitate some statistical analyses. Time period was assigned based on archaeological evidence (grave structure, burial style, and grave accompaniments) and radiocarbon dating (Baker, 2014). The overall demographics of the site are shown by age group and sex in Figure 2. Note that nearly all of the preadults (n=28) are from the Christian period (likely due to changes in burial practices). During the late Meroitic and Post-Meroitic periods, there are proportionally more males than females, while the reverse is true during the Christian period.

Data were collected on enamel hypoplasias (EH) for all observable individuals in the collection, using macroscopic observation with a small flashlight and magnifying glass, along with manual probing using a fingernail to assess indentation. For linear enamel hypoplasias (LEHs) in permanent teeth, the distance between each LEH and the cemento-enamel junction (CEJ) was measured using iGaging Origin Digital calipers, and age of formation was calculated using standards developed by Reid & Dean (2006) from their South African sample. The age at first stress episode (min LEH), represented by the age of the earliest formed LEH(s), was estimated for each individual (Table 1). A minimum number of stress episodes (MNSE) was assigned based on the maximum number of LEHs occurring on tooth crowns with non-contemporaneous teeth development (Table 1). Additionally, data were collected on localized hypoplasias of the deciduous canine (LHDCs). All observable deciduous canines were assessed for presence or absence of the defect, and individuals were scored as 1 if at least one LHDC was observed, and 0 if it was not observed on any canine (n=20).

The crania of all individuals in the collection (n=100) were examined for the presence of porotic hyperostosis (PH) and cribra orbitalia (CO); degree and healing status of each lesion were scored using standard methods (Buikstra & Ubelaker, 1994). Classification was based on macroscopic observation with the aid of a small flashlight and magnifying glass. Presence and healing status of periosteal reactions (PR) was assessed in all observable preadults in the collection, using standard methods (Buikstra & Ubelaker, 1994). Finally, the presence scores for EH, PH, and CO were summed to assign a cumulative stress index (CSI) score for each individual with data collected for all categories. A second CSI score was assigned to observable preadults, combining EH, PH, CO, and PR presence scores. Categories scored for each nonspecific indicator of stress are summarized in Table 1. Raw data are reported in Appendix B for each preadult individual.

Standard long bone measurements were taken using an osteometric board and calipers (Buikstra & Ubelaker, 1994). The left side was used if present and the right was substituted if not. For this study, femur maximum length (FML) was used as a proxy for stature, and maximum femur head diameter (FHD) was used as a proxy for body mass.

Studies indicate that length of distal limb bones is more variable than proximal limb bones, and more sensitive to environmental stress (Holliday & Ruff, 2001; Pomeroy et al., 2012), so two relative growth indices were also calculated based on standard formulae (Schultz, 1937): crural index (CI = tibia maximum length / FML), and brachial index (BI = radius maximum length / humerus maximum length). Raw data are reported for each adult in Appendix C. In order to account for sexual dimorphism while maintaining a larger sample size, male and female measurements and indices were separately converted into z-scores and then pooled.

Norris, Dahlstedt, & Baker (in preparation) assessed evidence of growth faltering in the preadults in this collection, including delayed skeletal growth and stunting. Dentition and epiphyseal fusion were used to produce independent skeletal and dental ages for each preadult individual, using published standards (Baker et al., 2005; Brothwell, 1981; Hillson, 1997; Moorrees, Fanning, & Hunt, 1963b, 1963a; Scheuer & Black, 2000; Schour & Massler, 1941; B. H. Smith, 1991; Steele & Bramblett, 1988; Ubelaker, 1989) Because skeletal development is understood to be more affected by environmental factors than dental development, differences between the two age estimates were used to identify individuals with delayed skeletal growth. Stature and body mass were estimated based on published formulae (Raxter et al., 2008; Schug, Gupta, Cowgill, Sciulli, & Blatt, 2013), and compared to WHO growth standards to assess stunting and wasting (World Health Organization, 2012). These conditions are included in Appendix B.

Statistical tests were performed tested using IMB SPSS Statistics 25. To assess the relationships between stress indicators, associations were tested between the two variables signifying accumulative stress (MNSE and CSI) and the other stress indicator variables shown in Table 1, using one-way ANOVA and Spearman's rank correlation coefficient. To assess the significance of the age at which stress was experienced, associations were tested between Min LEH and other stress indicator variables using one-way ANOVA and Spearman's rank correlation coefficient. To assess the relationship between stress and longevity, associations were tested between all stress indicator variables and age at death (adults vs. preadults, and adult age) using chi-square tests, one-way ANOVA, and Spearman's rank correlation coefficient. To assess the relationship between stress and growth, associations were tested between stress indicator variables and preadult growth faltering (delay, stunting, wasting), and between stress indicator variables and adult body size dimensions (FML, FHD, CI, BI) using chi-square tests, one-way ANOVA, Spearman's rank correlation coefficient, and Pearson's correlation coefficient. To assess the relationship between growth outcomes and longevity, associations were tested between adult body size dimensions and age at death using Pearson's correlation coefficient.

Results

Stress and Age

Frequencies of nonspecific indicators of stress are high in this collection, with most individuals (67%) displaying at least two of the lesions recorded (Table 2; Tables S1-S2). Presence and expression of these lesions show some variation by age group

(Tables 2 & 3, Figs. 3 & 4). Cribra orbitalia is present in 89% of preadults and a lower proportion (66%) of adults (Table 2). Mean CO degree scores are also higher for preadults (Table 3). Only three individuals have CO scored as active, and these are preadults less than ~7 years (Fig. 4). Most preadults have lesions scored as mixed (63%), while 25% have healed lesions (Fig. 4, Table 2). In adults, CO was healed in a majority (68%) of cases. Differences in adult mean age at death across activity categories are also statistically significant (Table 4). Mean age at death is highest for those with healed lesions (45.88±13.27), slightly surpassing both those without lesions present (37.52±12.42), and those with mixed activity lesions (31.30±15.57).

Porotic hyperostosis is present in 36% of preadults and 93% of adults (Table 2). PH frequency increases dramatically after the age of ~6 years: only one individual under this age was affected, while 92% of individuals above this age are affected (Fig. 3). Only one PH lesion, in a child of around 6 years, was scored as mixed; all others were scored as healed. Degree scores rarely exceeded a score of 2, and most lesions were pinprick porosities only. Mean PH degree scores do not differ between adults and preadults (Table 3). However, mean PH area is greater in adults (Table 3). PH degree is negatively correlated with adult age at death (Table 4).

Periosteal reactions are present in 46% of preadults and 67% of those lesions were at least partially active at death (Table 2). No association was found between preadult age and PR presence or PR activity. Enamel hypoplasias (including LHDC) are present in 70% of preadults and 71% of adults (Table 2). Mean age of first observable LEH was lower in preadults (2.31 years) than adults (3.49 years), though the mean MNSE did not differ between them (Table 3). Mean CSI is lower in preadults (1.81) than adults (2.21). Mean MNSE scores are higher in individuals with PH, and MNSE also showed a weak positive correlation with PH degree and PH area (Table 5). A statistically significant inverse correlation was also found between MNSE and min LEH age (Table 5). Finally, min LEH age is lower in individuals with CO present (3.1±1.3 vs. 3.9±1.4, p=0.026, n=67), and inversely correlated with CO degree, albeit weakly (Table 5).

Stress and Growth

No statistically significant associations were found between delayed growth in preadults and presence, degree, or activity of nonspecific stress indicators (CO, PH, PR). However, stunted growth in preadults is associated with the presence of active or mixed status cribra orbitalia (p=0.047, n=24). Active/mixed lesions are present in 92% of stunted individuals, and 57% of non-stunted individuals. Contrary to expectations, wasting is associated with a lower cumulative stress score (p=0.015), and absence of enamel hypoplasias (p=0.003).

Among adults, mean body mass (represented by FHD) is larger in individuals with PH present and weakly correlated with PH area, while stature (FML) increases with PH degree (Table 6). Crural index is positively correlated with CSI (Table 6). Brachial index is smaller on average in individuals with mixed active/healing CO (Table 6). No adult body size measurements or indices were statistically correlated with age at death. No statistically significant differences in body size were found between time periods.

Discussion

Frailty and Longevity

Individuals who developed LEHs earlier in life tended to experience more discrete stress episodes overall (higher MNSE), died at younger ages, were more likely to develop CO, and experience more severe expressions of CO. Minimum LEH age was also lowest in individuals who died with active/mixed CO lesions, although this trend was not statistically significant (p=0.065, n=67). Individuals who experienced more discrete stress episodes also tended to have more widespread and severe manifestations of PH. Temple (2014) observed similar patterns among Jomon foragers, where those with earlier formed LEHs were more likely to develop additional defects and die at younger ages. However, in contrast to some other studies (e.g., Amoroso et al., 2014; Armelagos et al., 2009), presence of EHs and frequency of episodes are not associated with age at death.

Individuals who died as preadults developed CO at higher frequencies than those who died as adults. They were also more likely to die with active/mixed status CO, while most adults have fully healed lesions. Adults with mixed activity CO also died at younger ages on average, although it is interesting to note that those with healed CO lived longer than those who never developed it. This observation may suggest more robust health in those who were able to survive and heal.

PH is less variable in this collection than CO, with nearly all individuals developing it after the age of 6. PH is also less severe in its expression, with lower degree scores, and nearly always healed. As such, PH appears to be a poor indicator of underlying frailty in this collection. The low degree scores and lack of active PH lesions may suggest that the etiology in this collection is primarily taphonomic rather than pathological. Radiographic examination may be necessary to assess the reliability of the macroscopic observations. Finally, experiencing more discrete stress episodes overall or developing more types of lesion (CSI) did not have any discernible effect on longevity.

These results may suggest that it is not quantity of nonspecific indicators of stress that reflects frailty, but the age at which they form. CO is thought to form earlier in childhood than PH (Brickley, 2018), which is the pattern observed here. Likewise, age of first LEH formation is more strongly associated with higher morbidity and mortality than the number of LEHs formed. Stress experienced earlier in life appears to have more significant consequences than stress experienced later.

Stress, Growth, and Frailty

Of the stress indicators tested, only cribra orbitalia showed an association with impaired growth, with stunted individuals showing higher frequencies of active/mixed lesions than their non-stunted peers. Active/mixed cribra orbitalia was also present in 100% of the four individuals identified as wasted who also have observable orbits, although the association between wasting and CO activity was not found to be statistically significant. Among adults, active/mixed CO was associated with smaller mean BI. This finding is similar to results from Pinhasi et al. (2014), who found smaller body size dimensions in preadults from medieval and postmedieval Croatia with active lesions compared to those with healed lesions.

Contrary to predictions, presence of PH is statistically associated with larger body size, higher degree of PH is correlated with increasing BI, and higher CSI with increasing CI. It should be noted that PH is only absent in five adults, and the variability in degree of expression is low, with most individuals assigned a score of 1. Among those individuals with measurable BI, only seven have a PH degree greater than 1. Furthermore, the correlation between increasing PH degree and increasing BI is relatively weak (r=0.308), as is the correlation between CSI and CI (r=0.300). The association between wasting and lower CSI is likely attributed to the young age of the individuals, since four of the five affected are under the age of six, and follow the pattern observed in this collection in that they lack PH. The absence of enamel hypoplasia is more difficult to explain, though it may be an indication that the severe acute malnutrition associated with wasting precluded the periods of recovery necessary for enamel hypoplasia formation (Briend et al., 2015; C G Victora, 1992; Wood et al., 1992).

Overall, there is limited evidence in this collection demonstrating that the presence of nonspecific indicators of stress, even when multiple insults occurred, had an adverse effect on adult body size. As several other studies have found (e.g., Boldsen, 1997; Temple, 2008), none of the LEH variables showed any association with adult body size. Although stunting in preadults is associated with active/mixed cribra orbitalia, in adults, the only associated body size parameter is BI, while no reduction is observed in FML, FHD, or CI. It is not clear why BI is affected and CI is not, since the lower distal limb typically shows more variability and sensitivity to environmental stress (Holliday & Ruff, 2001; Rectenwald, 2012; S. L. Smith & Buschang, 2004, 2005).

Adult body size dimensions were not associated with age at death, suggesting that smaller individuals were at no observable disadvantage in this community. In spite of the commonly observed inverse correlation between stature and mortality, in their investigation of stature and frailty in medieval London, DeWitte and Hughes-Morey (2012) concluded that short stature increased risk of mortality during the Black Death, but not under conditions of normal mortality. In this collection, it may also be the case that variability in adult body size is too limited to be a reliable indicator of heterogeneity of frailty. This suggests that individuals with impaired growth were more likely to die during childhood, or that those who survived to adulthood generally experienced catch-up growth.

Conclusion

The original manifestations of the DOHaD hypothesis were concerned with nutrition during the fetal period (Barker & Osmond, 1986; Gardner et al., 1984), and it has gradually expanded to include adverse experiences during early growth and development more broadly (Armelagos et al., 2009; Barker, 2004; Gowland, 2015). This study set out to examine three questions inspired by the DOHaD hypothesis: 1) Were those who suffered systemic stress in early life more susceptible to additional or more severe signs of morbidity? 2) Did those who suffered stress early in life then suffer earlier mortality? 3) Does suffering stress in early life have consequences for growth outcomes? Regarding the first and second questions, the results of this study suggest that stress experienced earlier in life may have a more pronounced effect on later frailty than the quantity of stress episodes experienced. The findings also indicate that not all nonspecific indicators of stress are equally reliable indicators of frailty. The strongest indicator of underlying frailty in this collection is cribra orbitalia; individuals who developed this lesion were more likely to die as preadults and those whose lesions did not heal fully were more likely to die at younger ages, even if they survived to adulthood.

Regarding the third question, cribra orbitalia is the only indicator associated with growth faltering. In general, however, there is little evidence here that childhood stress had a discernible effect on adult body size. If the processes that produced these lesions did interfere with these individuals' growth, it is likely that most of them experienced sufficient catch-up growth to compensate for the initial ill effects (see Chapter 2).

The data presented clearly indicate that childhood stress was a part of life for everyone at the Qinifab School site. Yet it is also evident that many people suffered repeated physiological insults and still survived to adulthood, and in some cases to old age. The interrelationships among nonspecific indicators of stress, frailty, longevity, and growth are complex, multifaceted, and often ambiguous. The evidence presented suggests that timing is a critical factor, with stress experienced at earlier ages having more lasting consequences. This investigation, therefore, supports the DOHaD hypothesis.

Author Contributions

ALN & BJB conceptualization of study. ALN: drafting and editing of manuscript, data acquisition, statistical analysis and interpretation. BJB: data acquisition and curation, contextualization, review and editing of manuscript., AD: data acquisition, review and editing of manuscript.

Tables and Figures

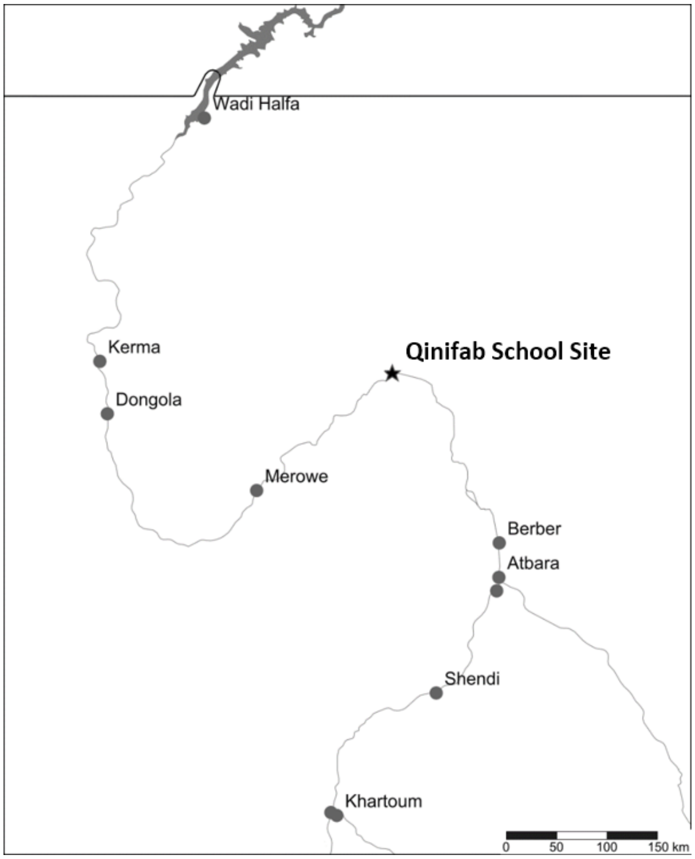

Figure 1 Map of Sudan showing location of the Qinifab School Site

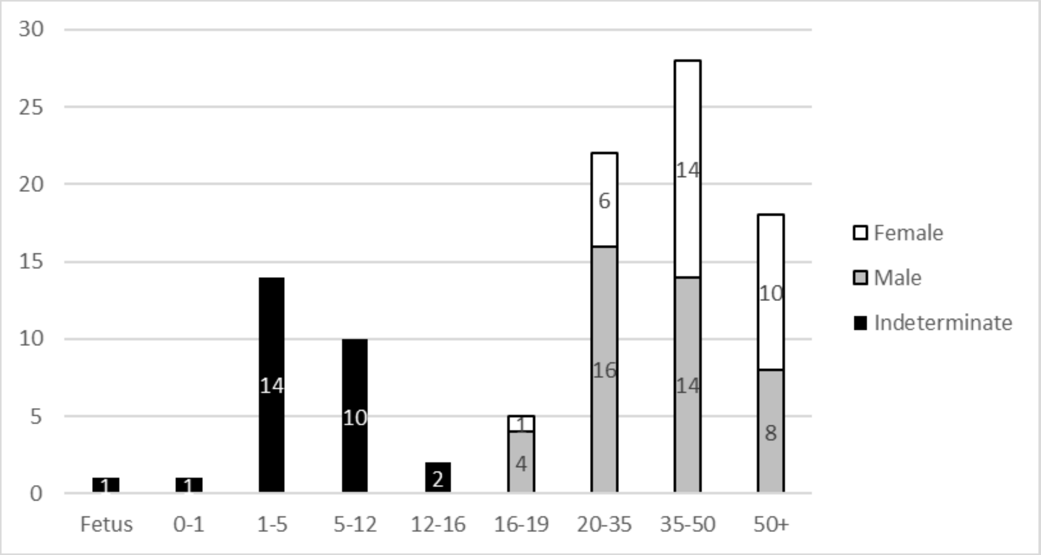

Figure 2 Site demographics by age and sex

Table 1 Nonspecific Indicators of Stress

Stress Indicator	**Factor**	**Description**
Cribra orbitalia (CO)	Presence	Presence (1) or absence (0) of lesion
	Activity	Active (1), mixed/healing (2), or healed (3)
	Degree	Extent/severity (1-4)
Porotic hyperostosis (PH)	Presence	Presence (1) or absence (0) of lesion
	Activity	Active (1), mixed/healing (2), or healed (3)
	Degree	Extent/severity (1-4)
	Area	Located at: sutures or squama (1), both (2)
Enamel hypoplasia (EH)	Presence	Presence (1) or absence (0) of enamel hypoplasia, including LHDC
	Min LEH	Minimum age of 1st stress episode (age of earliest formed LEH)
	MNSE	Maximum number of LEHs occurring on any single tooth (I1-M1), plus the maximum number of LEHs occurring on any M3, plus the maximum number of EHs (including LHDC) occurring on any deciduous tooth
Periosteal Reaction (PR)	Presence	Presence (1) or absence (0) of lesion
	Activity	Active (1), mixed/healing (2), or healed (3)
Cumulative Stress Index (CSI)	Presence	Calculated based on combination of presence scores for CO, PH, and EH. For analyses including preadults only, the PR score was also added

Table 2 Frequency of non-specific indicators of stress by age group

	Preadults			Adults			Total			Sig.
	#	%	N	#	%	N	#	%	N	
CO	24	88.9%	27	47	66.2%	71	71	72.4%	98	**0.025**
Active/Mixed CO	18	75.0%	24	15	31.9%	47	33	46.5%	71	**0.001**
PH	10	35.7%	28	67	93.1%	72	77	77.0%	100	**0.000**
EH	16	69.6%	23	45	71.4%	63	61	70.9%	86	0.866
PR	12	46.2%	26							
Active/Mixed PR	8	66.7%	12							

Table 3 Expression of stress indicators by age group

	Preadults			Adults			Total			Sig.
	Mean	SD	N	Mean	SD	N	Mean	SD	N	
CO Degree	2.50	0.78	24	1.98	0.92	47	2.15	0.90	71	**0.021**
PH Degree	1.10	0.32	10	1.16	0.41	67	1.16	0.40	77	0.639
PH Area	1.45	0.69	11	1.81	0.40	67	1.76	0.46	78	**0.018**
MNSE	1.32	1.03	25	1.55	0.98	69	1.49	0.99	94	0.322
Min LEH	2.31	0.70	9	3.49	1.33	58	3.33	1.32	67	**0.012**
CSI	1.81	0.92	27	2.21	0.73	72	2.10	0.80	99	0.029

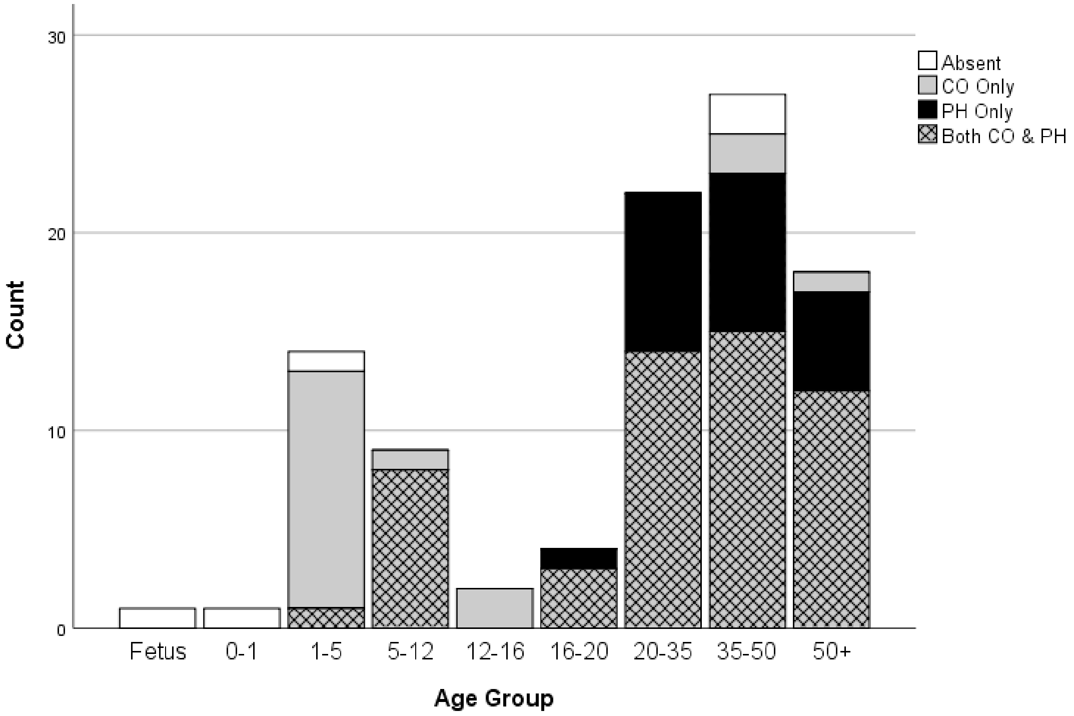

Figure 3 Cribra orbitalia and porotic hyperostosis frequency by age

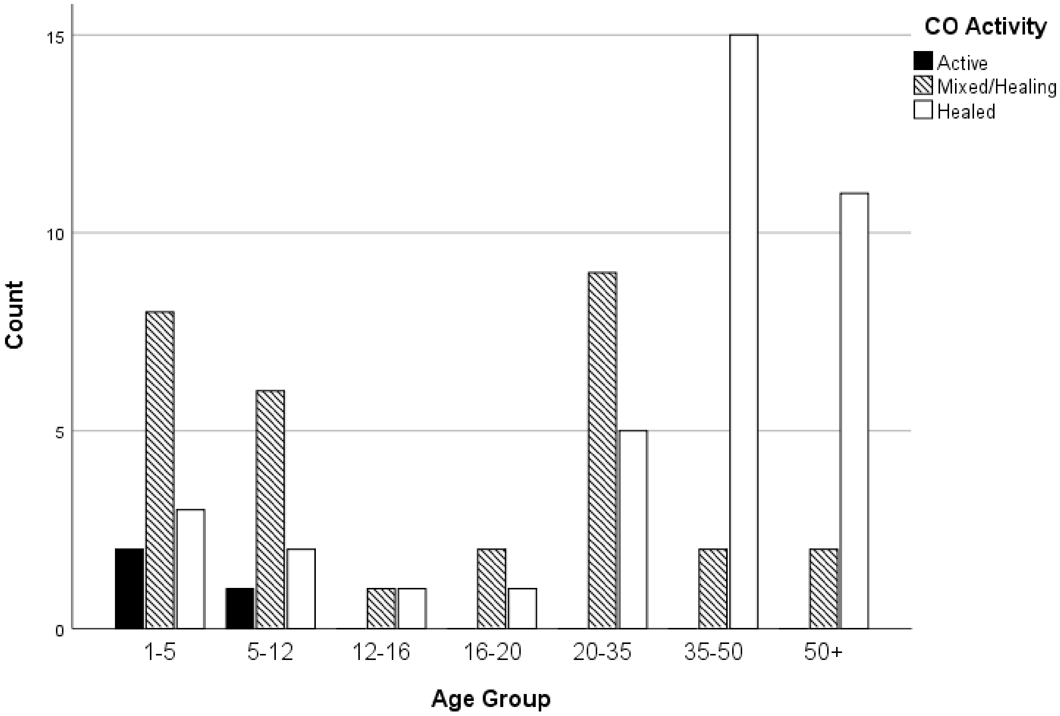

Figure 4 Healing status of CO by age

Table 4 Stress indicators and adult age at death

Stress Indicator	Factor	Sig.	N	r
Cribra orbitalia (CO)	Presence	0.313	71	
	Activity	**0.003**	**71**	
	Degree	0.672	71	-0.051
Porotic hyperostosis (PH)	Presence	0.190	72	
	Degree	**0.010**	**72**	**-0.301**
	Area	0.162	72	-0.167
Enamel hypoplasia (EH)	Presence	0.793	63	
	Min LEH age	0.254	58	0.152
	MNSE	0.692	69	-0.049
Cumulative Stress Index (CSI)	Presence	0.959	62	0.007

Table 5 Associations between stress indicators

Quantity	Factor	Sig.	N	r
CSI	CO Activity	0.113	63	
	CO Degree	0.539	63	0.079
	PH Degree	0.292	67	-0.131
	PH Area	0.386	67	-0.108
	Min LEH Age	0.118	60	-0.204
MNSE	CO Presence	0.680	94	
	CO Activity	0.444	94	
	CO Degree	0.584	94	0.057
	PH Presence	**0.004**	**94**	
	PH Degree	**0.003**	**94**	**0.308**
	PH Area	**0.019**	**94**	**0.241**
	Min LEH Age	**0.000**	**67**	**-0.503**
Min LEH	CO Presence	**0.026**	**67**	
	CO Activity	0.065	67	
	CO Degree	**0.037**	**67**	**-0.255**
	PH Presence	0.245	67	
	PH Degree	0.109	67	-0.198
	PH Area	0.237	67	-0.146

Table 6 Stress indicators and adult body size dimensions

Stress Indicator	Factor		Sig	N	r
CO	Presence	FML	0.629	56	
		FHD	0.313	66	
		CI	0.274	50	
		BI	0.543	48	
	Activity	FML	0.975	39	
		FHD	0.399	42	
		CI	0.866	36	
		BI	**0.036**	**36**	
	Degree	FML	0.087	39	0.278
		FHD	0.720	42	0.057
		CI	0.567	36	0.099
		BI	0.164	36	-0.237
PH	Presence	FML	0.191	57	
		FHD	**0.018**	**67**	
		CI	0.703	51	
		BI	0.946	49	
	Degree	FML	0.054	52	0.269
		FHD	0.188	62	-0.170
		CI	0.769	48	-0.044
		BI	**0.042**	**44**	**0.308**
	Area	FML	0.550	52	0.085
		FHD	0.456	62	0.096
		CI	0.403	48	-0.123
		BI	0.721	44	0.055
EH	Presence	FML	0.875	54	
		FHD	0.678	59	
		CI	0.056	48	
		BI	0.847	45	
	Min LEH	FML	0.927	50	-0.013
		FHD	0.431	54	0.109
		CI	0.247	44	-0.178
		BI	0.635	41	-0.076
	MNSE	FML	0.599	56	-0.072
		FHD	0.689	64	0.051
		CI	0.121	50	0.222
		BI	0.371	48	0.132
CSI	Presence	FML	0.714	57	0.050
		FHD	0.461	67	0.092
		CI	**0.032**	**51**	**0.300**
		BI	0.528	49	-0.092

CHAPTER 4

TEMPORAL TRENDS IN DIET AND MORBIDITY AT THE QINIFAB SCHOOL SITE, SUDAN

Norris AL, Baker BJ, Zolotova N, Knudson K. Target Journal: Journal of Archaeological Science: Reports

Abstract

Stable carbon and nitrogen isotope analyses were conducted on bone collagen and carbonate samples from individuals buried at the multicomponent Qinifab School site located between the fourth and fifth Nile cataracts in modern Sudan. The cemetery component dates from the late Meroitic through Christian periods, c. 250-1400 CE. Rib samples were taken from individuals dated to the Post-Meroitic (c. 350-550 CE) and Christian period (c. 550-1400 CE). A temporal shift in diet between the Post-Meroitic and Christian periods is indicated by differences in the carbon and nitrogen isotope values. No temporal shift was noted for the carbon values derived from carbonate, although the mean difference in collagen-carbonate carbon values increases over time. The lower nitrogen values and the greater difference in collagen-carbonate carbon values may indicate a shift toward intensified agriculture and decreased use of animal products. Comparison of the isotopic data with paleopathological data allows assessment of nutritional changes on health status. A greater proportion of individuals in the Christian period were affected by cribra orbitalia, a nonspecific skeletal stress indicator of ambiguous etiology that is often associated in the literature with nutritional deficiencies. The possible relationship between the observed changes in diet and pathology are

explored within the biocultural context of ancient Nubia. Diet at the Qinifab School site is compared with diet at other Nubian sites for which isotopic data are available.

Introduction

Beyond the basic biological need for food consumption, diet is an important component of human cultures. Diet often represents not only human exploitation and manipulation of the local ecosystem, but also a community's place in a trade network with interregional connections. Diet is used in the establishment of social identities, as a marker of group identity, a subject of ritual, and a foundation of wealth and status. Social change is often synonymous with a change in diet. The study of diet in archaeology spans numerous specializations, including archaeobotany, zooarchaeology, and bioarchaeology. One of the most direct methods of inferring what people in the past consumed is through biogeochemical analysis of human tissues, most commonly through analysis of stable carbon and nitrogen isotopes in bones and teeth.

This study presents stable carbon and nitrogen isotope data for skeletal material from the Qinifab School site, a multicomponent site in northern Sudan. Its cemetery component dates from ~250-1400 CE. Stable isotope evidence is used to explore temporal and demographic variations in diet among those interred at the site, and to compare diet across the broader ancient Nubian landscape. In addition to dietary reconstruction, we also examine potential ramifications for human health through comparison with paleopathological data.

Principles of Stable Isotope Analysis

Bone is a bipartite tissue composed of both organic and inorganic material. The organic portion of bone is primarily collagen, while the mineral portion is hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), a form of calcium phosphate (White et al., 2011). Both carbon and nitrogen are a significant part of the chemical make-up of collagen; in bone collagen and tooth dentine these elements are ultimately derived from dietary protein (Ambrose and Norr, 1993; Tieszen and Fagre, 1993). Carbon isotopes can also be analyzed in bone mineral or tooth enamel (Lee-Thorp and van der Merwe, 1991; Sullivan and Krueger, 1981). In this case, the carbon derives from carbonate (CO_3), which may substitute for phosphate (PO_4). Carbonate enters bone via bicarbonate dissolved in blood and represents carbon values more reflective of the whole diet rather than just the protein component reflected in collagen (Ambrose and Norr, 1993; Krueger and Sullivan, 1984; Tieszen and Fagre, 1993).

Stable isotope analysis examines the ratio of one stable (as opposed to radiogenic) isotope form of an element to another, measured via isotope ratio mass spectrometry. This ratio is then compared to a standard, which is either internal to the laboratory or an international standard produced by the International Atomic Energy Agency or the National Bureau of Standards (Katzenberg, 2008). These results are reported using a delta notation, in parts per mil (‰), where $\delta = [(R_{sample}-R_{standard})/R_{standard}]*1000$ (Katzenberg, 2008; Pollard et al., 2007).

Carbon has two stable isotope forms, ^{12}C and ^{13}C, which have natural terrestrial abundances of 98.98% and 1.11% respectively (Ehleringer and Rundel, 1989). As carbon is incorporated from the atmosphere into the food web, the ratio of ^{13}C:^{12}C changes, as the differing masses of the two isotopes cause them to be affected differently by ensuing chemical reactions. Common sources of $\delta^{13}C$‰ variation include different photosynthetic pathways in plants, and marine versus terrestrial origin (Chisholm et al., 1982; Vogel and van der Merwe, 1977). For example, plants that fix carbon using the Hatch-Slack or C_4 photosynthetic pathway discriminate less against ^{13}C than do plants that use the Calvin or C_3 photosynthetic pathway, meaning that C_4 plants have elevated $\delta^{13}C$ compared to C_3 plants (Hatch and Slack, 1967, 1966). Animals and humans consuming these C_4 plants will likewise have a corresponding elevation in $\delta^{13}C$ values (DeNiro and Epstein, 1978; Vogel, 1978; Vogel and van der Merwe, 1977).

Nitrogen also has two stable isotope forms, ^{14}N and ^{15}N, which have average terrestrial abundances of 99.63% and 0.37% respectively (Ehleringer and Rundel, 1989). One of the primary factors in nitrogen isotope fractionation is known as the trophic level effect (DeNiro and Epstein, 1981; Schoeninger and DeNiro, 1984). Each trophic level is, essentially, a rung on the food chain. The value of $\delta^{15}N$ increases by about 3‰ with each new trophic level, from primary consumer to secondary consumer, and so on (Schoeninger and DeNiro, 1984). In addition, diet, physiology, and environment all play a part in determining individual $\delta^{15}N$. Marine-based diets result in elevated $\delta^{15}N$ values in comparison to terrestrial-based diets (Schoeninger and DeNiro, 1984), and living in a hot, dry environment tends to increase an individual's $\delta^{15}N$ values compared to living in a cold or humid region (Ambrose, 1991; Schwarcz et al., 1999). Water stress, which leads to increased excretion of ^{14}N via urine, and protein stress, which also results in depletion of ^{14}N, can both cause a correspondent elevation in $\delta^{15}N$ values (Ambrose and Deniro, 1986; Fuller et al., 2005; Hobson et al., 1993). Hair samples from pregnant women have shown a decrease in δ^{15}N values during gestation, likely related to the processes of synthesizing fetal tissues (Fuller et al., 2004). Additionally, there is evidence that δ^{15}N values in pathological bone may differ from normal bone in the same individual (Katzenberg and Lovell, 1999; Olsen et al., 2014).

Studies comparing individuals with and without pathological lesions associated with nutritional deficiencies and other diseases have had variable results (Reitsema and Holder, 2018; Richards and Montgomery, 2012). For example, both Carroll et al. (2018) and Viva et al. (2021) found no difference in δ^{13}C or δ^{15}N in individuals with cribra orbitalia or porotic hyperostosis, while White (1991) observed slightly lower δ^{15}N values in individuals with CO. Differences in isotopic values have also been found in association with conditions such as rickets (Waters-Rist and Hoogland, 2018), osteopenia (White and Armelagos, 1997), enamel defects (Garland et al., 2018), and in modern samples, anorexia (Mekota et al., 2006).

Subsistence and Social Change in Ancient Nubia

“Nubia” denotes a geographical area located between the first cataract at Aswan, Egypt, to roughly the sixth cataract north of Khartoum, Sudan (Edwards, 2004; Lacovara, 2012). Centered along the Nile Valley (Fig. 1), this region was home to one of the earliest urbanized states in Africa known as Kush (Welsby, 2013). The rise and fall of Kushite states of Nubia were accompanied by changes in the nature and scale of food production, with corresponding implications for social structure (e.g., Fuller, 2014; Haaland, 2012), health (e.g., Martin et al., 1984; Rudney and Greene, 1981), and skeletal morphology (e.g., Armelagos et al., 1984). Beginning in the Neolithic, the dominant subsistence economy in the region was initially more pastoral or agropastoral than agricultural, and livestock such as goats, sheep, and especially cattle were of central importance, though later periods saw an increasing intensification of crop agriculture (Chaix and Honegger, 2015; Edwards, 2004; Fuller, 2014). The local cuisine developed at a crossroads between two distinct food cultures: to the north, the Egyptian and Near Eastern tradition of bread and beer made from winter-grown wheat and barley (C_3 plants) and, to the south, the Sub-Saharan tradition of porridge and beer made from summer-grown sorghum and millet, C_4 plants adapted to the African savannah (Haaland, 2012). Recent microbotanical finds have established the presence of the Near Eastern domestic cereals, wheat (*Triticum* spp.) and barley (*Hordeum vulgare*) in northern Sudan (near the third cataract) by 5000 BCE. (Madella et al., 2014; Out et al., 2016). Winchell and colleagues (2017) argued, based on plant impressions found in ceramic sherds dating to 3500-3000 BCE, that the origins of sorghum (*Sorghum bicolor*) domestication lie in the southern Atbai region of Eastern Sudan. In the Nile Valley, however, evidence for domestic sorghum does not antedate the Napatan period (c. 1000-350 BCE), and is only unambiguously present in the Meroitic period, c. 350 BCE-350 CE (Fuller, 2014, 2004; Winchell et al., 2018). Pearl millet (*Pennisetum glaucum*), from the western Sahel region, had reached eastern Sudan by c. 1850 BCE. and Chinese broomcorn millet (*Panicum miliaceum*) has been found at one Kerma period site in the Nile Valley (Beldados et al., 2018; Winchell et al., 2018). In addition to the domestic crops, there is substantial archaeobotanical evidence throughout

Sudan for the exploitation of native wild grasses (predominantly C_4) dating back to the Mesolithic (Out et al., 2016).

By 2500 BCE, the site of Kerma, near the third cataract (Fig. 1), had become a substantial, urbanized center of a state exerting political power and cultural influence over much of Nubia (Bonnet, 2014, 1992; Edwards, 2004; Fisher, 2012; Welsby, 2013). The cemeteries of Kerma reveal marked social stratification (Bonnet, 1992; Honegger, 2018). Kerma was situated on a wide floodplain, far better for agricultural development than much of the surrounding region (Thompson et al., 2008). Stable isotopic evidence at Kerma suggests consumption of a mix of C_3 (e.g., wheat, barley, most fruits and vegetables) and C_4 (e.g., millet, sorghum, native grasses consumed by domesticates) plants (Iacumin et al., 1998; Thompson et al., 2008). Iacumin and colleagues (1998) found that C_4 plants were more important during the Early Kerma phase than in the Middle and Classic phases and, while goats/sheep, fish, and cattle were used throughout, cattle were more important during the Early Kerma phase. A well-developed agricultural program was suggested by the presence of cereal grains and legumes (Iacumin et al., 1998; Thompson et al., 2008). Thompson and colleagues (2008) had broadly similar results with a larger sample from the site of Kerma dated to the Middle and Classic phases. They found a mix of both C_3 and C_4 plants in the diets of both fauna and humans, though the faunal diets had a greater C_4 input overall. They note that the mean carbon isotope values were higher on average than those typically observed in individuals from the Egyptian Nile Valley, which is not unexpected given the greater abundance of native C_4 plants in Nubia (Thompson et al., 2008). Cattle held particular importance at Kerma, economically and ritually; bucrania (cattle skulls) are commonly associated with graves, and sometimes number in the thousands, suggesting that funereal feasting involved the consumption of large quantities of meat (Haaland, 2012). However, in outlying areas away from the urban center of Kerma, goats and sheep predominate and fewer cattle are present (e.g., Bangsgaard, 2014; Ptacek and Baker, 2020), and it is likely that cattle consumption was primarily the province of the elite or reserved for festivals (Ikram, 2012).

The Kushite kingdom centered at Kerma was conquered by Egypt around 1500 BCE, and the conquest was followed by a period of Egyptian hegemony and colonization, lasting until 1069 BCE (Edwards, 2004; Fisher, 2012). Egyptian immigrants, the controlling elite, brought with them their own culinary practices, but Nubian traditions endured (Haaland, 2012). In addition to the presence of Nubian-style pottery (Haaland, 2012), Nubian-style cooking is also supported by isotopic evidence (Buzon and Bowen, 2010). Stable carbon isotope values from bone apatite at the colonial site of Tombos (Fig. 1) indicate greater consumption of the C_4 foods typical of the Nubian diet than at contemporaneous Egyptian sites (Buzon and Bowen, 2010).

Following the period of Egyptian control, a new Kushite state rose to power, centered first at Napata (c. 1000 BCE-350 BCE), then farther south at Meroe (Fig. 1; Edwards, 2004; Fisher, 2012; Welsby, 1996). Artwork of the period suggests that domesticated sorghum held some degree of ritual, symbolic importance, and sorghum residue has been found in sacrificial bread-molds associated with a temple to Amun at Dangeil (Fuller, 2014). Toward the end of the Meroitic or during the Post-Meroitic period

(c. 350-550 CE), an important innovation in Nubian agriculture occurred with the introduction of the *saqia*, or waterwheel, for irrigation (Edwards, 2004; Fuller, 2014; Fisher, 2012). Traditionally, agriculture throughout the Nile Valley had depended on planting winter crops (wheat and barley) in the floodplain after the recession of the annual flood (Edwards, 2004). Large-scale adoption of the *saqia* in this period allowed for the development of a seasonal, multi-harvest agricultural system incorporating summer savannah grains like sorghum, thus allowing crops to be harvested year round (Edwards, 2004). Fuller (2014) argued that the increased agricultural production stimulated by this technological advance (including the increase in cash crops such as cotton) led to a redistribution of power that ultimately contributed to the decline of the Meroitic empire.

Isotopic data suggest that C_3 plants (wheat and/or barley staples, along with mixed fruit and vegetables) continued to dominate the diet throughout the Meroitic, Post-Meroitic, and Christian (c. 550-1400 CE) periods, but consumption of millet and/or sorghum increased significantly in the Post-Meroitic period in Lower (northern) Nubia (White, 1991; White et al., 2004; White and Schwarcz, 1994). Isotopic values from Christian period Kulubnarti are similar to those from contemporaneous samples from Wadi Halfa (Glasgow, 2011; Turner et al., 2007). In their analysis of hair samples, however, Basha and colleagues (2016) noted a slight enrichment in ^{13}C at Kulubnarti compared to Wadi Halfa hair samples, suggesting more C_4 input in the diet. Isotopic evidence derived from segments of human hair from individuals at Post-Meroitic and Christian period Wadi Halfa sites (Schwarcz and White, 2004; White, 1993; White et al., 1999), and Christian period Kulubnarti (Basha et al., 2018) supports the hypothesis that diet fluctuated seasonally, with C_3 food sources dominating the diet in winter and C_4 sources dominating during the summer. In their analysis of nitrogen isotope values at Wadi Halfa, White and colleagues (1994) concluded that dietary protein sources primarily derived from caprine and cattle pastoralism, with limited consumption of legumes and fish. At Kulubnarti, researchers found that nitrogen values in skin and muscle (Basha et al., 2016), as well as hair (Fares et al., 2015) were lower than those at Wadi Halfa, suggesting a smaller proportion of dietary protein obtained from animal sources.

Finally, isotopic data also have been used to reconstruct weaning practices, and weanling and post-weaning diets in preadults. White and Armelagos (1997) used $\delta^{15}N$ values to estimate that breast-feeding may have continued up to age four at Wadi Halfa sites. This find was later corroborated by $\delta^{18}O$ data, which indicated a transition in water source between the ages of three and seven (White et al., 2004a). In a sample of Late Meroitic individuals from Sai Island, the average weaning age was estimated to be 2.7 years using stable carbon and nitrogen isotope analysis in serial samples of permanent first molars, though the results also indicated significant interindividual variation in weaning times (Eerkens et al., 2018). Variable weaning practices were also found in the isotopic data from Kulubnarti, and the results suggest that individuals in this sample who survived to adulthood were weaned earlier on average than non-survivors (Sandberg, 2012; Sandberg et al., 2014; Turner et al., 2007). Furthermore, Turner and colleagues (2007:21) postulate the existence of a "childhood diet" that involved less consumption of animal proteins than the adult diet. Sandberg (2006) suggested that dependence on a weanling gruel made from sorghum, millet, or barley may have been the source of the age-related variation in protein intake, potentially resulting in iron and other nutritional deficiencies.

Evidence for Nutritional Deficiency in Nubia

In addition to archaeological and biogeochemical evidence, diet in Nubia has also been interpreted through skeletal indicators of nutritional stress. The most commonly used indictors are porotic hyperostosis and cribra orbitalia, indicated by areas of porosity occurring on the cranial vault and in the eye orbits, respectively. The lesions are generally assumed to be produced by marrow hyperplasia, which is caused by an increase in red blood cell (RBC) production as a compensatory reaction to deficiency in the hemoglobin of RBCs (Aufderheide and Rodriguez-Martin, 1998; Ortner, 2003). Both lesions are thought to develop during childhood, when marrow in the cranium is primarily of the red type and increasing RBC production thus leads to marrow expansion (Brickley, 2018; Stuart-Macadam, 1985). Cribra orbitalia has often been observed to occur at earlier ages, which may relate to the developmental pattern of marrow conversion in the skull (Brickley, 2018; Stuart-Macadam, 1989), although Rivera and Lehr (2017) have argued that, in the absence of porotic hyperostosis, cribra orbitalia may be associated with thinning of the diploe instead of the expansion caused by marrow hyperplasia. Cole and Waldron (2019) have even argued that simple porosities of the orbit, without new bone formation or further alteration of orbit morphology, may represent nonpathological developmental variation, and dismiss any connection to porotic hyperostosis.

Cribra orbitalia and porotic hyperostosis have long been considered indicative of anemia in the bioarchaeological literature, particularly iron-deficiency anemia often linked to diet; however, the etiology of anemia is complex, and may be related not only to diet, but also to parasite load, disease, or genetics (see Walker et al., 2009; Wapler et al., 2004). Furthermore, the orbits are thin and prone to perforation caused by numerous non-anemic conditions, particularly inflammation ensuing from hemorrhage (Brickley, 2018). As such, lesions commonly denoted cribra orbitalia have additionally been linked to scurvy, rickets, and other vitamin deficiencies (Rivera and Lahr, 2017; Walker et al., 2009). Wapler and colleagues (2004) examined cribra orbitalia in 93 ancient Nubians from Missiminia in northern Sudan (Meroitic to Christian period) and found that over 50% of the sample did *not* have histological evidence of anemia. They cited inflammation as another common cause of the lesion, at least in the adults and adolescents they examined (Wapler et al., 2004). In an examination of a modern sample with known causes of death, O'Donnell et al. (2020) found that respiratory infections increased the odds of having CO or PH, and that heart conditions increased the odds of having CO but not PH. Rothschild et al. (2020) suggested that lesions in the orbits with no observable porosity represent vascular imprints and propose several hypotheses for their etiology.

High rates of cribra orbitalia and porotic hyperostosis have been documented in Nubian collections and throughout the Nile Valley in general (Alvrus, 2006; Armelagos, 1968; Buzon, 2006; Carlson et al., 1974; Mittler and Van Gerven, 1994; Smith-Guzmán, 2015). Most of these studies posit that the etiology of cribra orbitalia and porotic hyperostosis in ancient Nubian contexts is primarily dietary, and also associated with high parasite load (e.g., Armelagos et al., 1968; Carlson et al., 1974; Sandford et al., 1983; Smith-Guzmán, 2015). While cause is mostly linked to a Nubian diet heavily reliant on cereal grains low in iron, leading to high rates of anemia, this assertion is rarely tested, and it is uncommon to see studies that directly compare isotopic and paleopathological lines of evidence. In one rare exception, White (1991) noted a tendency for individuals with cribra orbitalia to exhibit lower δ^{15}N values and higher δ^{13}C values in bone collagen compared to those without this lesion. This difference was not detected in soft-tissue isotope values. White (1991:200) proposes that, since the differences in isotopic values between "anemic" and "non-anemic" individuals are only present in bone and, therefore, represent long-term rather than short-term dietary differences, the anemic individuals may have had a different childhood diet than non-anemic individuals. Additionally, Baker (1992) found no significant difference in the amounts of hydroxylysine and hydroxyproline, the amino acids dependent upon iron for their formation, between adults with lesions and those without lesions in the Wadi Halfa NAX cemetery also sampled by White. The lower nitrogen isotope values found by White (1991), however indicate a diet with less animal protein, while the increase in carbon values indicates more reliance on C_4 plants, which are lower in iron than C_3 plants (White, 1991), yet dietary differences were not sufficient to affect normal collagen formation (Baker, 1992).

Materials and Methods

Qinifab School Site

The Qinifab School site (UCSB 03-01 and UCSB 03-02), excavated from 2007-2009, is a multicomponent site containing a Late Meroitic-Christian period cemetery dated from c. 250-1400 CE (Baker, 2014, 2008). It is located between the fourth and fifth Nile cataracts, on the north bank of the Nile near the westernmost end of Mograt Island, west of Abu Hamed (Fig. 1). Prior to the initiation of the Merowe Dam Archaeological Salvage Project (MDASP) in 1996 (Ahmed, 2003), the region upstream of the fourth cataract had received little archaeological attention due to assumptions that settlements in the area were sparse, or of limited interest (Adams, 1977; Breasted, 1908; Emberling, 2012; Gissema, 2014).

The Qinifab School cemetery contained 37 stone tumuli, 30 smaller superstructures consisting of rock cairns, and 36 subsurface shafts (Baker, 2014, 2008). The human remains from the cemetery are housed in the Bioarchaeology of Nubia Expedition laboratory at Arizona State University; a total of 100 individuals is available for analysis. The demographics for this collection are given by age, sex, and time period in Figure 2. Temporal designations recorded in the field were based on grave architecture/style, orientation, body position, and accompanying grave goods where present, and were confirmed or refined with radiocarbon dating (see Baker, 2014) and further analyses. Age and sex were estimated using standard osteological methods (Buikstra and Ubelaker, 1994), primarily pelvic and cranial morphology for sex (e.g., Phenice, 1967), while adult age was estimated primarily by assessment of the pubic symphyseal face (Brooks and Suchey, 1990), auricular surface (Lovejoy et al., 1985), and cranial suture closure (Meindl and Lovejoy, 1985). Supplemental information regarding dental development and eruption (Hillson, 1997; Moorrees et al., 1963a, 1963b; Schour and Massler, 1941; Smith, 1991; Ubelaker, 1989) and ossification and epiphyseal fusion (Baker et al., 2005; Brothwell, 1981; Scheuer and Black, 2000; Steele and Bramblett, 1988) was used to refine estimated age ranges for preadults and produce separate dental and skeletal age estimates (see Chapter 2). For analyses here, the mean dental age was favored because dental development patterns are considered more accurate than bone growth and development, which are more likely to be affected by environmental stressors such as malnutrition or disease (Cardoso, 2007; Conceição and Cardoso, 2011; Hoppa and Fitzgerald, 1999). Preadults are defined here as individuals less than approximately 16 years, because sex could generally be estimated for individuals above that age and archaeological evidence suggests individuals of this age were treated more like adults in death. Additionally, marrow conversion in the skull is generally complete by around 15 years, meaning that porotic lesions resulting from compensatory marrow expansion are unlikely to form in the cranium after this age (Brickley, 2018).

Stable Isotope Analysis

The 60 individuals sampled for isotopic analyses were selected to reflect the demographic composition of the site. Individuals from the Meroitic period were excluded due to poor preservation of collagen based on attempts to obtain radiocarbon dates, with the exception of three males designated as late Meroitic or Post-Meroitic (categorized here as Post-Meroitic for the sake of analysis given that the oldest dated burials predate the beginning of this period by only 100 years). The sample included 20 individuals from the Post-Meroitic (6 females, 12 males, 2 preadults), 39 from the Christian period (14 females, 10 males, 15 preadults), and 1 preadult from either the Post-Meroitic or Christian period. (This ambiguously dated individual was excluded from analyses in which time periods were considered separately.) One rib was selected from each individual and a 1-2g section was removed, avoiding pathology wherever possible (some individuals sampled have well-healed periosteal reactions on nearly all available ribs). All bone samples were prepared using standard laboratory procedures and protocols developed by the Archaeological Chemistry Laboratory at Arizona State University, which are based on methods well established in the isotopic literature (e.g., Ambrose, 1990; Koch et al., 1997). The rib samples were mechanically cleaned to remove surface contaminants using handheld Dremel saws and drills. Samples were then divided and weighed for separate collagen and carbonate analysis.

To isolate collagen, samples were immersed in 0.25 M hydrochloric (HCl) acid. They were checked every 48 hours and, if not fully demineralized, the acid was decanted and replaced. When fully demineralized, samples were rinsed and treated with a chloroform:methanol solution to remove lipids. Samples were then treated with 0.125 M sodium hydroxide to remove humic substances. Finally, the collagen was solubilized in a pH 3 HCl solution and freeze-dried. Samples were then analyzed at the Metals, Environmental and Terrestrial Analytical Laboratory (METAL) at Arizona State University using a Delta Plus Mass Spectrometer coupled to a Costech Elemental Analyzer.

Carbonate samples were ground into a powder with a mortar and pestle and weighed. They were then chemically cleaned via treatment first with bleach, then with acetic acid to remove any diagenetic carbonates. Samples were then weighed and sent to Northern Arizona University (NAU) to be analyzed on a Delta V Advantage isotope ratio mass spectrometer (IRMS) equipped with a Gas Bench II at the Colorado Plateau Stable Isotope Laboratory. Accuracy and precision of the carbonate measurements were checked using the isotope standards NBS-18, NBS-19, and LSVEC. Resulting mean values for each standard were 0.01-0.02‰ from expected values, with mean reproducibility of ±0.2‰. Temporal variation in the isotopic data was assessed using independent samples t-tests, and independent samples Mann-Whitney U tests when evaluated by sex. All statistical analyses were performed using IBM SPSS Statistics 25.

Paleopathology

Presence, degree, and healing status of cribra orbitalia and porotic hyperostosis were assessed in a previous study (see Chapter 3). Lesions were recorded using codes modified from Standards (Buikstra and Ubelaker, 1994). Temporal variation in paleopathological data was assessed using Pearson chi-square tests. Relationships between isotopic values and paleopathological lesions were tested using independent samples t-tests and independent samples Mann-Whitney U tests. Because nearly all adults in the collection have some evidence of porotic hyperostosis, isotopic differences between afflicted and non-afflicted individuals were tested for preadults separately. The reverse is true for cribra orbitalia, with all preadults sampled here being affected. In addition, because healed lesions can persist in the skeleton for many years, isotopic values in individuals with healed lesions are unlikely to represent the diet consumed when the lesions were forming (see section 1.3 above). In order to account for the complicated relationship between cribra orbitalia and bone remodeling, differences in isotopic values were tested between adults with mixed/healing lesions and adults with no lesions or completely healed lesions using independent samples t-tests.

Results

Of the 60 bone collagen samples, eleven had atomic C:N ratios outside the acceptable range (2.9-3.5), and three more showed values outside the calibration range (Appendix G). These fourteen samples were excluded from further analyses. All raw carbon (collagen and apatite) and nitrogen isotope values are shown in Appendix G. Descriptive statistics shown by demographic can be found in Table 1. The preadult of uncertain date (4C-03-01-B79) is incorporated into the totals for all time periods, and the raw data for that sample can be found in Appendix G. Stable carbon ($\delta^{13}C_{COLL}$) and nitrogen ($\delta^{15}N$) values from bone collagen are displayed graphically in Figure 3, with different symbols to indicate time period and sex, while stable carbon values from collagen and apatite ($\delta^{13}C_{AP}$) are shown in Figure 4. Figure 5 shows distribution of $\delta^{15}N$ values in preadults by age, with markers indicating presence or absence of porotic hyperostosis, compared with the adult female mean in order to assess the effects of weaning. Independent samples t-test showed a statistically significant difference in mean $\delta^{15}N$ (p=0.005), $\delta^{13}C_{COLL}$ (p=0.000), and $\delta^{13}C_{AP-COLL}$ (p=0.001) values between time periods (Table 2). These differences were also found to be statistically significant when preadults under the age of five (the majority of which are from the Christian period) were excluded from analysis. Independent samples Mann-Whitney U tests showed a statistically significant difference in $\delta^{15}N$, $\delta^{13}C_{COLL}$, and $\delta^{13}C_{AP-COLL}$ values between sexes when time periods were pooled, although no statistically significant differences were found between sexes when time periods were tested separately (Table 3).

Figure 6 shows the frequency of cribra orbitalia for the Post-Meroitic and Christian periods by demographic, while Figure 7 shows the frequency of porotic hyperostosis. For cribra orbitalia, the difference in frequency between time periods is statistically significant, regardless of whether preadults under age five years are included (p=0.001 when included and p=0.002 when excluded). When the sexes were examined separately, only females showed a statistically significant difference in cribra orbitalia rates between time periods (females: p=0.008, males: p=0.635). For porotic hyperostosis, the difference in frequency between time periods is statistically significant (p=0.029) when all individuals are included. However, when preadults under age five years are excluded, no statistically significant difference is observed (p=0.811). Independent samples Mann-Whitney U tests showed no statistically significant difference between individuals with and without porotic hyperostosis, either when all individuals were tested (δ^{15}N, p=1.000; $\delta^{13}C_{COLL}$, p=0.859; $\delta^{13}C_{AP}$, p=0.739; $\delta^{13}C_{AP\text{-}COLL}$, p=0.800) or when preadults were tested separately (δ^{15}N, p=0.051; $\delta^{13}C_{COLL}$, p=0.366; $\delta^{13}C_{AP}$, p=0.479; $\delta^{13}C_{AP\text{-}COLL}$, p=0.445). When all individuals were tested, a statistically significant difference was found in $\delta^{13}C_{COLL}$ values between those with cribra orbitalia and those without (Table 4). In addition, a statistically significant difference was also found between the $\delta^{13}C_{COLL}$ and $\delta^{13}C_{AP\text{-}COLL}$ values in adults with mixed/healing cribra orbitalia and those without the lesion or with fully healed lesions (Table 5).

Discussion

Qinifab Diet Trends in Context

To assess the likely components of the diet of the Qinifab individuals, the results were compared with published data from other archaeological cemetery samples in Sudan (Table 6, Figs. 8-9). A selection of data is presented in Table 6 from Kerma (Thompson et al., 2008), Tombos (Buzon and Bowen, 2010), Al Khiday (Iacumin et al., 2016), Sai Island (Raisor, 2020), Wadi Halfa (White, 1991), Kulubnarti (Turner et al., 2007), and the Qinifab School site (see Fig. 1 for locations). All data are from human bone samples, with the exception of Tombos, which derives from human permanent tooth enamel (Buzon and Bowen, 2010). The samples at Kerma are composed of adults only, and for Kulubnarti, Sai Island, Wadi Halfa, and Qinifab, only the adult mean and range for bone collagen values is reported for comparison. There is an evident shift in the collagen carbon values from a C_4 dominant diet to a more C_3/C_4 mixed diet from the Post-Meroitic to the Christian periods (Table 1), supporting the statistically significant difference previously found between periods in a pilot study conducted by Masoner et al. (2011) for 11 individuals from the Qinifab School site. However, no such pattern emerges for the apatite carbon values.

Controlled feeding experiments have demonstrated that the carbon isotope ratios in bone collagen primarily reflect the protein portion of the diet, while the values in carbonate reflect the whole diet (Ambrose and Norr, 1993; Jim et al., 2004; Tieszen and Fagre, 1993). The difference between the two is indicative of the proportion of protein in the diet—the smaller the difference, the greater the contribution of the protein component. The mean difference between the collagen and apatite carbon values increases significantly in the Christian period, suggesting that protein made up a smaller part of the diet (Table 1). This interpretation is also supported by the nitrogen data. There is a statistically significant decrease in nitrogen values between the Post-Meroitic and Christian periods (Table 1). This change is suggestive of a decline in the reliance on animal products over time. If the animals used during the Post-Meroitic period were primarily foddered on the native wild C_4 plants, this practice could also help to explain the decline seen in the collagen carbon values but not the carbonate carbon values.

Compared to other Sudanese sites (Buzon and Bowen, 2010; Iacumin et al., 2016; Raisor, 2020; Thompson et al., 2008; Turner et al., 2007; White, 1991), both the collagen and carbonate $\delta^{13}C$ values demonstrate that the inhabitants from the Qinifab School site were more reliant on C_4 resources than individuals at sites downriver (Table 6, Figure 8). Only the southernmost site, Al Khiday, located upriver and just south of modern Khartoum (Fig. 1), had comparable mean $\delta^{13}C_{AP}$ values (Fig. 8). At Al Khiday, there is remarkable continuity between the Meroitic period and the Neolithic (4500–4200 BCE) in the $\delta^{13}C$ values, and both are very similar to the Qinifab School sample, though the latter does have a greater range in values.

The northern sites are remarkably similar, despite the disparate temporal horizons represented. Winter crops like wheat and barley depended upon the annual inundation of the Nile, and the wider floodplains of the Dongola reach may have allowed a greater abundance of these crops to be cultivated compared to the narrower floodplain around the Qinifab School site. Additionally, Żurawski (2014) noted that there are far fewer archaeological finds associated with *saqia* agriculture from the fourth cataract region compared with sites farther downriver, which could have further limited the cultivation of these crops. However, these explanations are not satisfactory for comparison with the data from Kulubnarti, which also had a constricted floodplain and where there is no evidence for the use of *saqia* technology (Hibbs et al., 2011). In comparing carbon isotope values in soft tissue samples from Kulubnarti and Wadi Halfa, Basha and colleagues (2016) found that the former were slightly elevated compared to the latter and suggested more productive cultivation of C_3 crops at Wadi Halfa was responsible. The wild C_4 plants that dominated the Nubian landscape and C_4 grains like millet and sorghum are better adapted to hotter, dryer conditions (Fuller, 2014; Haaland, 2012).

Nitrogen values from bone samples are similar among the Qinifab School, Wadi Halfa, Kulubnarti, and Sai Island samples compared to the higher levels at Kerma. It is likely that this difference indicates a greater reliance on animal husbandry at Kerma, while the values at the other three sites reflect more intensive agriculture. The range of δ^{15}N values at Kerma (12.4-15.4‰) fall within the range (12.1-17.7‰) reported by Ambrose and DeNiro (1986) for groups with a primarily pastoralist economy from southern and eastern Africa, while δ^{15}N values at the other sites (see Table 6) are closer to the range (7.7-12.3‰) reported for primarily agricultural groups. Kerma was the urban capital of a state society, with better access to expanses of fertile land to facilitate the maintenance of large herds of animals. Cattle in particular were regarded as socially and ritually important at Kerma, and considered signifiers of status (Chaix et al., 2012). Additionally, Kerma is by far the oldest of the sites for which nitrogen data are available (Edwards, 2004; Fuller, 2014), in a period when agriculture was less intensive. At both

Wadi Halfa and the Qinifab School site, δ^{15}N values decline over time, reaching their lowest point during the Christian period.

Of the sites under discussion, only the isotopic data from Wadi Halfa covers all the temporal horizons represented by the Qinifab data. Although there is a greater reliance overall on C_4 resources at Qinifab compared to Wadi Halfa, a similar pattern of increased incorporation of C_3 resources in the Christian period can be observed in both places. As discussed above, both samples also show a decline in δ^{15}N values over time, which may be a result of the broad trend toward intensification of crop agriculture. The consistency of these isotopic trends despite the geographic distances is striking and suggests the influence of broader cultural and sociopolitical factors in both areas.

White and Schwarcz (1994) observed lower $\delta^{13}C_{COLL}$ values in both the Meroitic and Christian period compared to the period between them (known as the Ballana period in Lower Nubia versus Post-Meroitic period in Upper Nubia), and hypothesized that the decline of the Meroitic empire resulted in a decline in the importation of C_3 crops like wheat and barley, and/or less demand for the export of these crops. The increased reliance on C_4 plants in the Ballana period may also have been influenced by drier conditions created by lower Nile levels (White and Schwarcz, 1994).

No individuals from the Meroitic period were incorporated in this study. Previous work by Masoner and colleagues (2011), however, did produce a $\delta^{13}C_{AP}$ value for one individual from the Meroitic period. The bone carbonate value of -3.6‰ is within the range of the $\delta^{13}C_{AP}$ values in this study, although it is considerably elevated above the mean. It is difficult to assess this result without additional data from the Meroitic period, but it does suggest that the greater reliance on C_4 plants compared to other sites has a long history in the region, and may even have been more pronounced in earlier periods. This trend is the opposite of that observed by Iacumin and colleagues (1998), in which $\delta^{13}C$ values in the area near Kerma were found to be highest at Christian period Koya, suggesting increasing C_4 input over time.

Diet and Demography at Qinifab

Demographic differences are also observed in the isotopic data. A statistically significant difference is found between males and females in $\delta^{15}N$, $\delta^{13}C_{COLL}$, and $\delta^{13}C_{COLL-AP}$, when time periods are pooled (Table 3). Examination of the mean values given in Table 1 shows virtually no difference between males and females during the Post-Meroitic period; it is only during the Christian period that mean values diverge somewhat. When time periods are tested separately, however, no statistically significant differences are found in either time period. The differences between males and females in the pooled sample most likely reflect the differences in sample demographics between the two periods, rather than suggesting pronounced differences in access to protein sources between the sexes. The similarity in $\delta^{15}N$ and $\delta^{13}C_{COLL-AP}$ suggest similar access to animal products between the sexes for both time periods.

No differences in isotope values by sex were reported at Kerma (Iacumin et al., 1998; Thompson et al., 2008) or Kulubnarti (Basha et al., 2016; Turner et al., 2007). At Wadi Halfa, White and Schwarcz (1994) found that $\delta^{15}N$ values were higher in males than females during the Meroitic and Ballana periods, though not during the Christian period. During the Meroitic period only, females had higher $\delta^{13}C_{COLL}$ values, indicating a greater C_4 contribution to their diet. At a Meroitic period cemetery on Sai Island, Brock (2019) found that males had a slightly larger C_4 proportion in their diets, but also a greater range of values overall. No clear pattern in dietary sex differences is evident in comparing the Qinifab School site to other Nubian sites.

Finally, the effects of age on diet are also explored. Because breastfeeding infants are consuming their mothers' tissues, they exhibit elevated $\delta^{15}N$ values due to the trophic level effect (Fuller et al., 2006). In examining the preadult $\delta^{15}N$ values shown in Figure 5, there are only two individuals (both around 3 years old) with nitrogen values elevated over one standard deviation above the adult female (Christian period) mean. Three other individuals of presumed weaning age (2-3 years) show values above the mean, but still within one standard deviation. It is difficult to draw broad conclusions about weaning practices from such a small sample size. Moreover, because these preadults are non-survivors, it cannot be assumed that they represent "normal" weaning behavior (Wood et al., 1992). The evidence here suggests that weaning behavior was variable, and that in at least some cases breastfeeding continued to at least 3 years of age. This observation is comparable to the findings of weaning studies at other Nubian sites. At Wadi Halfa, assessment of both $\delta^{15}N$ and $\delta^{18}O$ values indicated that weaning was complete by around age three (White, 1991; White et al., 2004b). At Christian period Kulubnarti, both cross-sectional sampling of bone collagen and apatite and high-resolution serial dentine sampling indicate considerable interindividual variation in weaning practices, with weaning concluding between the ages of ~2 and ~5 years (Sandberg, 2012; Sandberg et al., 2014; Turner et al., 2007). At Meroitic period Sai Island, Gregoire (2019) estimated based on analysis of bone collagen that preadults were weaned between 2 and 4 years, while Eerkens and colleagues (2018) estimated an average weaning age of 2.7 years based on serial dentine sampling. Both studies also noted variation among individuals.

Diet and Pathology at Qinifab

In addition to the dietary change suggested by the isotope data, a statistically significant increase in the frequency of cribra orbitalia is observed between the Post-Meroitic and Christian periods (Fig. 6). There is no change in the frequency of porotic hyperostosis, which is present in 67 of the 72 adults in the collection. When porotic hyperostosis and cribra orbitalia manifest from marrow hyperplasia, cribra orbitalia should appear at an earlier age than porotic hyperostosis, based on the pattern of marrow conversion in the skull (Brickley, 2018). If the two lesions arose from a shared etiology at the Qinifab School site, the data suggest that conditions were more variable for younger children than for older children. Suggested etiologies for the marrow hyperplasia associated with these lesions include iron-deficiency anemia (Stuart-Macadam, 1987), and megaloblastic anemia, which is most commonly caused by Vitamin B_{12} deficiency or folic acid deficiency (Walker et al., 2009). These deficiencies are most common in individuals who consume no or limited amounts of animal products (Olivares et al., 1999; Walker et al., 2009). Nursing infants are the most susceptible to developing these conditions and experiencing the most pronounced effects. These deficiencies may also be caused or exacerbated by gastrointestinal distress, which can be produced by any number of bacterial, viral or parasitic agents, and are most dangerous to very young children (Briend et al., 2015; Ehrhardt et al., 2006; Kossmann et al., 2000; Olivares et al., 1999).

Previous work on this collection indicates that individuals with cribra orbitalia were more likely to die as preadults, and preadults with active/healing lesions were more likely to have stunted growth (see Chapter 3).

The isotopic evidence suggests that the consumption of animal products declined between the Post-Meroitic and Christian periods; therefore, a dietary etiology seems the most likely explanation for the increase in cribra orbitalia, although other factors cannot be discounted. When the isotopic values for adults with healing cribra orbitalia lesions are compared to those without lesions or with fully healed lesions, there is a statistically significant difference in $\delta^{13}C_{COLL}$ and $\delta^{13}C_{COLL\text{-}AP}$. Although the greater $\delta^{13}C_{COLL\text{-}AP}$ among those with healing lesions would seem to support the dietary etiology hypothesis, it is perplexing that no such difference is found in the nitrogen values, such as White (1991) observed. Nutritional stress, however, can cause an elevation in $\delta^{15}N$, so it is possible that the trophic level effect could be masked (Fuller et al., 2005). In addition, White and Armelagos (1997) found that females with osteopenia had significantly elevated nitrogen levels; clearly, the relationship between diet, pathology, and $\delta^{15}N$ is not simple or straightforward to interpret.

Preadults with porotic hyperostosis have lower $\delta^{15}N$ on average than their unaffected peers, but this difference is not statistically significant (p=0.051). As shown in Figure 5, there is a clear relationship between porotic hyperostosis and age, wherein no individuals under the age of 6 have the lesion in this sample. It appears that the higher $\delta^{15}N$ values of the unaffected has been skewed due to the breastfeeding signature present in two of the younger preadults. The absence of a difference in isotopic values between those with and without porotic hyperostosis suggests that the etiology of this lesion is unlikely to be dietary, unlike cribra orbitalia. Expansion of agriculture and irrigation systems can increase exposure to parasites (Alvrus, 2006; Hibbs et al., 2011). However, if this increased parasite exposure were implicated in the change in CO frequency, it seems somewhat inexplicable that PH frequency did not also change over time. Additionally, rates of porotic hyperostosis did not change over time the way both cribra orbitalia rates and diet did. The etiology of porotic hyperostosis may be connected more to age-related differences in exposure to infectious agents, such as parasites. For instance, Alvrus (2006) found that young preadults at Semna South also had the lowest rates of schistosome infection. In addition, the mean age of linear enamel hypoplasia in this collection is 4.1 years, which may corroborate the idea that exposure increases post-weaning. Similarly, Ritzman and colleagues (2008) suggested increased parasite exposure for their observation of a peak in LEH formation around 4.5-5.5 years when calculated using the Reid and Dean's (2006) histological analyses.

Conclusion

The isotopic evidence at the Qinifab School site suggests a change in dietary protein sources between the Post-Meroitic and Christian periods, and a reduced consumption of animal products. This finding is consistent with a trend toward crop agriculture intensification over time observed at other Nubian sites. There is a pattern through the Nile Valley that sites farther upriver (south) show greater reliance on C4 resources during the Meroitic to Christian periods in comparison to downriver (northern) sites. It is interesting to note that the isotopic values from the Qinifab School site are more similar to Neolithic and Meroitic Al Khiday, south of the sixth cataract, than they are to contemporaneous sites downstream (Fig. 1).

Agricultural practices have often been implicated for high frequencies of cribra orbitalia and porotic hyperostosis at Nubian sites, but rarely have direct comparisons been made between isotopic and paleopathological data. At the Qinifab School site, increased rates of cribra orbitalia in the Christian period accompanied the change in diet revealed by the isotopic data. This finding would seem to provide compelling circumstantial evidence in support of the interpretation that reduced protein intake was directly responsible for the increase in nutritional deficiencies in this period, as other studies have suggested. However, at an individual level, direct correlations between diet and the presence or active status of a lesion did not show the expected difference in nitrogen isotope ratios predicted by this hypothesis. Further complicating matters, porotic hyperostosis rates remained constant over time, suggesting that the development of these lesions was unaffected by the change in diet. In any case, even if the increase in cribra orbitalia in the Christian period is not directly causally linked to a change in subsistence strategy, the contemporaneous shift in both diet and morbidity point to a period of social change in the region with implications for preadult health.

Author Contributions

ALN: drafting and editing of manuscript, collection of paleopathological data, collecting and processing samples for isotopic analysis, statistical analysis and interpretation. BJB: conceptualization, funding acquisition, supervision, data acquisition and curation, drafting, review, and editing of manuscript. KK: laboratory protocols for isotopic sample processing, review and editing of manuscript. NZ: mass spectrometry analysis, review of manuscript.

Tables and Figures

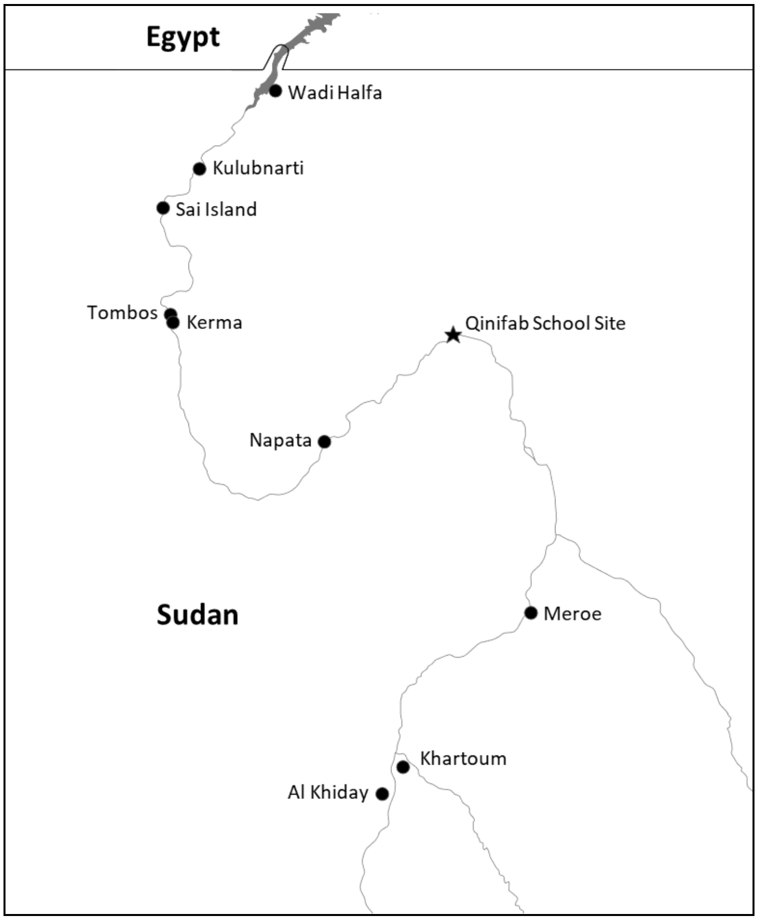

Figure 5 Map of Sudan showing the Qinifab School site and other sites mentioned in the text

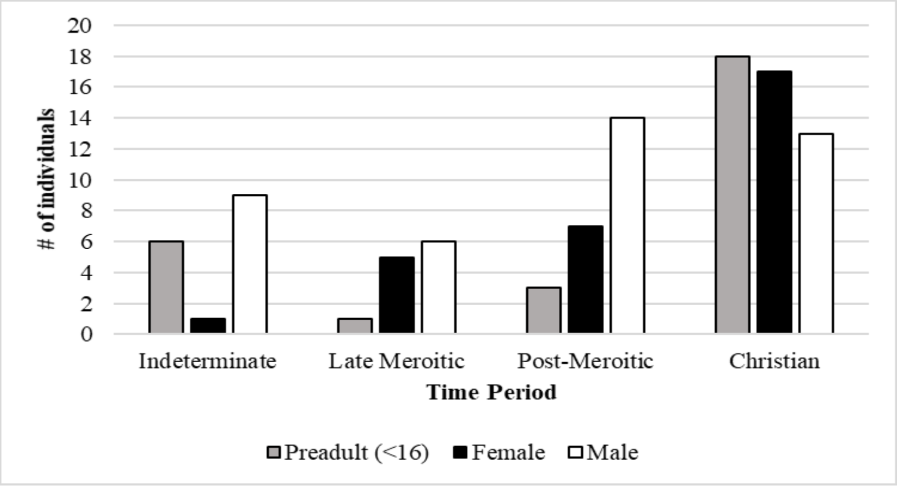

Figure 2 Qinifab School site demographics by age, sex, and time period

Table 1 Descriptive statistics for isotopic analyses

		$\delta^{13}C_{COLL}$			$\delta^{13}C_{AP}$			$\delta^{13}C_{AP\text{-}COLL}$			$\delta^{15}N$		
		n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD
Post-Meroitic	Adult Females	3	-8.9	0.2	6	-7.9	2.8	3	2.2	1.9	3	11.9	1.1
	Adult Males	8	-8.8	1.0	12	-7.3	2.6	8	2.0	1.5	8	12.3	0.7
	Preadults (<16 yrs)	1	-8.8		2	-5.7	3.3	1	5.4		1	10.4	
	All	**12**	**-8.8**	**0.8**	**20**	**-7.3**	**2.6**	**12**	**2.3**	**1.7**	**12**	**12.0**	**0.9**
Christian	Adult Females	14	-12.8	1.7	14	-6.0	2.5	14	6.8	3.6	14	10.7	1.1
	Adult Males	8	-11.3	1.6	10	-6.4	1.8	8	4.5	2.6	8	11.6	1.1
	Preadults (<16 yrs)	11	-12.6	1.5	15	-7.3	1.2	11	5.1	1.3	11	11.0	0.8
	All	**33**	**-12.4**	**1.7**	**39**	**-6.6**	**2.0**	**33**	**5.7**	**2.9**	**33**	**11.0**	**1.0**
All Periods	Adult Females	17	-12.1	2.2	20	-6.6	2.7	17	6.0	3.8	17	10.9	1.2
	Adult Males	16	-10.0	1.8	22	-6.9	2.2	16	3.2	2.4	16	11.9	1.0
	Preadults (<16 yrs)	13	-12.3	1.7	18	-7.1	1.5	13	5.1	1.2	13	11.0	0.8
Total Sample		**46**	**-11.4**	**2.2**	**60**	**-6.9**	**2.2**	**46**	**4.8**	**3.0**	**46**	**11.3**	**1.1**

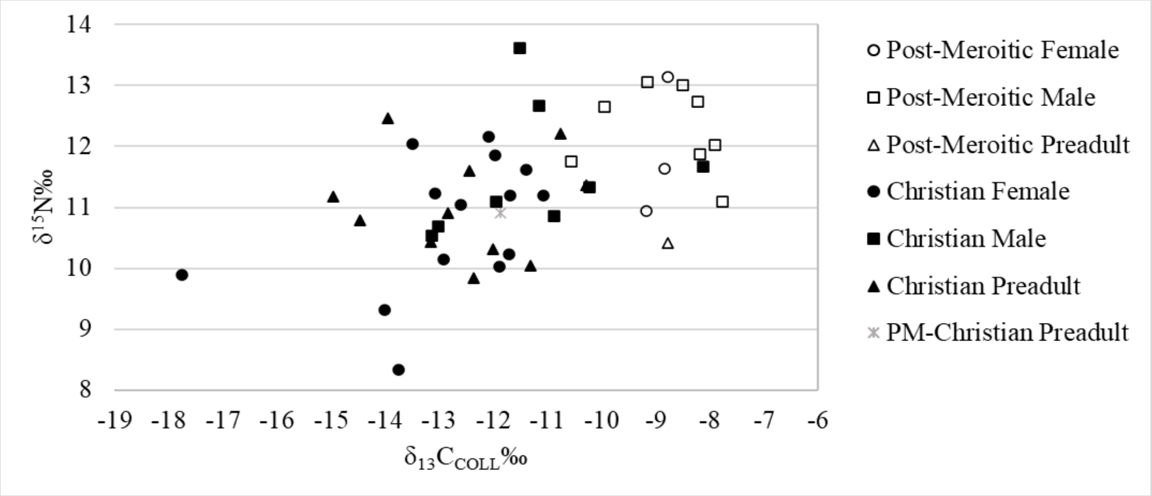

Figure 3 $\delta^{13}C_{COLL}$ and $\delta^{15}N$ by time period and demographic

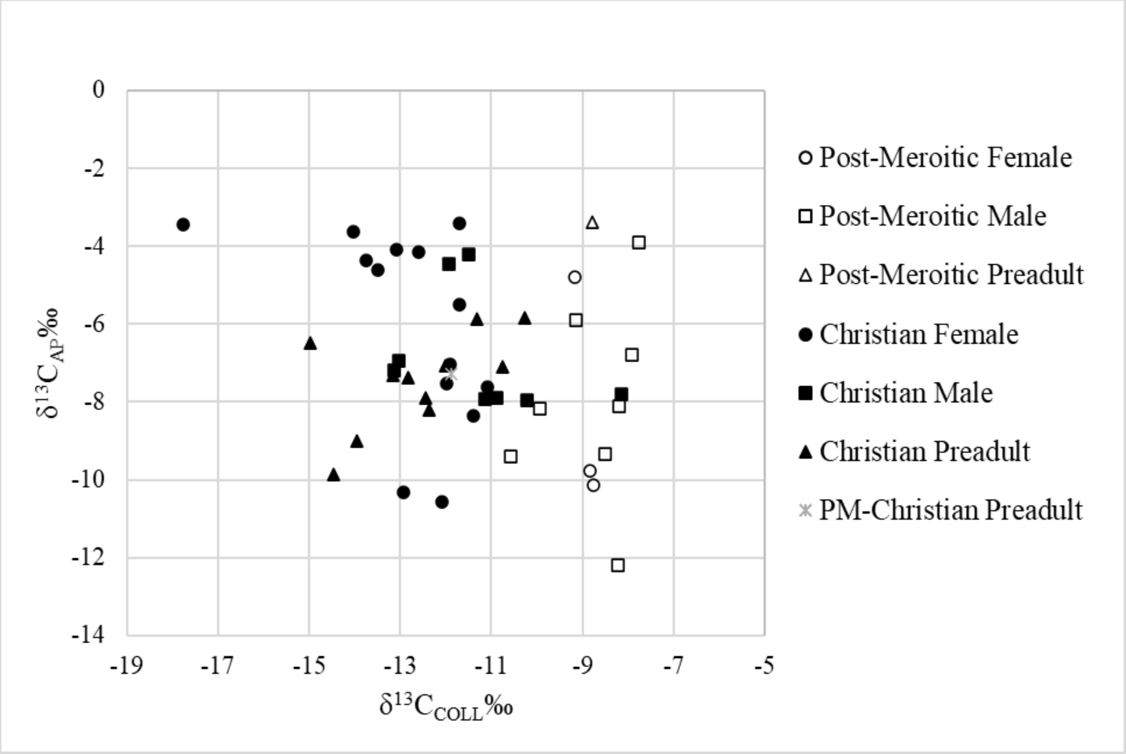

Figure 4 $\delta^{13}C_{COLL}$, and $\delta^{13}C_{AP}$ by time period and demographic

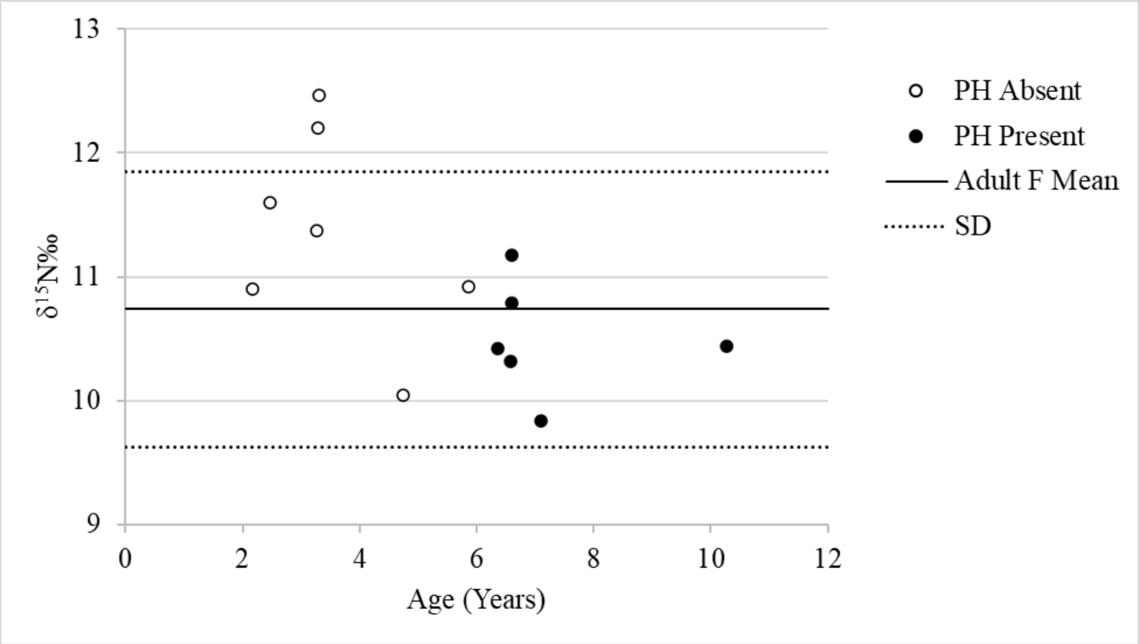

Figure 5 Preadult δ^{15}N values shown by age, and presence or absence of porotic hyperostosis, with lines representing mean and standard deviation for adult female values

Table 2 Independent samples t-test for mean isotope values by time period

	t-test for Equality of Means								
								95% Confidence Interval of the Difference	
	Sample	N	t	df	Sig. (2-tailed)	Mean Diff.	Std. Error Diff.	Lower	Upper
$\delta^{13}C_{COLL}$	*All*	*46*	6.969	43	**0.000**	3.547	0.509	2.521	4.574
	5+	*40*	6.849	37	**0.000**	3.644	0.532	2.566	4.722
$\delta^{13}C_{AP}$	*All*	*60*	-1.113	57	0.270	-0.671	0.603	-1.878	0.536
	5+	*50*	-1.201	47	0.236	-0.820	0.682	-2.192	0.553
$\delta^{13}C_{AP-COLL}$	*All*	*46*	-3.739	43	**0.001**	-3.329	0.890	-5.125	-1.533
	5+	*40*	-3.627	37	**0.001**	-3.532	0.974	-5.505	-1.559
$\delta^{15}N$	*All*	*46*	2.941	43	**0.005**	1.000	0.340	0.314	1.686
	5+	*40*	3.073	37	**0.004**	1.090	0.355	0.371	1.808

Table 3 Independent samples Mann-Whitney U test for isotope values by sex and time period

	All	PM	C
$\delta^{13}C_{COLL}$	**0.003**	0.497	0.05
$\delta^{13}C_{AP}$	0.821	0.385	0.585
$\delta^{13}C_{AP\text{-}COLL}$	**0.021**	0.776	0.11
$\delta^{15}N$	**0.031**	0.63	0.238

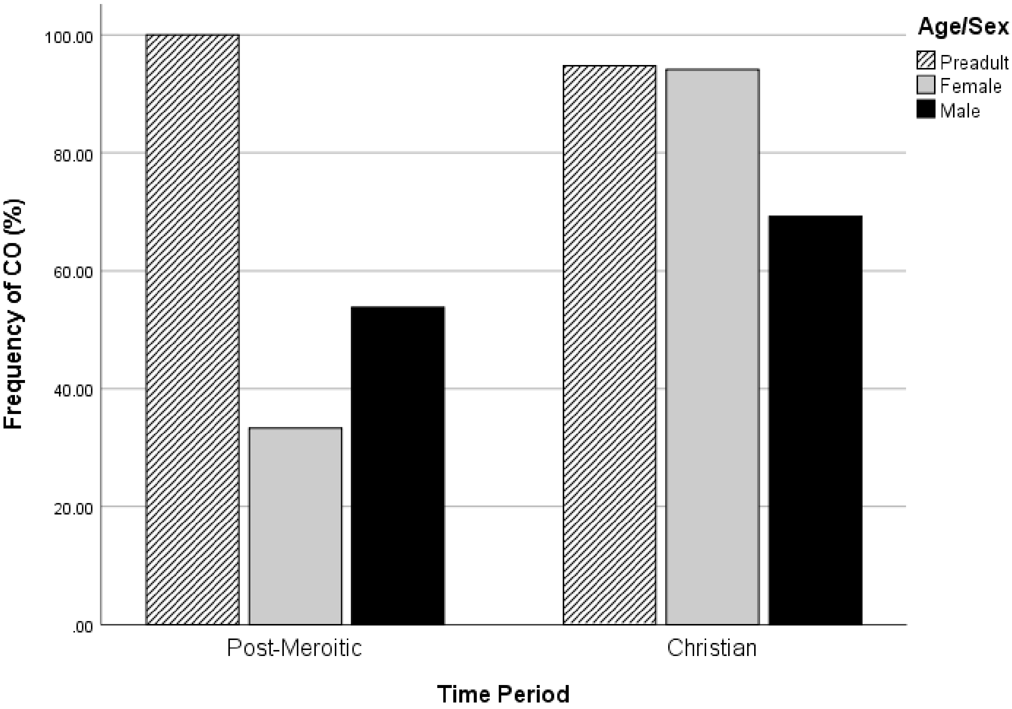

Figure 6 Frequency of cribra orbitalia by time period and demographic

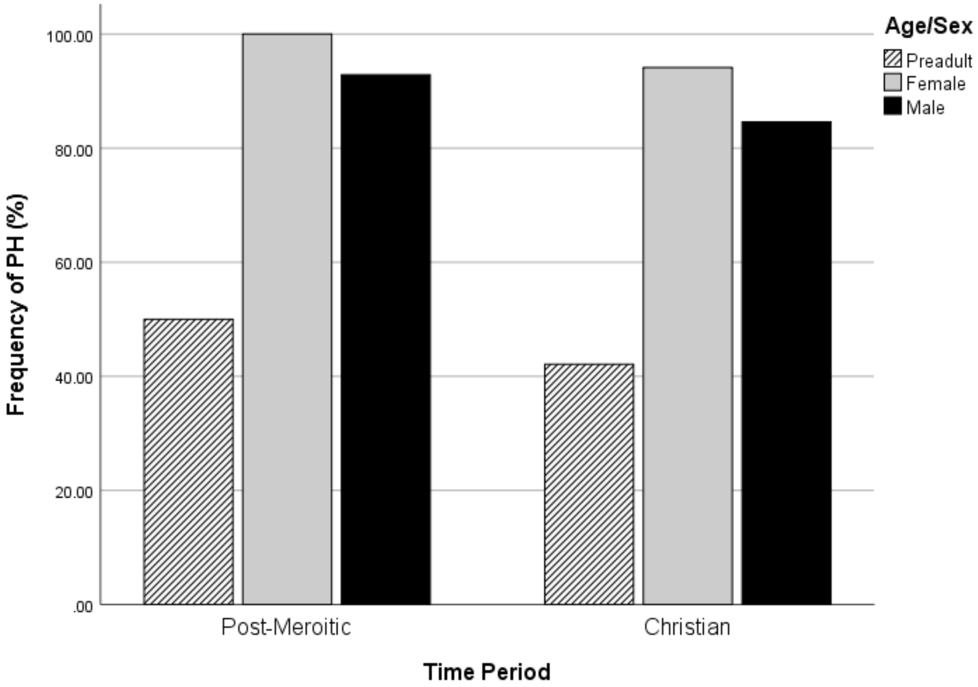

Figure 7 Frequency of porotic hyperostosis by time period and demographic

Table 4 Independent samples t-test for isotopic values in individuals with and without CO

	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						Lower	Upper
$\delta^{15}N$	0.904	44	0.371	0.364	0.403	-0.448	1.176
$\delta^{13}C_{COLL}$	3.468	44	**0.001**	2.490	0.718	1.043	3.936
$\delta^{13}C_{AP}$	-0.103	15	0.919	-0.090	0.870	-1.946	1.767
$\delta^{13}C_{AP\text{-}COLL}$	-1.850	44	0.071	-1.991	1.076	-4.160	0.178

Table 5 Independent samples t-test for isotopic values in adults with partially active cribra orbitalia lesions vs adults without active lesions

	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						Lower	Upper
$\delta^{15}N$	0.554	31	0.584	0.264	0.477	-0.709	1.238
$\delta^{13}C_{COLL}$	2.526	31	**0.017**	2.131	0.844	0.410	3.851
$\delta^{13}C_{AP}$	-0.560	40	0.579	-0.497	0.887	-2.290	1.296
$\delta^{13}C_{AP\text{-}COLL}$	-2.065	31	**0.047**	-2.750	1.332	-5.466	-0.034

Table 6 Comparison of isotopic data from different sites in Sudan

Site	**Time Period**	**$\delta^{13}C_{COLL}$**			**$\delta^{13}C_{AP}$**			**$\delta^{15}N$**		
		Mean	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Wadi Halfa	Meroitic	-18.3	-20.7	-15.5				12.0	10.2	13.6
	Post-Meroitic	-16.8	-19.4	-11.3				11.4	9.1	13.5
	Christian	-18.1	-21.3	-15.9				10.3	8.7	12.7
Kulubnarti	Christian	-17.6	-19.7	-11.8	-11.8	-13.7	-7.4	10.4	7.3	14.8
Sai Island	Meroitic	-16.7	-18.5	-15.2				11.6	10.0	13.2
Kerma	Kerma	-17.7	-19.9	-11.9				13.9	12.4	15.4
Tombos	Egyptian Coloniz-ation				-11.8	-13.4	-7.2			
Qinifab School	Post-Meroitic	-8.8	-10.6	-7.8	-7.5	-12.2	-3.5	12.2	10.9	13.1
	Christian	-12.3	-17.8	-8.1	-6.2	-10.6	-3.2	11.0	8.3	13.6
Al Khiday	Pre-Mesolit-hic				-2.7	-5.8	-0.2			
	Neolithic				-6.9	-8.2	-5.1			
	Meroitic				-7.0	-9.0	-4.2			
Sources (in order of site listing): White, 1991; Turner et al., 2007; Raisor, 2020; Thompson et al., 2008; Buzon and Bowen, 2010; Iacumin et al., 2016										

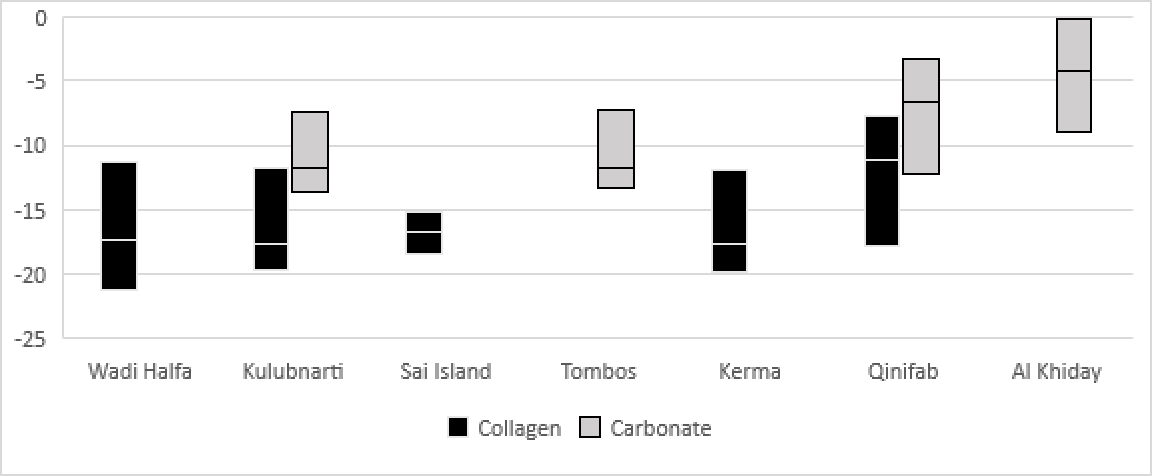

Figure 8 Comparison of carbon isotope data from different sites in Sudan, shown from north (left) to south (right)

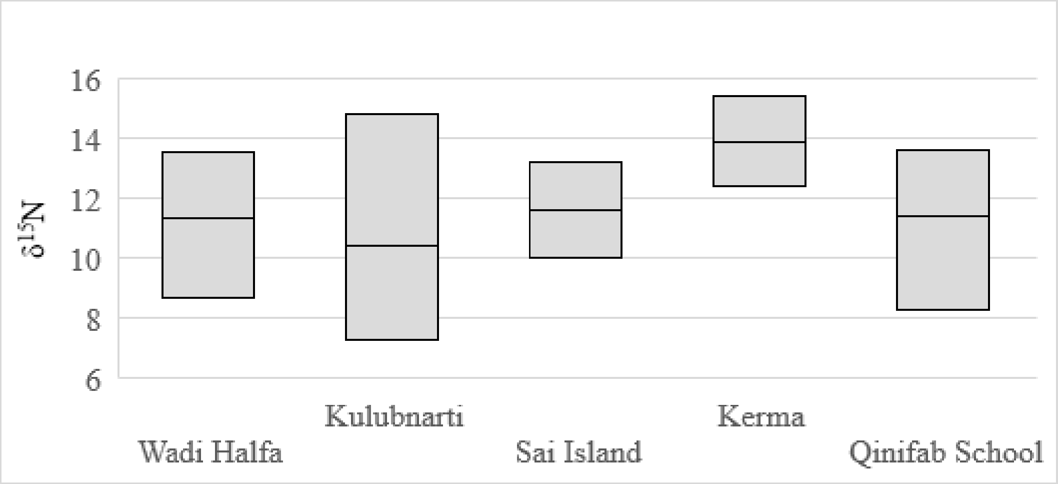

Figure 9 Comparison of nitrogen isotope data from different sites in Sudan, shown from north (left) to south (right)

CHAPTER 5

CONCLUSION

The three articles that compose this dissertation explore different dimensions of stress in an ancient Nubian skeletal collection from the Qinifab School site, Sudan, through a combination of osteological, paleopathological, and biogeochemical methods. The first article tested two hypotheses: 1) individuals with delayed skeletal development also had reduced body size dimensions, and 2) individuals with normal development are more likely to match the WHO growth standards than individuals with delayed development. While the latter is supported by the analysis, the former is somewhat ambiguous. A statistically significant association was found between stunting and delayed development, but not between wasting and stunting or wasting and delayed development. There is nothing to suggest that impaired growth affected adult stature, suggesting that preadults who experienced growth delays tended either to die before reaching adulthood or experienced catch-up growth in later adolescence. The estimated growth trajectory for preadults at the Qinifab School site matched the WHO standards more closely than the growth trajectories for Wadi Halfa and Kulubnarti did, and the al-Qinifab adults were among the tallest when compared to other sites across the Nile Valley. This result suggests that conditions for preadults at the Qinifab School site may have been more favorable than those at comparable sites. However, further work on the biocultural context and biological distance among these populations is required to elucidate these differences more fully.

The second article examined three questions: 1) Were those who suffered systemic stress in early life more susceptible to additional or more severe signs of morbidity? 2) Did those who suffered stress early in life then suffer earlier mortality? 3) Does suffering stress in early life have consequences for growth outcomes? The results suggest that different nonspecific indicators of stress are not equally reliable as indicators of individual frailty, and that timing of lesion formation may be more significant than quantity of lesions formed. Cribra orbitalia was found to be the strongest indicator of underlying frailty, in that those with active lesions were more likely to die at younger ages. Furthermore, it was the only lesion associated with growth faltering, although the presence or severity of the lesion was not associated with reduced body dimensions in adults.

The third article identified two temporal trends: a change in diet between the Post-Meroitic and Christian periods, and an increase in the frequency of cribra orbitalia. Decreased $\delta^{13}C_{COLL}$ values indicate an increased reliance on C_3 plants relative to C_4 plants over time, while a decrease in $\delta^{15}N$ and an increase in the $\delta^{13}C_{AP\text{-}COLL}$ difference suggests decline in reliance on animal products, possibly in accordance with an intensification of crop agriculture. This combination of factors provides circumstantial evidence that the increase in cribra orbitalia, a symptom of nutritional deficiency, may have resulted from reduced protein consumption. At an individual level, however, no direct correlation was found between nitrogen isotope ratios and the presence or active status of a lesion. This result may be because the isotopic values reflect diet over the last few years of an individual’s life, whereas cribra orbitalia is a lesion formed in early childhood. Finally, porotic hyperostosis, similarly associated with nutritional deficiency, remained constant over time. Different etiologies, thus, may underlie these two lesions.

Support for the DOHaD hypothesis is limited in this collection. Most of the nonspecific indicators of stress analyzed do not provide a straightforward proxy for elucidating underlying frailty. However, one element that is of particular interest concerns the findings related to cribra orbitalia. The isotope results suggest an etiology related to diet or changing agricultural practices. The effects were consequential: those who developed the lesion were more likely to die younger and have impaired growth. However, many people in this collection survived to adulthood in spite of having suffered multiple stress episodes in childhood. Although there is evidence for growth faltering in those who died as preadults, those who lived to adulthood show no evidence of growth stunting and were in fact taller on average than many other sampled groups in the region. Most individuals in the Qinifab School site sample have multiple indicators of physiological stress recorded in their skeletons. Nevertheless, many of them survived well into adulthood and either never experienced growth faltering or experienced catch-up growth in adolescence. These studies speak to the complexity of teasing out the causes, effects, and interactions among stress, growth, and diet, and the relationship between stress indicators and frailty.

This study only incorporates isotopic data derived from bone collagen and carbonate, which has some disadvantages. Bone is a tissue that regenerates throughout an individual's life, meaning that isotope ratios from bone collagen will only reflect the last few years prior to death. In order to better understand the relationship between diet and nonspecific indicators of stress that form in early life, it would be useful to incorporate tooth enamel and dentine, tissues that form in the first few years of life and do not regenerate once formed. Therefore, they contain a record of dietary information from that period of the individual’s life. For added precision, intra-tooth serial microsampling of dentine could be used in future work. This technique involves taking multiple samples from the same tooth and can thus be used to track dietary changes during the critical period of weaning. Evaluating inter-individual differences in weaning behavior, weanling diet, and post-weaning diet could shed more light on the factors influencing the development on stress indicators in the Qinifab School site collection.

REFERENCES

Adams, W. Y. (1977). Nubia Corridor to Africa. Princeton: Princeton University Press.

Adamson, P. B. (1973). Schistosomiasis in antiquity. *Medical History*, *20*(2), 176–188. https://doi.org/10.1017/S0025727300022237

Ahmed, S. M. (2003). Merowe Dam Archaeological Salvage Project (MDASP). *Sudan and Nubia*, *7*, 11–14.

Alderman, H., Hoddinott, J., & Kinsey, B. (2006). Long term consequences of early childhood malnutrition. *Oxford Economic Papers*, *58*(3), 450–474. https://doi.org/10.1093/oep/gpl008

Alvrus, A. B. (2006). *The Conqueror Worm: Schistosomiasis in Ancient Nubia*. Arizona State University.

Ambrose, S. H. (1990). Preparation and characterization of bone and tooth collagen for isotopic analysis. *Journal of Archaeological Science*, *17*(4), 431–451.

Ambrose, S. H. (1991). Effects of diet, climate and physiology on nitrogen isotope abundances in terrestrial foodwebs. *Journal of Archaeological Science*, *18*(3), 293–317.

Ambrose, S. H., & Deniro, M. J. (1986). Reconstruction of African human diet using bone collagen carbon and nitrogen isotope ratios. *Nature*, *319*(6051), 321–324. https://doi.org/10.1038/319321a0

Ambrose, S. H., & Norr, L. (1993). Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In J. Lambert & G. Grupe (Eds.), *Prehistoric Human Bone: Archaeology at the Molecular Level* (pp. 1–37). Retrieved from http://link.springer.com/chapter/10.1007/978-3-662-02894-0_1

Amoroso, A., Garcia, S. J., & Cardoso, H. F. V. (2014). Age at death and linear enamel hypoplasias: Testing the effects of childhood stress and adult socioeconomic circumstances in premature mortality. *American Journal of Human Biology*, *26*(4), 461–468. https://doi.org/10.1002/ajhb.22547

Armelagos, G. J. (1968). *Paleopathology of Three Archaeological Populations from Sudanese Nubia*. University of Colorado.

Armelagos, G. J., & Van Gerven, D. P. (2017). *Life and Death on the Nile: A Bioethnography of Three Ancient Nubian Communities*. Gainesville: University

Press of Florida.

Armelagos, G. J., Dewey, J. R., & Bartley, M. (1968). Cribra orbitalia in Sudanese Nubian archaeological populations. *American Journal of Physical Anthropology, 29*(1), 131.

Armelagos, G. J., Goodman, A. H., Harper, K. N., & Blakey, M. L. (2009). Enamel hypoplasia and early mortality: Bioarcheological support for the Barker hypothesis. *Evolutionary Anthropology: Issues, News, and Reviews*, *18*(6), 261–271.

Armelagos, G. J., Huss-Ashmore, R., & Martin, D. L. (1982). Morphometrics as indicators of dietary stress in prehistoric Sudanese Nubia.pdf. *MASCA Journal*, *2*(1), 22–26.

Armelagos, G. J., Mielke, J. H., Owen, K. H., Van Gerven, D. P., Dewey, J. R., & Mahler, P. E. (1972). Bone growth and development in prehistoric populations from Sudanese Nubia. *Journal of Human Evolution*, *1*(1), 89–119. https://doi.org/10.1016/0047-2484(72)90049-8

Armelagos, G. J., Van Gerven, D. P., Martin, D. L., & Huss-Ashmore, R. (1984). Effects of nutritional change on the skeletal biology of northeast African (Sudanese Nubian) populations. In J. Clark & S. Brandt (Eds.), *From Hunters to Farmers: The Causes and Consequences of Food Production in Africa* (pp. 132–146). Berkeley: University of California Press.

Aufderheide, A. C., & Rodriguez-Martin, C. (1998). *The Cambridge Encyclopedia of Human Paleopathology*. Cambridge: Cambridge University Press.

Baker, B. J. (1992). *Collagen Composition in Human Skeletal Remains from the NAX Cemetery (A.D. 350-550) in Lower Nubia*. University of Massachusetts, Amherst.

Baker, B. J. (1997). Contributions of biological anthropology to the understanding of ancient Egyptian and Nubian societies. In J. Lustig (Ed.), *Anthropology and Egyptology: A Developing Dialogue* (pp. 106–116). Sheffield: Sheffield Academic Press.

Baker, B. J. (2008). Post-Meroitic to early Christian period mortuary activity at Ginefab: The 2007 field season of the UCSB-ASU Fourth Cataract Project. In B. Gratien (Ed.), *Actes de la 4e Conférence Internationale sur L'Archéologie de la 4e Cataracte du Nil* (pp. 217–224). Villeneuve-d'Ascq: Cahiers De Recherches De L'Institut De Papyrologie Et D'Égyptologie De Lille, Suppl. 7. Université Charles-de-Gaulle-Lille 3, Lille, France.

Baker, B. J. (2014). Tracking transitions in the fourth cataract region of el-Ginefab: Results of the Arizona State University fieldwork. In J. R. Andersen & D. A.

Welsby (Eds.), *The Fourth Cataract and Beyond: Proceedings of the 12th International Conference for Nubian Studies* (pp. 841–855). Leuven: Peeters.

Baker, B. J. (2016). Biocultural investigations of ancient Nubia. In M. Zuckerman & D. L. Martin (Eds.), *New Directions in Biocultural Anthropology* (pp. 181–200). Hoboken: Wiley-Blackwell.

Baker, B. J., & Judd, M. A. (2012). Development of Paleopathology in the Nile Valley. In J. E. Buikstra & C. A. Roberts (Eds.), *The Global History of Paleopathology: Pioneers and Prospects* (pp. 209–234). Oxford: Oxford University Press.

Baker, B. J., & Schellinger, S. M. (2017). The Qatar-Sudan Archaeological Project - Fourth Cataract Preliminary Investigation of a Recently Discovered Fort in the ASU BONE Concession near el-Qinifab, Sudan. *Sudan & Nubia, 21*, 169–176.

Baker, B. J., Dupras, T. L., & Tocheri, M. W. (2005). *The Osteology of Infants and Children*. College Station: Texas A&M University Press.

Bangsgaard, P. (2014). Animal Deposits at H29, a Kerma Ancien cemetery in the Northern Dongola Reach. *Sudan and Nubia*, *18*, 20–25.

Bañuls, A. L., Hide, M., & Prugnolle, F. (2007). Leishmania and the Leishmaniases: A Parasite Genetic Update and Advances in Taxonomy, Epidemiology and Pathogenicity in Humans. *Advances in Parasitology*, *64*. https://doi.org/10.1016/S0065-308X(06)64001-3

Barakat, R. M. R. (2013). Epidemiology of Schistosomiasis in Egypt: Travel through Time: Review. *Journal of Advanced Research*, *4*(5), 425–432.

Barker, D J. (2004). The Developmental Origins of Adult Disease. *Journal of the American College of Nutrition*, *23*(sup6), 588S-595S. https://doi.org/10.1080/07315724.2004.10719428

Barker, David J, & Osmond, C. (1986). Infant mortality, childhood nutrition, and ischaemic heart disease in England and Wales. *The Lancet*, *327*(8489), 1077–1081.

Barker, David J. (2007). The origins of the developmental origins theory. *Journal of Internal Medicine*, *261*(5), 412–417.

Basha, W. A., Chamberlain, A. T., Zaki, M. E., Kandeel, W. A., & Fares, N. H. (2016). Diet reconstruction through stable isotope analysis of ancient mummified soft tissues from Kulubnarti (Sudanese Nubia). *Journal of Archaeological Science: Reports*, *5*(February), 71–79. https://doi.org/10.1016/j.jasrep.2015.10.036

Basha, W. A., Lamb, A. L., Zaki, M. E., Kandeel, W. A., Fares, N. H., & Chamberlain, A. T. (2018). Dietary seasonal variations in the Medieval Nubian population of

Kulubnarti as indicated by the stable isotope composition of hair. *Journal of Archaeological Science: Reports*, *18*, 161–168. https://doi.org/10.1016/j.jasrep.2018.01.010

Beldados, A., Manzo, A., Murphy, C., Stevens, C. J., & Fuller, D. Q. (2018). Evidence of sorghum cultivation and possible pearl millet in the second millenium BCE at Kassala, Eastern Sudan. In A. Mercuri, A. Hohn, & A. C. D'Andrea (Eds.), *Plants and People, Progress in African Archaeobotany*. New York: Springer.

Bianchi, R. S. (2004). *Daily Life of the Nubians*. Santa Barbara: Greenwood Publishing Group.

Bianucci, R., Mattutino, G., Lallo, R., Charlier, P., Jouin-Spriet, H., Peluso, A., … Rabino Massa, E. (2008). Immunological evidence of Plasmodium falciparum infection in an Egyptian child mummy from the Early Dynastic Period. *Journal of Archaeological Science*, *35*(7), 1880–1885. https://doi.org/10.1016/j.jas.2007.11.019

Bogin, B. (1997). Evolution of childhood and contemporary sociopolitical challenges. In D. F. Roberts, P. Rudan, & T. Skaric-Juric (Eds.), *Growth and Development in the Changing World* (pp. 225–250). Zagreb: Croatian Anthropological Society.

Bogin, B. (1999). *Patterns of Human Growth* (2nd ed.). Cambridge: Cambridge University Press.

Bogin, B., & Varela-Silva, M. I. (2010). Leg length, body proportion, and health: A review with a note on beauty. *International Journal of Environmental Research and Public Health*, *7*(3), 1047–1075. https://doi.org/10.3390/ijerph7031047

Boldsen, J. L. (1997). Lasting consequences of episodes of ill health in early childhood - a study of a medieval village community. In D. F. Roberts, P. Rudan, & T. Skaric-Juric (Eds.), *Growth and Development in the Changing World* (pp. 167–193). Zagreb: Croatian Anthropological Society.

Bonnet, C. (1992). Excavations at the Nubian royal town of Kerma: 1975–91. *Antiquity*, *66*(252), 611–625. https://doi.org/10.1017/S0003598X00039338

Bonnet, C. (2014). Forty years research on Kerma cultures. In J. Anderson & D. A. Welsby (Eds.), *The Fourth Cataract and Beyond: Proceedings of the 12th International Conference for Nubian Studies* (pp. 81–93). Peeters: British Museum.

Bourke, J. B. (1971). The palaeopathology of the vertebral volumn in ancient Egypt and Nubia. *Medical History*, *15*(04), 363–375. https://doi.org/10.1017/S0025727300016914

Brahin, J., & Fleming, S. J. (1982). Children's health problems: Some guidelines for their occurrence in ancient Egypt.pdf. *MASCA Journal*, *2*(3), 75–81.

Breasted, J. (1908). Second Preliminary Report of the Egyptian Expedition. *The American Journal of Semitic Language and Literature*, *25*, 1–110.

Brickley, M. B. (2018). Cribra orbitalia and porotic hyperostosis: A biological approach to diagnosis. *American Journal of Physical Anthropology*, *167*(4), 896–902. https://doi.org/10.1002/ajpa.23701

Briend, A., Khara, T., & Dolan, C. (2015). Wasting and stunting--similarities and differences: Policy and programmatic implications. *Food and Nutrition Bulletin*, *36*(1), S15–S23. https://doi.org/10.1177/15648265150361S103

Brock, A. (2019). *The elite Meroitic experience on Sai Island, Sudan: using stable isotope analysis to identify patterns related to sex and age for the interpretation of social identiry*. University of Central Florida.

Brooker, S., Peshu, N., Warn, P., Mosobo, M., Guyatt, H., & March, K. (1999). The Epidemiology of Hookworm Infection and its Contribution to Anemia among Pre-School Children on the Kenya Coast. *Tran Saharan Research Tropical Medicine Hygiene*, *93*(March), 240–246.

Brothwell, D. R. (1981). *Digging Up Bones*. Oxford: Oxford University Press.

Brush, G., Harrison, G. A., & Waterlow, J. C. (1997). Effects of early disease on later growth, and early growth on later disease, in Khartoum infants. *Annals of Human Biology*, *24*(3), 187–195. https://doi.org/10.1080/03014469700004922

Buikstra, J. E., & Cook, D. C. (1980). Palaeopathology : An American Account. *Annual Review of Anthropology*, *9*, 433–470.

Buikstra, J. E., & Ubelaker, D. H. (1994). *Standards for data collection from human skeletal remains. Arkansas Archaeological Survey research series no. 44*. Fayetteville: University of Arkansas.

Buikstra, J. E., Baker, B. J., & Cook, D. C. (1993). What diseases plagued ancient Egyptians? A century of controversy considered. In W. Davies & R. Walker (Eds.), *Biological Anthropology and the Study of Ancient Egypt* (pp. 24–53). London: British Museum Press.

Buzon, M. R. (2006). Health of the non-elites at Tombos: Nutritional and disease stress in New Kingdom Nubia. *American Journal of Physical Anthropology*, *130*(1), 26–37. https://doi.org/10.1002/ajpa.20303

Buzon, M. R. (2014). Tombos during the Napatan period (~750-660 BC): Exploring the consequences of sociopolitical transitions in ancient Nubia. *International Journal of Paleopathology*, *7*, 1–7. https://doi.org/10.1016/j.ijpp.2014.05.002

Buzon, M. R., & Bowen, G. J. (2010). Oxygen and carbon isotope analysis of human tooth enamel from the New Kingdom site of Tombos in Nubia. *Archaeometry*, *52*(5), 855–868.

Buzon, M. R., & Judd, M. A. (2008). Investigating health at Kerma: Sacrificial versus nonsacrificial individuals. *American Journal of Physical Anthropology, 136*(1), 93–99. https://doi.org/10.1002/ajpa.20781

Cameron, N. (2012). The Human Growth Curve, Canalization and Catch-up Growth. In N. Cameron & B. Bogin (Eds.), *Human Growth and Development* (2nd ed., pp. 1–22). Cambridge: Academic Press.

Cantani, A. (2008). *Pediatric allergy, asthma and immunology*.

Cardoso, H. F. V. (2007). Environmental Effects on Skeletal Versus Dental Development: Using a Documented Subadult Skeletal Sample to Test a Basic Assumption in Human Osteological Research. *American Journal of Physical Anthropology*, *132*, 223–233.

Carlson, D. S., Armelagos, G. J., & van Gerven, D. P. (1974). Factors influencing the etiology of cribra orbitalia in prehistoric Nubia. *Journal of Human Evolution*, *3*(5), 405–410. https://doi.org/10.1016/0047-2484(74)90203-6

Carroll, G., Inskip, S., & Waters-Rist, A. (2018). Pathophysiological Stable Isotope Fractionation: Assessing the Impact of Anemia on Enamel Apatite δ18O and δ13C Values and Bone Collagen δ15N and δ13C Values. *Bioarchaeology International*, *2*(2), 117–146. https://doi.org/10.5744/bi.2018.1021

Chaix, L, & Honegger, M. (2015). New data on animal exploitation from the Mesolithic to the Neolithic periods in Northern Sudan. *Climate and Ancient Societies*, 197–214.

Chaix, Louis, Dubosson, J., & Honegger, M. (2012). Bucrania from the Eastern Cemetery at Kerma (Sudan) and the Practice of Cattle Horn Deformation. *Prehistory of Northeastern Africa, New Ideas and Discoveries, Studies in African Archaeology 11*, (Chaix 1994), 189–212.

Chisholm, B. S., Nelson, D. E., & Schwarcz, H. P. (1982). Stable-carbon isotope ratios as a measure of marine versus terrestrial protein in ancient diets. *Science*, *216*(4550), 1131–1132.

Cockburn, A., Barraco, R. A., Reyman, T. A., & Peck, W. H. (1975). Autopsy of an Egyptian Mummy. *Science*, *187*(4182), 1155–1160.

Cole, G., & Waldron, T. (2019). Cribra orbitalia: Dissecting an ill-defined phenomenon. *International Journal of Osteoarchaeology*, *29*, 613–621.

Conceição, E. L. N., & Cardoso, H. F. V. (2011). Environmental effects on skeletal versus dental development II: Further testing of a basic assumption in human osteological research. *American Journal of Physical Anthropology*, *144*(3), 463–470.

Cook, D. C. (1979). Part four: Subsistence base and health in prehistoric Illinois Valley: Evidence from the human skeleton. *Medical Anthropology*, *3*(1), 109–124. Retrieved from http://ejournals.ebsco.com/direct.asp?ArticleID=472EA1D63316F96D3739

Cowgill, L. W., & Hager, L. D. (2007). Variation in the development of postcranial robusticity: An example from ??atalh??y??k, Turkey. *International Journal of Osteoarchaeology*, *17*(3), 235–252. https://doi.org/10.1002/oa.882

Dabernat, H., & Crubézy, É. (2010). Multiple bone tuberculosis in a child from predynastic Upper Egypt (3200 BC). *International Journal of Osteoarchaeology*, *20*(6), 719–730. https://doi.org/10.1002/oa.1082

DeNiro, M. J., & Epstein, S. (1978). Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta*, *42*(5), 495–506.

DeNiro, M. J., & Epstein, S. (1981). Influence of diet on the distribution of nitrogen isotopes in animals. *Geochimica et Cosmochimica Acta*, *45*(3), 341–351.

DeWitte, S. N., & Hughes-Morey, G. (2012). Stature and frailty during the Black Death: the effect of stature on risks of epidemic mortality in London, A.D. 1348-1350. *Journal of Archaeological Research*, *39*(5), 1–18. https://doi.org/10.3174/ajnr.A1256.Functional

DeWitte, S. N., & Stojanowski, C. M. (2015). The Osteological Paradox 20 Years Later: Past Perspectives, Future Directions. *Journal of Archaeological Research*, *23*(4), 397–450. https://doi.org/10.1007/s10814-015-9084-1

Edwards, D. N. (2004). *The Nubian Past*. New York: Routledge.

Eerkens, J. W., de Voogt, A., Dupras, T. L., Francigny, V., & Greenwald, A. M. (2018). Early childhood diets on the Nile: δ13C and δ15N in serial samples of permanent first molars in an elite Meroitic population from Sai Island, Sudan. *International Journal of Osteoarchaeology*, *28*(5), 552–562. https://doi.org/10.1002/oa.2679

Ehleringer, J. R., & Rundel, P. W. (1989). Stable isotopes: History, units, and instrumentation. In P. W. Rundel, J. R. Ehleringer, & K. A. Nagy (Eds.), *Stable Isotopes in Ecological Research* (pp. 1–15). Berlin: Springer-Verlag.

Ehrhardt, S., Burchard, G. D., Mantel, C., Cramer, J. P., Kaiser, S., Kubo, M., … Mockenhaupt, F. P. (2006). Malaria, Anemia, and Malnutrition in African

Children—Defining Intervention Priorities. *The Journal of Infectious Diseases*, *194*(1), 108–114. https://doi.org/10.1086/504688

El Samani, E. F. Z., Willett, W. C., & Ware, J. H. (1988). Association of malnutrition and diarrhea in children aged under five years: A prospective follow-up study in a rural Sudanese community. *American Journal of Epidemiology*, *128*(1), 93–105.

Emberling, G. (2012). Archaeological Salvage in the Fourth Cataract, Northern Sudan (1991-2008). In M. Fisher, P. Lacovara, S. Ikram, & S. D'Auria (Eds.), *Ancient Nubia: African Kingdoms on the Nile* (pp. 71–77). Cairo: The American University in Cairo Press.

Ezeamama, A. E., McGarvey, S. T., Acosta, L. P., Zierier, S., Manalo, D. L., Wu, H. W., … Friedman, J. F. (2008). The synergistic effect of concomitant schistosomiasis, hookworm, and trichuris infections on children's anemia burden. *PLoS Neglected Tropical Diseases*, *2*(6). https://doi.org/10.1371/journal.pntd.0000245

Fares, N. H., Zaki, M. E., Kandeel, W. A., Chamberlain, A. T., & Basha, W. A. (2015). Hair nitrogen isotopic com positions as a dietary indicator of the protein intake in the Kulubnarti Nubian population. *Egyptian Journal of Experimental Biology*, *11*(2), 143–149.

Fisher, M. M. (2012). The History of Nubia. In M. Fisher, P. Lacovara, S. Ikram, & S. D'Auria (Eds.), *Ancient Nubia: African Kingdoms on the Nile* (pp. 10–44). Cairo: The American University in Cairo Press.

Foster, K., Chapman, S., & Johnson, K. (2004). MRI of the marrow in the paediatric skeleton. *Clinical Radiology*, *59*(8), 651–673. https://doi.org/10.1016/j.crad.2004.02.001

Friedman, J. F., Kanzaria, H. K., & McGarvey, S. T. (2005). Human schistosomiasis and anemia: The relationship and potential mechanisms. *Trends in Parasitology*, *21*(8), 386–392. https://doi.org/10.1016/j.pt.2005.06.006

Fuller, B. T., Fuller, J. L., Sage, N. E., Harris, D. A., O'Connell, T. C., & Hedges, R. E. M. (2004). Nitrogen balance and δ15N: why you're not what you eat during pregnancy. *Rapid Communications in Mass Spectrometry*, *18*(23), 2889–2896.

Fuller, B. T., Fuller, J. L., Sage, N. E., Harris, D. A., O'Connell, T. C., & Hedges, R. E. M. (2005). Nitrogen balance and δ15N: why you're not what you eat during nutritional stress. *Rapid Communications in Mass Spectrometry*, *19*(18), 2497–2506. https://doi.org/10.1002/rcm.2090

Fuller, B. T., Fuller, J., Harris, D., & Hedges, R. (2006). Detection of breastfeeding and weaning in modern human infants with carbon and nitrogen stable isotope ratios. *American Journal of Physical Anthropology*, *129*(2), 279–293.

Fuller, D. Q. (2004). Early Kushite Agriculture: Archaeobotanical Evidence from Kawa. *Sudan and Nubia*, *8*, 70–74.

Fuller, D. Q. (2014). Agricultural Innovation and State Collapse in Meroitic Nubia: The Impact of the Savannah Package. In C. J. Stevens, S. Nixon, M. A. Murray, & D. Q. Fuller (Eds.), *Archaeology of African plant use* (Vol. 61, pp. 165–177). Walnut Creek: Left Coast Press.

Gage, T. B., & Zansky, S. M. (1995). Anthropometric indicators of nutritional status and level of mortality. *American Journal of Human Biology*, *7*(6), 679–691. https://doi.org/10.1002/ajhb.1310070602

Gardner, M., Winter, P., & Barker, D. J. (1984). *Atlas of mortality from selected diseases in England and Wales 1968-1978*. Chichester: John Wiley & Sons.

Garland, C., Reitsema, L., Larsen, C. S., & Thomas, D. H. (2018). Early Life Stress at Mission Santa Catalina de Guale: An Integrative Analysis of Enamel Defects and Dentin Incremental Isotope Variation in Malnutrition. *Bioarchaeology International*, *2*(2), 75–94. https://doi.org/10.5744/bi.2018.1019

Giha, H. A., ElGhazali, G., A-Elgadir, T. M. E., A-Elbasit, I. E., Eltahir, E. M., Baraka, O. Z., … Elbashir, M. I. (2005). Clinical pattern of severe Plasmodium falciparum malaria in Sudan in an area characterized by seasonal and unstable malaria transmission. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *99*(4), 243–251. https://doi.org/10.1016/j.trstmh.2004.04.002

Gissema, K. H. (2014). The Merowe Dam Salvage Archaeological Project (Sudan). In J. R. Anderson & D. A. Welsby (Eds.), *The Fourth Cataract and Beyond: Proceedings of the 12th International Conference for Nubian Studies* (pp. 1049–1056). Peeters: British Museum.

Godlewski, W. (2014). The Kingdom of Makuria. In J. R. Anderson & D. A. Welsby (Eds.), *The Fourth Cataract and Beyond: Proceedings of the 12 th International Conference for Nubian Studies* (pp. 155–169). Leuven: Peeters.

Goodman, A. H., Brooke Thomas, R., Swedlund, A. C., & Armelagos, G. J. (1988). Biocultural perspectives on stress in prehistoric, historical, and contemporary population research. *American Journal of Physical Anthropology*, *31*(9 S), 169–202. https://doi.org/10.1002/ajpa.1330310509

Gowland, R. L. (2015). Entangled lives: Implications of the developmental origins of health and disease hypothesis for bioarchaeology and the life course. *American Journal of Physical Anthropology*, *158*(4), 530–540. https://doi.org/10.1002/ajpa.22820

Greene, D. L. (1982). Discrete dental variations and biological distances of Nubian populations. *American Journal of Physical Anthropology*, *58*, 75–79.

Gregoire, R. (2019). *Estimation of weaning patterns in the elite Meroitic population (8-B-5.A) from Sai Island, Sudan using stable nitrogen and carbon isotopes*. University of Central Florida.

Guerrant, R. L., Oriá, R. B., Moore, S. R., Oriá, M. O. B., & Lima, A. A. A. M. (2008). Malnutrition as an enteric infectious disease with long-term effects on child development. *Nutrition Reviews*, *66*(9), 487–505. https://doi.org/10.1111/j.1753-4887.2008.00082.x

Haaland, R. (2012). Changing food ways as indicators of emerging complexity in Sudanese Nubia: From Neolithic agropastoralists to the Meroitic civilisation. *Azania*, *47*(3), 327–342. https://doi.org/10.1080/0067270X.2012.708990

Halcrow, S. E., & Tayles, N. (2008). The Bioarchaeological Investigation of Childhood and Social Age: Problems and Prospects. *Journal of Archaeological Method and Theory*, *15*(2), 190–215. https://doi.org/10.1007/sl0816-008-9052-x

Hales, C. N., & Barker, D. J. P. (2001). The thrifty phenotype hypothesis: Type 2 diabetes. *British Medical Bulletin*, *60*(1), 5–20. https://doi.org/10.1093/bmb/60.1.5

Hatch, M. D., & Slack, C. R. (1966). Photosynthesis by sugar-cane leaves: A new carboxylation reaction and the pathway of sugar formation. *Biochemistry Journal*, *101*, 103–111.

Hatch, M. D., & Slack, C. R. (1967). Further studies on a new pathway of photosynthetic carbon dioxide fixation in sugar-cane and its occurrence in other plant species. *Biochemistry Journal*, *102*, 417–422.

Herbst, G., & Smith, S. T. (2014). Pre-Kerma Transition at the Nile Fourth Cataract: First Assessments of a Multi-component, Stratified Prehistoric Settlement in the UCSB/ASU Salvage Concession. In J. R. Anderson & D. A. Welsby (Eds.), *The Fourth Cataract and Beyond: Proceedings of the 12 th International Conference for Nubian Studies* (pp. 311–320). Leuven: Peeters.

Hibbs, A. C., Secor, W. E., Van Gerven, D., & Armelagos, G. J. (2011). Irrigation and infection: the immunoepidemiology of schistosomiasis in ancient Nubia. *American Journal of Physical Anthropology*, *145*(2), 290–298.

Hillson, S. (1997). *Dental Anthropology*. Cambridge: Cambridge University Press.

Himes, J. H. (2004). Why study child growth and maturation? In R. C. Hauspie, N. Cameron, & L. Molinari (Eds.), *Methods in Human Growth Research* (pp. 3–26). Cambridge: Cambridge University Press.

Hobson, K. A., Alisauskas, R. T., & Clark, R. G. (1993). Stable-Nitrogen Isotope Enrichment in Avian Tissues Due To Fasting and Nutritional Stress: Implications for Isotopic Analyses of Diet'. *The Condor*, *95*(2), 388–394. https://doi.org/10.2307/1369361

Holder, S., Miliauskienė, Ž., Jankauskas, R., & Dupras, T. L. (2020). An integrative approach to studying plasticity in growth disruption and outcomes : A bioarchaeological case study of Napoleonic soldiers. *American Journal of Human Biology*, *e23457*, 1–15. https://doi.org/10.1002/ajhb.23457

Holliday, T. W., & Ruff, C. B. (2001). Relative variation in human proximal and distal limb segment lengths. *American Journal of Physical Anthropology*, *116*(1), 26–33. https://doi.org/10.1002/ajpa.1098

Honegger, M. (2018). New data on the origins of Kerma. In M. Honegger (Ed.), *Nubian Archaeology in the XXIst Century: Proceedings of the 13th International Conference for Nubian Studies, Neuchâtel, 1st-6th September 2014.* (pp. 19–34). Leuven: Peeters.

Hoppa, R. D., & Fitzgerald, C. M. (1999). From head to toe: integrating studies from bones and teeth in biological anthropology. In R. D. Hoppa & C. M. Fitzgerald (Eds.), *Human Growth in the Past: Studies from Bones and Teeth* (pp. 1–31). Cambridge: Cambridge University Press.

Hotez, P. J., Brooker, S., Bethony, J. M., Bottazzi, M. E., Loukas, A., & Xiao, S. (2004). Hookworm Infection. *October*, 799–807.

Hummert, J. R. (1983). Cortical bone growth and dietary stress among subadults from Nubia's Batn el Hajar. *American Journal of Physical Anthropology*, *62*(2), 167–176.

Hummert, J. R., & Van Gerven, D. P. (1983). Skeletal growth in a Medieval population from Sudanese Nubia. *American Journal of Physical Anthropology*, *60*(4), 471–478.

Huss-Ashmore, R. (1981). Bone growth and remodeling as a measure of nutritional stress. In D. L. Martin & M. Bumsted (Eds.), *Biocultural Adaptation: Comprehensive Approaches to Skeletal Analysis. Research Reports No. 20* (pp. 84–95). Amherst: University of Massachusetts, Amherst.

Iacumin, P., Bocherens, H., Chaix, L., & Marioth, A. (1998). Stable carbon and nitrogen isotopes as dietary indicators of ancient Nubian populations (Northern Sudan). *Journal of Archaeological Science*, *25*(4), 293–301. https://doi.org/10.1006/jasc.1997.0206

Ikram, S. (2012). From Food to Furniture: Animals in Ancient Nubia. In M. Fisher, P. Lacovara, S. Ikram, & S. D'Auria (Eds.), *Ancient Nubia: African Kingdoms on the Nile* (pp. 210–224). Cairo: The American University in Cairo Press.

Jacobi, K. P., & Danforth, M. E. (2002). Analysis of interobserver scoring patterns in porotic hyperostosis and cribra orbitalia. *International Journal of Osteoarchaeology*, *12*(4), 248–258.

Jim, S., Ambrose, S. H., & Evershed, R. P. (2004). Stable carbon isotopic evidence for differences in the dietary origin of bone cholesterol, collagen and apatite: Implications for their use in palaeodietary reconstruction. *Geochimica et Cosmochimica Acta*, *68*(1), 61–72. https://doi.org/10.1016/S0016-7037(03)00216-3

Judd, M. (2014). Growing Up in Gabati: an overview of health. In J. R. Anderson & D. A. Welsby (Eds.), *The Fourth Cataract and Beyond: Proceedings of the 12 th International Conference for Nubian Studies* (pp. 1115–1123). Leuven: British Museum Press.

Katzenberg, M Anne. (2008). Stable isotope analysis: a tool for studying past diet, demography, and life history. In M A Katzenberg & S. R. Saunders (Eds.), *Biological Anthropology of the Human Skeleton* (2nd ed., pp. 413–441). Hoboken: John Wiley & Sons.

Katzenberg, M. A., Herring, D., & Saunders, S. R. (1996). Weaning and infant mortality: Evaluating the skeletal evidence. *American Journal of Physical Anthropology*, *101*(S23), 177–199. https://doi.org/10.1002/(SICI)1096-8644(1996)23+<177::AID-AJPA7>3.0.CO;2-2

Kemkes-Grottenthaler, A. (2005). The short die young: The interrelationship between stature and longevity - Evidence from skeletal remains. *American Journal of Physical Anthropology*, *128*(2), 340–347. https://doi.org/10.1002/ajpa.20146

Keys, A., Karvonen, N., Kimura, N., & Taylor, H. (1972). Indices of relative weight and obesity. *Journal of Chronic Disease*, *25*, 329–343.

Klaus, H. D. (2014). Frontiers in the bioarchaeology of stress and disease: Cross-disciplinary perspectives from pathophysiology, human biology, and epidemiology. *American Journal of Physical Anthropology*, *155*(2), 294–308. https://doi.org/10.1002/ajpa.22574

Koch, P. L., Tuross, N., & Fogel, M. L. (1997). The effects of sample treatment and diagenesis on the isotopic integrity of carbonate in biogenic hydroxylapatite. *Journal of Archaeological Science*, *24*, 417–430.

Kossmann, J., Nestel, P., Herrera, M., El-Amin, A., & Fawzi, W. (2000). Undernutrition and childhood infections: a prospective study of childhood infections in relation to growth in the Sudan. *Acta Paediatrica*, *89*(9), 1122–1128. https://doi.org/10.1080/713794561

Krueger, H. W., & Sullivan, C. H. (1984). Models for Carbon Isotope Fractionation

Between Diet and Bone. *Stable Isotopes in Nutrition. American Chemical Society Symposium Series 258. Washington, DC: American Chemical Society.*, pp. 205–220. https://doi.org/10.1021/bk-1984-0258.ch014

Lacovara, P. (2012). The Land of Nubia. In M M Fisher, P. Lacovara, S. Ikram, & S. D'Auria (Eds.), *Ancient Nubia: African Kingdoms on the Nile* (pp. 5–9). Cairo: The American University in Cairo Press.

Lalremruata, A., Ball, M., Bianucci, R., Welte, B., Nerlich, A. G., Kun, J. F. J., & Pusch, C. M. (2013). Molecular Identification of Falciparum Malaria and Human Tuberculosis Co-Infections in Mummies from the Fayum Depression (Lower Egypt). *PLoS ONE*, *8*(4), 9–12. https://doi.org/10.1371/journal.pone.0060307

Lee-Thorp, J. A., & van der Merwe, N. J. (1991). Aspects of the chemistry of modern and fossil biological apatites. *Journal of Archaeological Science*, *18*(3), 343–354.

Littleton, J. (2011). Moving from the Canary in the Coalmine: Modeling Childhood in Bahrain. In *Social Bioarchaeology* (pp. 361–389). Hoboken: Wiley-Blackwell.

Madella, M., García-Granero, J. J., Out, W. A., Ryan, P., & Usai, D. (2014). Microbotanical evidence of domestic cereals in Africa 7000 years ago. *PLoS ONE*, *9*(10). https://doi.org/10.1371/journal.pone.0110177

Małkiewicz, A., & Dziedzic, M. (2012). Bone marrow reconversion - imaging of physiological changes in bone marrow. *Polish Journal of Radiology / Polish Medical Society of Radiology*, *77*(4), 45–50. https://doi.org/10.1136/ip.2007.016220

Martin, D. L., Armelagos, G. J., Goodman, A. H., & Van Gerven, D. P. (1984). The effects of socioeconomic change in prehistoric Africa: Sudanese Nubia as a case study. In M. N. Cohen & G. J. Armelagos (Eds.), *Paleopathology at the Origins of Agriculture* (pp. 193–214). Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+Effects+of+Socioeconomic+Change+in+Prehistoric+Africa:+Sudanese+Nubia+as+a+Case+Study#0

Masoner, M. A., Baker, B. J., & Knudson, K. J. (2011). Preliminary isotopic analysis of Post-Meroitic to Christian period Nubians from the Ginefab School site, Sudan. *American Journal of Physical Anthropology*, *144*, 207–208.

Masterson, E. E., Fitzpatrick, A. L., Enquobahrie, D. A., Mancl, L. A., Conde, E., & Hujoel, P. P. (2017). Malnutrition-related early childhood exposures and enamel defects in the permanent dentition: A longitudinal study from the Bolivian Amazon. *American Journal of Physical Anthropology*, *164*(2), 416–423. https://doi.org/10.1002/ajpa.23283

Mcilvaine, B. K. (2015). Implications of Reappraising the Iron-Deficiency Anemia

Hypothesis. *International Journal of Osteoarchaeology, 25*(6), 997–1000. https://doi.org/10.1002/oa.2383

Mekota, A. M., Grupe, G., Ufer, S., & Cuntz, U. (2006). Serial analysis of stable nitrogen and carbon isotopes in hair: monitoring starvation and recovery phases of patients suffering from anorexia nervosa. *Rapid Communications in Mass Spectrometry, 20*(10), 1604–1610.

Miller, R. L., Armelagos, G. J., Ikram, S., De Jonge, N., Krijger, F. W., & Deelder, A. M. (1992). Palaeoepidemiology of Schistosoma infection in mummies. *BMJ : British Medical Journal*, *304*(February), 555–556. https://doi.org/10.1136/bmj.304.6826.555

Miller, R. L., Ikram, S., Armelagos, G. J., Walker, R., Harer, W. B., Shiff, C. J., … Maret, S. M. (1994). Diagnosis of Plasmodium falciparum infections in mummies using the rapid manual ParaSight-F test. *Transactions of the Royal Society of Tropical Medicine and Hygiene, 88,* 31–32. https://doi.org/10.1016/0035-9203(94)90484-7

Mittler, D. M., & Van Gerven, D. P. (1994). Developmental, diachronic, and demographic analysis of cribra orbitalia in the Medieval Christian populations of Kulubnarti. *American Journal of Physical Anthropology*, *93*(3), 287–298.

Mittler, D. M., Van Gerven, D. P., Sheridan, S. G., & Beck, R. (1992). The epidemiology of enamel hypoplasia, cribra orbitalia, and subadult mortality in an ancient Nubian population. In A. H. Goodman & L. Capasso (Eds.), *Recent contributions to the study of enamel developmental defects* (pp. 143–150). Teramo: Edigrafital.

Molinari, L., & Gasser, T. (2004). The human growth curve: distance, velocity and acceleration. In R. C. Hauspie, N. Cameron, & L. Molinari (Eds.), *Methods in Human Growth Research* (pp. 27–54). Cambridge: Cambridge University Press.

Moorrees, C., Fanning, E., & Hunt, E. (1963a). Age variation of formation stages for ten permanent teeth. *Journal of Dental Research*, *42*, 1490–1502.

Moorrees, C., Fanning, E., & Hunt, E. (1963b). Formation and resorption of three deciduous teeth in children. *American Journal of Physical Anthropology, 21*, 205–213.

Morse, D., Brothwell, D. R., & Ucko, P. J. (1964). Tuberculosis in Ancient Egypt. *American Review of Respiratory Disease*, *90*(4), 524–541.

Mummert, A., Esche, E., Robinson, J., & Armelagos, G. J. (2011). Stature and robusticity during the agricultural transition: Evidence from the bioarchaeological record. *Economics and Human Biology*, *9*(3), 284–301. https://doi.org/10.1016/j.ehb.2011.03.004

Norris, A. L., Dahlstedt, A., & Baker, B. J. (2015). Growing up at the 4th Cataract: Preadult growth and morbidity at the Ginefab School site. *Poster Presented at the Paleopathology Association Annual Meeting*. St. Louis, Missouri, March 24-25.

O'Connor, D. B. (1993). *Ancient Nubia: Egypt's Rival in Africa*. Philadelphia: University of Pennsylvania.

O'Donnell, L., Hill, E. C., Anderson, A. S. A., & Edgar, H. J. H. (2020). Cribra orbitalia and porotic hyperostosis are associated with respiratory infections in a contemporary mortality sample from New Mexico. *American Journal of Physical Anthropology*, *173*(4), 721–733. https://doi.org/10.1002/ajpa.24131

Obłuski, A. (2014). Rank-Size Rule in Nubian Settlement Systems. In J. R. Anderson & D. A. Welsby (Eds.), *The Fourth Cataract and Beyond: Proceedings of the 12th International Conference for Nubian Studies* (pp. 867–874). Peeters: British Museum.

Olivares, M., Walter, T., Hertrampf, E., & Pizarro, F. (1999). Anaemia and iron deficiency disease in children. *British Medical Bulletin*, *55*(3), 534–543.

Olsen, A., Magnussen, I., Oumaz, J. H., Andreassens, J., & Friis, H. (1998). The contribution of hookworm and other parasitic iron status among children and adults in western infections Kenya to haemoglobin and. *Trans R Soc Trop Med Hyg*, *92*(March), 643–649.

Olsen, K. C., White, C. D., Longstaffe, F. J., Heyking, K., McGlynn, G., Grupe, G., & Rühli, F. J. (2014). Intraskeletal isotopic compositions (δ13C, δ15N) of bone collagen: Nonpathological and pathological variation. *American Journal of Physical Anthropology*, *153*(4), 598–604.

Ortner, D. J. (2003). *Identification of Pathological Conditions in Human Skeletal Remains* (2nd ed.). San Diego: Academic Press.

Out, W. A., Ryan, P., García-Granero, J. J., Barastegui, J., Maritan, L., Madella, M., & Usai, D. (2016). Plant exploitation in Neolithic Sudan: A review in the light of new data from the cemeteries R12 and Ghaba. *Quaternary International*, *412*, 36–53. https://doi.org/10.1016/j.quaint.2015.12.066

Pearson, O. M. (2000). Activity, Climate, and Postcranial Robusticity. *Current Anthropology*, *41*(4), 569–607. https://doi.org/10.1086/317382

Pelletier, D. L., Frongillo Jr, E. A., & Habicht, J. P. (1993). Epidemiologic evidence for a potentiating effect of malnutrition on child mortality. *American Journal of Public Health*, *83*(8), 1130.

Pelletier, D. L., Frongillo Jr, E. A., Schroeder, D. G., & Habicht, J. P. (1995). The effects of malnutrition on child mortality in developing countries. *Bulletin of the World Health Organization*, *73*(4), 443.

Perkins, D. J., Were, T., Davenport, G. C., Kempaiah, P., Hittner, J. B., & Ong'echa, J. M. (2011). Severe malarial anemia: Innate immunity and pathogenesis. *International Journal of Biological Sciences, 7*(9), 1427–1442. https://doi.org/10.7150/ijbs.7.1427

Perrin, P., Herbreteau, V., Hugot, J., & Morand, S. (2010). Biogeography, humans, and their Parasites. *Distribution*, (2014), 41–58.

Pinhasi, R. (2007). Growth in Archaeological Populations. In *Advances in Human Palaeopathology* (pp. 363–380). https://doi.org/10.1002/9780470724187.ch16

Pinhasi, R., Timpson, A., Thomas, M., & Slaus, M. (2014). Bone growth, limb proportions and non-specific stress in archaeological populations from Croatia. *Annals of Human Biology*, *41*(2), 127–137. https://doi.org/10.3109/03014460.2013.835443

Pollard, M., Batt, C., Stern, B., & Young, S. M. M. (2007). *Analytical Chemistry in Archaeology*. Cambridge University Press.

Pomeroy, E., Stock, J. T., Stanojevic, S., Miranda, J. J., Cole, T. J., & Wells, J. C. K. (2012). Trade-Offs in Relative Limb Length among Peruvian Children: Extending the Thrifty Phenotype Hypothesis to Limb Proportions. *PLoS ONE*, *7*(12). https://doi.org/10.1371/journal.pone.0051795

Prendergast Moore, K., Thorp, S., & Van Gerven, D. P. (1986). Pattern of dental eruption, skeletal maturation and stress in a medieval population from Sudanese Nubia. *Human Evolution*, *1*(4), 325–330.

Ptacek, Alexandra J., & Brenda J. Baker. Faunal remains in Kerma to Napatan period burials from the ASU BONE concession. *Sudan & Nubia* 24:147-161.

Raisor, B. (2020). *Meroitic childhood diet and weaning at Sai Island, Sudan: a carbon and nitrogen isotopic study of site 8-B-52.B* (University of Central Florida). https://doi.org/10.1017/CBO9781107415324.004

Raxter, M. H. (2011). *Egyptian Body Size: A Regional and Worldwide Comparison*. University of South Florida.

Raxter, M. H., Ruff, C. B., Azab, A., Erfan, M., Soliman, M., & El-Sawaf, A. (2008). Stature estimation in ancient Egyptians: a new technique based on anatomical reconstruction of stature. *American Journal of Physical Anthropology, 136*(2), 147–155.

Rectenwald, K. R. (2012). *Relative Long Bone Proportions and Developmental Stress in* *a Modern Thai Population*. North Carolina State University.

Reid, D. J., & Dean, M. C. (2006). Variation in modern human enamel formation times. *Journal of Human Evolution*, *50*(3), 329–346.

Reitsema, L., & Holder, S. (2018). Stable Isotope Analysis and the Study of Human Stress, Disease, and Nutrition. *Bioarchaeology International*, *2*(2), 63–74. https://doi.org/10.5744/bi.2018.1018

Richards, M., & Montgomery, J. (2012). Isotope Analysis and Paleopathology: A Short Review and Future Developments. In J. E. Buikstra & C. Roberts (Eds.), The Global History of Paleopathology: Pioneers and Prospects (pp. 718–731). Oxford: Oxford University Press.

Ritzman, T. B., Baker, B. J., & Schwartz, G. T. (2008). A fine line: a comparison of methods for estimating ages of linear enamel hypoplasia formation. *American Journal of Physical Anthropology*, *135*(3), 348–361.

Rivera, F., & Lahr, M. M. (2017). New evidence suggesting a dissociated etiology for cribra orbitalia and porotic hyperostosis. *American Journal of Physical Anthropology*, *164*(1), 76–96. https://doi.org/10.1002/ajpa.23258

Rothschild, B. M., Zdilla, M. J., Jellema, L. M., & Lambert, H. W. (2020). Cribra orbitalia is a vascular phenomenon unrelated to marrow hyperplasia or anemia: Paradigm shift for cribra orbitalia. *Anatomical Record*, (June), 1–8. https://doi.org/10.1002/ar.24561

Rudney, J. D. (1983). The age-related distribution of dental indicators of growth disturbance in ancient Lower Nubia: an etiological model from the ethnographic record. *Journal of Human Evolution*, *12*(6), 535–543.

Rudney, J. D., & Greene, D. L. (1981). *Interpopulatlon Differences in the Severity of Early Cl ~ ildhood Stress in & nclent Lower Nubia : Inlplications for Hypotheses of X-group Orlgins*. *0*(I 982), 559–565.

Ruff, C. B., Garofalo, E., & Holmes, M. A. (2013). Interpreting skeletal growth in the past from a functional and physiological perspective. *American Journal of Physical Anthropology*, *150*(1), 29–37. https://doi.org/10.1002/ajpa.22120

Sandberg, P. A. (2006). *An isotopic investigation of health and illness in two skeletal populations from Kulubnarti, Sudanese Nubia*. University of Colorado.

Sandberg, P. A. (2012). *Investigating childhood diet and early life history events in the archaeological record using biogeochemical techniques* (University of Colorado at Boulder). Retrieved from http://pl8cg5fc8w.search.serialssolutions.com.ezproxy1.lib.asu.edu/?ctx_ver=Z39.88

-2004&ctx_enc=info:ofi/enc:UTF-8&rfr_id=info:sid/ProQuest+Dissertations+%252526+Theses+Full+Text&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&rft.genre=dissertations+%25252

Sandberg, P. A., & Van Gerven, D. (2016). “Canaries in the Mineshaft”: The Children of Kulubnarti. In M. K. Zuckerman & D. L. Martin (Eds.), *New Directions in Biocultural Anthropology* (pp. 159–181). Hoboken: John Wiley & Sons.

Sandberg, P. A., Sponheimer, M., Lee-Thorp, J., Van Gerven, D. P., Lee-Thorp, J., & Van Gerven, D. P. (2014). Intra-tooth stable isotope analysis of dentine: A step toward addressing selective mortality in the reconstruction of life history in the archaeological record. *American Journal of Physical Anthropology*, *155*(2), 281–293.

Sandford, M. K., Van Gerven, D. P., & Meglen, R. R. (1983). Elemental hair analysis: new evidence on the etiology of cribra orbitalia in Sudanese Nubia. *Human Biology*, *55*(4), 831–844.

Saunders, S. R., & Hoppa, R. D. (1993). Growth deficit in survivors and non-survivors: Biological mortality bias in subadult skeletal samples. *American Journal of Physical Anthropology*, *36*(17 S), 127–151. https://doi.org/10.1002/ajpa.1330360608

Scheuer, L., & Black, S. (2000). *Developmental Juvenile Osteology*. San Diego: Elsevier Academic Press.

Schillaci, M. A., Nikitovic, D., Akins, N. J., Tripp, L., & Palkovich, A. M. (2011). Infant and juvenile growth in ancestral Pueblo Indians. *American Journal of Physical Anthropology*, *145*(2), 318–326. https://doi.org/10.1002/ajpa.21509

Schoeninger, M. J., & DeNiro, M. J. (1984). Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochimica et Cosmochimica Acta*, *48*(4), 625–639.

Schour, I., & Massler, M. (1941). The Development of the Human Dentition. *Journal of the American Dental Association*, *28*, 1153–1160.

Schug, G. R., Gupta, S., Cowgill, L. W., Sciulli, P. W., & Blatt, S. H. (2013). Panel regression formulas for estimating stature and body mass from immature human skeletons: A statistical approach without reference to specific age estimates. *Journal of Archaeological Science*, *40*(7), 3076–3086. https://doi.org/10.1016/j.jas.2013.02.025

Schultz, A. H. (1937). Proportions, variability and asymmetries of the long bones of the limbs and the clavicles in man and apes. *Human Biology*, *9*(3), 281–328.

Schwarcz, H. P., & White, C. D. (2004). The grasshopper or the ant?: cultigen-use strategies in ancient Nubia from C-13 analyses of human hair. *Journal of Archaeological Science*, *31*(6), 753–762.

Schwarcz, H. P., Dupras, T. L., & Fairgrieve, S. I. (1999). 15N enrichment in the Sahara: in search of a global relationship. *Journal of Archaeological Science*, *26*(6), 629–636.

Sheridan, S. G., & Van Gerven, D. P. (1997). Female biological resiliency: differential stress response by sex in human remains from ancient Nubia. *Human Evolution*, *12*(4), 241–252.

Skinner, M. F., Rodrigues, A. T., & Byra, C. (2014). Developing a pig model for crypt fenestration-induced localized hypoplastic enamel defects in humans. *American Journal of Physical Anthropology*, *154*(2), 239–250.

Smith, B. H. (1991). Standards of human tooth formation and dental age assessment. In M. Kelly & C. Larsen (Eds.), *Advances in Dental Anthropology* (pp. 143–168). New York: Wiley-Liss.

Smith, S. L., & Buschang, P. H. (2004). Variation in longitudinal diaphyseal long bone growth in children three to ten years of age. *American Journal of Human Biology*, *16*(6), 648–657. https://doi.org/10.1002/ajhb.20077

Smith, S. L., & Buschang, P. H. (2005). Longitudinal models of long bone growth during adolescence. *American Journal of Human Biology*, *17*(6), 731–745. https://doi.org/10.1002/ajhb.20441

Smith, S. T., & Herbst, G. (2005). The UCSB West (Left) Bank Archaeological Survey from el-Kab to Mograt. *Gdansk Archaeological Museum African Reports*, *4*, 133–144.

Smith-Guzmán, N. E. (2015). Cribra orbitalia in the ancient Nile Valley and its connection to malaria. *International Journal of Paleopathology*, *10*, 1–12. https://doi.org/10.1016/j.ijpp.2015.03.001

Smith-Guzmán, N. E. (2015b). The skeletal manifestation of malaria: An epidemiological approach using documented skeletal collections. *American Journal of Physical Anthropology*, *158*(4), 624–635. https://doi.org/10.1002/ajpa.22819

Steckel, R. (1995). Stature and the Standard of Living. *Journal of Economic Literature*, *33*(4), 1903–1940.

Steele, D., & Bramblett, C. (1988). *The Anatomy and Biology of the Human Skeleton*. College Station: Texas A&M University Press.

Stuart-Macadam, P. (1985). Porotic hyperostosis: Representative of a childhood condition. *American Journal of Physical Anthropology*, *66*(4), 391–398.

Stuart-Macadam, P. (1987). Porotic hyperostosis: New evidence to support anemia theory. *American Journal of Physical Anthropology*, *74*(4), 521–526.

Stuart-Macadam, P. (1989). Porotic hyperostosis: Relationship between orbital and vault lesions. *American Journal of Physical Anthropology*, *80*(2), 187–193.

Sullivan, C. H., & Krueger, H. W. (1981). Carbon isotope analysis of separate chemical phases in modern and fossil bone. *Nature*, *292*(5821), 333–335.

Taha, S. A. (1978). The prevalence and severity of protein-calorie malnutrition in Sudanese children. *Journal of Tropical Pediatrics and Environmental Child Health*, *24*(5), 203–206.

Temple, D. H. (2008). What can variation in stature reveal about environmental differences between prehistoric Jomon foragers? Understanding the impact of systemic stress on developmental stability. *American Journal of Human Biology*, *20*(4), 431–439. https://doi.org/10.1002/ajhb.20756

Temple, D. H. (2014). Plasticity and constraint in response to early-life stressors among late/final Jomon period foragers from Japan: Evidence for life history trade-offs from incremental microstructures of enamel. *American Journal of Physical Anthropology*, *155*(4), 537–545. https://doi.org/10.1002/ajpa.22606

Thompson, A. H., Chaix, L., & Richards, M. P. (2008). Stable isotopes and diet at Ancient Kerma, Upper Nubia (Sudan). *Journal of Archaeological Science*, *35*(2), 376–387. https://doi.org/10.1016/j.jas.2007.03.014

Tieszen, L. L., & Fagre, T. (1993). Effect of diet quality and composition on the isotopic composition of respiratory CO2, bone collagen, bioapatite, and soft tissues. In J. B. Lambert & G. Grupe (Eds.), *Prehistoric Human Bone: Archaeology at the Molecular Level* (pp. 121–155). Berlin: Springer-Verlag.

Turner, B. L., Edwards, J. L., Quinn, E. A., Kingston, J. D., & Van Gerven, D. P. (2007). Age-related variation in isotopic indicators of diet at medieval Kulubnarti, Sudanese Nubia. *International Journal of Osteoarchaeology*, *17*(1), 1–25.

Ubelaker, D. H. (1989). *Human Skeletal Remains: Excavation, Analysis, Interpretation*. Washington, D.C.: Smithsonian Institution Press.

Vagn Nielson, O. (1970). *The Nubian skeleton through 4000 years*. University of Copenhagen.

Van Gerven, D. P. (1982). The contribution of time and local geography to craniofacial variation in Nubia's Batn el Hajar. *American Journal of Physical Anthropology*, *59*, 307–316.

Van Gerven, D. P., Hummert, J., Prendergast Moore, K., & Sandford, M. (1990). Nutrition, disease and the human life cycle: A bioethnography of a medieval Nubian community. In C. DeRousseau (Ed.), *Primate Life History and Evolution* (pp. 297–324). New York: Wiley-Liss.

Vercellotti, G., Piperata, B. A., Agnew, A. M., Wilson, W. M., Dufour, D. L., Reina, J. C., … Sciulli, P. W. (2014). Exploring the multidimensionality of stature variation in the past through comparisons of archaeological and living populations. *American Journal of Physical Anthropology*, *155*(2), 229–242. https://doi.org/10.1002/ajpa.22552

Victora, C G. (1992). The association between wasting and stunting: an international perspective. *The Journal of Nutrition*, *122*(5), 1105–1110.

Victora, Cesar G., Adair, L., Fall, C., Hallal, P. C., Martorell, R., Richter, L., & Sachdev, H. S. (2008). Maternal and child undernutrition: consequences for adult health and human capital. *The Lancet*, *371*(9609), 340–357. https://doi.org/10.1016/S0140-6736(07)61692-4

Viva, S., Fabbri, P. F., Ricci, P., Bianchi, G., Hodges, R., & Lubritto, C. (2021). Project nEU-Med. The Contribution of Isotopic Analysis in the Differential Diagnosis of Anemia, the Case of the Medieval Cemetery of Vetricella (Scarlino, GR) in Tuscany. *Environmental Archaeology*, *0*(0), 1–14. https://doi.org/10.1080/14614103.2020.1867290

Vogel, J. (1978). Isotopic assessment of the dietary habits of ungulates. *South African Journal of Science*, *74*, 298–301.

Vogel, J., & van der Merwe, N. J. (1977). Isotopic evidence for early maize cultivation in New York state. *American Antiquity*, *42*(2), 238–242.

Walker, P. L., Bathurst, R. R., Richman, R., Gjerdrum, T., & Andrushko, V. A. (2009). The causes of porotic hyperostosis and cribra orbitalia: A reappraisal of the iron-deficiency-anemia hypothesis. *American Journal of Physical Anthropology*, *139*(2), 109–125.

Wapler, U., Crubezy, E., & Schultz, M. (2004). Is cribra orbitalia synonymous with anemia? Analysis and interpretation of cranial pathology in Sudan. *American Journal of Physical Anthropology*, *123*(4), 333–339.

Waterflow, J. C. (1974). Some aspects of childhood malnutrition as a public health problem. *British Medical Journal*, *4*(October), 88–90.

Waters-Rist, A., & Hoogland, M. (2018). The Role of Infant Feeding and Childhood Diet in Vitamin D Deficiency in a Nineteenth-Century Rural Dutch Community. *Bioarchaeology International*, *2*(2), 95–116. https://doi.org/10.5744/bi.2018.1020

Webber, R. (1996). *Communicable Disease Epidemiology and Control: A Global Perspective* (2nd ed.). Wallingford: CABI Publishing.

Welsby, D A. (1996). *Kingdom of Kush: The Napatan and Meroitic Empires*. London: British Museum Press.

Welsby, D. (2013). Kerma and Kush and Their Neighbours. In P. Mitchell & P. J. Lane (Eds.), *The Oxford Handbook of African Archaeology* (pp. 751–764). https://doi.org/10.1093/oxfordhb/9780199569885.013.0051

Welsby, Derek A. (2002). *Medieval Kingdoms of Nubia: Pagans, Christians and Muslims in the Middle Nile*. London: British Museum Press.

Weston, D. A. (2008). Investigating the specificity of periosteal reactions in pathology museum specimens. *American Journal of Physical Anthropology*, *137*(1), 48–59. https://doi.org/10.1002/ajpa.20839

Weston, D. A. (2012). Nonspecific Infection in Paleopathology: Interpreting Periosteal Reactions. In A. L. Grauer (Ed.), *A Companion to Paleopathology* (pp. 492–512). Hoboken: Wiley-Blackwell.

Wheeler, S. M. (2009). Bioarchaeology of Infancy and Childhood at the Kellis 2 Cemetery, Dakhleh Oasis, Egypt. *Graduate Program in Anthropology*, *PhD*.

White, C. D. (1991). *Isotopic analysis of multiple human tissues from three ancient Nubian populations*. University of Toronto.

White, C. D. (1993). Isotopic determination of seasonality in diet and death from nubian mummy hair. *Journal of Archaeological Science*, Vol. 20, pp. 657–666. https://doi.org/10.1006/jasc.1993.1040

White, C. D., & Armelagos, G. J. (1997). Osteopenia and stable isotope ratios in bone collagen of Nubian female mummies. *American Journal of Physical Anthropology*, *103*, 185–199.

White, C. D., & Schwarcz, H. P. (1994). Temporal trends in stable isotopes for Nubian mummy tissues. *American Journal of Physical Anthropology*, *93*(2), 165–187. https://doi.org/10.1002/ajpa.1330930203

White, C. D., Longstaffe, F. J., & Law, K. R. (1999). Seasonal stability and variation in diet as reflected in human mummy tissues from the Kharga Oasis and the Nile Valley. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *147*(3), 209–222.

White, C. D., Longstaffe, F. J., & Law, K. R. (2004). Exploring the effects of environment, physiology and diet on oxygen isotope ratios in ancient Nubian bones and teeth. *Journal of Archaeological Science*, *31*(8), 233–250. https://doi.org/10.1016/j.jas.2003.08.007

White, T. D., Black, M. T., & Folkens, P. A. (2011). *Human Osteology* (3rd ed.). https://doi.org/10.1007/s13398-014-0173-7.2

WHO. (2015). *Sudan: WHO Statistical Profile*. Retrieved from http://www.who.int/gho/en

Winchell, F., Brass, M., Manzo, A., Beldados, A., Perna, V., Murphy, C., … Fuller, D. Q. (2018). On the Origins and Dissemination of Domesticated Sorghum and Pearl Millet across Africa and into India: a View from the Butana Group of the Far Eastern Sahel. *African Archaeological Review*, 483–505. https://doi.org/10.1007/s10437-018-9314-2

Winchell, F., Stevens, C. J., Murphy, C., Champion, L., & Fuller, D. (2017). Evidence for Sorghum Domestication in Fourth Millennium BC Eastern Sudan: Spikelet Morphology from Ceramic Impressions of the Butana Group. *Current Anthropology*, *58*(5), 673–683. https://doi.org/10.1086/693898

Wood, J. W., Milner, G. R., Harpending, H. C., & Weiss, K. M. (1992). The osteological paradox: Problems of inferring prehistoric health from skeletal samples. *Current Anthropology*, *33*(4), 343–370.

World Health Organization, & United Nations Childrens Fund. (2009). WHO child growth standards and the identification of severe acute malnutrition in infants and children. *World Health Organization*, 11. https://doi.org/http://www.who.int/nutrition/publications/severemalnutrition/9789241598163/en/

World Health Organization. (2012). Weight-for-age BOYS. *Child Growth Standards*, 10–12. Retrieved from http://www.who.int/childgrowth/standards/WFA_boys_0_5_zscores.pdf

Zumrawi, F. Y., Dimond, H., & Waterlow, J. C. (1987). Effects of infection on growth in Sudanese children. *Human Nutrition: Clinical Nutrition*, *41*(6), 453–461.

Żurawski, B. (2014). The Fourth Cataract in the Medieval Period. In J. R. Anderson & D. A. Welsby (Eds.), *The Fourth Cataract and Beyond: Proceedings of the 12 th International Conference for Nubian Studies* (pp. 135–153). Peeters: British Museum.

APPENDIX A

RAW DATA FOR CHAPTER 2 (GROWTH)

Burial	Dental Age	Skeletal Age	Age Difference	Wasted	Stunted
4C-03-01-B11	6.6	2.5	-4.1	0	1
4C-03-01-B14	18	18	0	0	1
4C-03-01-B15	2.1	1	-1.1	UO	UO
4C-03-01-B16	17	17	0	UO	1
4C-03-01-B24	1.69	2	0.3	0	0
4C-03-01-B25	1	2	1	0	0
4C-03-01-B28	3.34	4	0.7	0	0
4C-03-01-B32	6.24	8.5	2.3	0	0
4C-03-01-B33	17.5	17.5	0	0	0
4C-03-01-B40	0.08	0.5	0.4	0	0
4C-03-01-B41	7.14	7	-0.1	0	0
4C-03-01-B46	6.5	6.5	0	1	0
4C-03-01-B47	4.45	4.5	0	0	1
4C-03-01-B52	16.5	18.5	2	0	0
4C-03-01-B53	3.26	2.5	-0.8	0	1
4C-03-01-B55	1.39	1.5	0.1	0	0
4C-03-01-B58	14.73	12	-2.7	UO	1
4C-03-01-B59	6.36	5	-1.4	0	1
4C-03-01-B60	16.5	17	0.5	0	0
4C-03-01-B62	2.47	2.5	0	0	1
4C-03-01-B63	15.78	14.5	-1.3	0	0
4C-03-01-B64	4.75	2.5	-2.3	1	1
4C-03-01-B65	2.17	2	-0.2	1	1
4C-03-01-B66	10.15	10.5	0.4	0	0
4C-03-01-B68	2.36	3.5	1.1	1	0
4C-03-01-B70	3.29	3	-0.3	0	1
4C-03-01-B74	10.27	9.5	-0.8	0	1
4C-03-01-B76	6.59	5	-1.6	0	0
4C-03-01-B79	5.86	5	-0.9	1	1
4C-03-01-B86	6.57	4.5	-2.1	0	0
4C-03-02-B14	1.12	2	0.9	0	0

APPENDIX B

RAW DATA FOR CHAPTER 2 (MEASUREMENTS)

Burial	FDL/FML*	FHD*	FMB*	BMI	Stature	Body Mass
4C-03-01-B11	20.4	UO	44	14.05	96.75	13.15
4C-03-01-B14	41.6	4.06	UO	20.37	157.82	50.75
4C-03-01-B15	UO	UO	UO	UO	UO	UO
4C-03-01-B16	36.7	UO	64	UO	146.76	UO
4C-03-01-B24	15.1	UO	33	13.66	79.68	8.67
4C-03-01-B25	12.1	UO	28	15.26	70.01	7.48
4C-03-01-B28	18.6	UO	43	15.32	90.79	12.62
4C-03-01-B32	29.1	UO	63	18.77	124.77	29.22
4C-03-01-B33	46.3	4.56	UO	22.24	168.43	63.08
4C-03-01-B40	8.1	UO	14	25.15	57.13	8.21
4C-03-01-B41	29.5	2.93	53	15.38	126.06	24.44
4C-03-01-B46	31.6	UO	53	10.85	132.82	19.13
4C-03-01-B47	19.6	UO	42	13.67	94.17	12.13
4C-03-01-B52	47	4.21	UO	18.84	170.01	54.45
4C-03-01-B53	16.7	UO	37	13.89	84.83	9.99
4C-03-01-B55	13.2	UO	33	16.1	73.4	8.67
4C-03-01-B58	33.3	UO	65	UO	139.09	UO
4C-03-01-B59	21.9	UO	47	14.42	101.58	14.87
4C-03-01-B60	40.5	3.3	55.1	17.57	151.76	40.46
4C-03-01-B62	14.3	UO	33	14.59	77.1	8.67
4C-03-01-B63	37.9	4.11	67	19.56	149.47	43.7
4C-03-01-B64	20.4	UO	38	11.08	96.75	10.37
4C-03-01-B65	14.8	UO	27	11.79	78.71	7.3
4C-03-01-B66	32.6	3.47	67	17.1	136.04	31.64
4C-03-01-B68	16.7	UO	30	11.02	84.67	7.9
4C-03-01-B70	17.8	UO	40	14.35	88.37	11.2
4C-03-01-B74	28.4	2.79	50	15.3	122.52	22.96
4C-03-01-B76	25.9	UO	50	12.91	114.3	16.86
4C-03-01-B79	21.4	UO	43	12.63	99.97	12.62
4C-03-01-B86	25.5	UO	50	13.16	113.17	16.86
4C-03-02-B14	14	UO	34	15.48	76.13	8.97

*FDL=femur diaphyseal length; FML=maximum femur length; FHD=maximum femur head diameter; FMB=femur metaphyseal breadth

APPENDIX C

RAW DATA FOR CHAPTER 3 (PREADULTS: AGE, CO, PH, PR)

Burial	Mean Age		CO			PH			PR	
	Dental	Skeletal	Presence	Activity	Degree	Presence	Degree	Area	Presence	Activity
4C-03-01-B11	6.6	2.5	1	2	4	1	1	2	1	1
4C-03-01-B15	2.1	1	1	3	3	0			0	0
4C-03-01-B24	1.7	2	1	2	2	0			1	3
4C-03-01-B25	1	2	1	3	3	1	1	1	1	1
4C-03-01-B28	3.3	4	1	2	4	0			1	3
4C-03-01-B32	6.2	8.5	1	2	3	1	1	2	0	0
4C-03-01-B40	0.1	0.5	0			0			0	0
4C-03-01-B41	7.1	7	1	3	2	1	1	2	0	0
4C-03-01-B46	6.5	6.5				1	1	2	0	0
4C-03-01-B47	4.5	4.5	0			0			0	0
4C-03-01-B53	3.3	2.5	1	2	3	0			1	2
4C-03-01-B55	1.4	1.5	1	1	2	0			0	0
4C-03-01-B58	14.7	12	1	2	3	0			0	0
4C-03-01-B59	6.4	5	1	2	2	1	1	1	0	0
4C-03-01-B62	2.5	2.5	1	2	2	0			0	0
4C-03-01-B63	15.8	14.5	1	3	2	0			1	2
4C-03-01-B64	4.8	2.5	1	2	3	0			1	3
4C-03-01-B65	2.2	2	1	2	3	0			1	3
4C-03-01-B66	10.2	10.5	1	2	2	1	1	2	1	2
4C-03-01-B68	2.4	3.5	1	2	2	0			1	1
4C-03-01-B70	3.3	3	1	2	3	0			1	1
4C-03-01-B74	10.3	9.5	1	2	2	1	1	2	0	0
4C-03-01-B76	6.6	5	1	3	3	1	2	1	1	1

4C-03-01-B79	5.9	5	1	2	1	0			0	0
4C-03-01-B86	6.6	4.5	1	1	3	1	1	1	0	0
4C-03-02-B05	4	4	1	1	2	0				
4C-03-02-B14	1.1	2	1	3	1	0			0	0

APPENDIX D

RAW DATA FOR CHAPTER 3 (PREADULTS: EH, CSI, GROWTH)

Burial	EH				CSI 1	CSI 2	Delayed	Wasted	Stunted
	Presence	LHDC	MinLEH	MNSE					
4C-03-01-B11	0	0	2	2	2	3	1	0	1
4C-03-01-B15	1	0		1	2	2	1		
4C-03-01-B24	1	0		1	2	3	0	0	0
4C-03-01-B25	1	1		1	3	4	0	0	0
4C-03-01-B28	1	0		2	2	3	0	0	0
4C-03-01-B32	1	1		1	3	3	0	0	0
4C-03-01-B40					0	0	0	0	0
4C-03-01-B41	1	0	2.7	1	3	3	0	0	0
4C-03-01-B46							0	1	0
4C-03-01-B47	1	1		1	1	1	0	0	1
4C-03-01-B53	1	1		2	2	3	1	0	1
4C-03-01-B55	0	0		0	1	1	0	0	0
4C-03-01-B58	1		2.7	1	2	0	1		1
4C-03-01-B59	1	0	2	2	3	3	1	0	1
4C-03-01-B62	1	1		2	2	2	0	0	1
4C-03-01-B63	1		3.7	1	2	0	1	0	0
4C-03-01-B64	0	0		0	1	2	1	1	1
4C-03-01-B65	0	0		0	1	2	0	1	1
4C-03-01-B66	0	0	2.1	2	2	3	0	0	0
4C-03-01-B68	0	0		0	1	2	0	1	0
4C-03-01-B70	1	1		1	2	3	0	0	1
4C-03-01-B74	1		1.3	3	3	0	1	0	1

4C-03-01-B76	1	1		1	3	4	1	0	0
4C-03-01-B79	0	0		0	1	1	1	1	1
4C-03-01-B86	1	1	2.6	4	3	3	1	0	0
4C-03-02-B05	0		1.7	3	1	1	0		
4C-03-02-B14				1	1	0	0	0	0

APPENDIX E

RAW DATA FOR CHAPTER 3 (ADULTS: AGE, CO, PH)

Burial	Median Age	CO			PH		
		Presence	Activity	Degree	Presence	Degree	Area
4C-03-01-B01	25	1	2	3	1	1	1
4C-03-01-B02	50	1	3	1	1	3	2
4C-03-01-B03	35	0			1	1	1
4C-03-01-B04	31	0			1	1	2
4C-03-01-B05	65	1	3	3	1	1	2
4C-03-01-B06	35	1	3	3	1	1	2
4C-03-01-B07	41.5	1	3	1	1	1	2
4C-03-01-B08	45	1	3	2	1	1	1
4C-03-01-B09	50	1	3	3	1	1	1
4C-03-01-B13	60	0			1	1	2
4C-03-01-B14	18	1	3	2	1	1	2
4C-03-01-B16	17	1	2	3	1	1	2
4C-03-01-B17	50	1	3	1	1	1	2
4C-03-01-B18	24	0			1	2	1
4C-03-01-B19	60	1	3	2	1	1	2
4C-03-01-B20	53	1	3	1	1	1	2
4C-03-01-B21	40	1	3	1	0		
4C-03-01-B22	43	1	3	1	1	1	2
4C-03-01-B23	53	0			1	1	1
4C-03-01-B26	40	1	3	1	1	1	1

4C-03-01-B27	45	0			0		
4C-03-01-B29	30	1	2	3	1	1	2
4C-03-01-B30	35	0			1	1	2
4C-03-01-B33	17.5	0			1	1	2
4C-03-01-B34	23	1	2	3	1	2	2
4C-03-01-B35	42	1	2	3	1	1	2
4C-03-01-B36	40	0			1	1	2
4C-03-01-B37	40	0			1	1	2
4C-03-01-B38	21	1	2	3	1	1	2
4C-03-01-B39	22	1	2	3	1	1	2
4C-03-01-B42	30	1	3	1	1	1	2
4C-03-01-B43	53	1	3	1	1	1	2
4C-03-01-B44	23	0			1	1	2
4C-03-01-B45	22	1	2	3	1	1	2
4C-03-01-B48	40	1	3	1	1	1	2
4C-03-01-B49	70	1	3	2	1	1	2
4C-03-01-B50	43	1	2	3	1	1	2
4C-03-01-B51	23	1	2	3	1	2	2
4C-03-01-B52	16.5	-			1	2	2
4C-03-01-B54	33	1	3	2	1	1	2
4C-03-01-B56	43	0			1	1	2
4C-03-01-	40	0			1	1	2

B57							
4C-03-01-B60	16.5	1	2	2	1	1	1
4C-03-01-B61	30	1	2	3	1	1	2
4C-03-01-B67	30	1	2	3	1	1	2
4C-03-01-B69	70	1	3	1	0		
4C-03-01-B71	42	1	3	3	1	1	2
4C-03-01-B72	42	0			0		
4C-03-01-B73	48	1	3	3	1	1	2
4C-03-01-B75	42	1	3	1	1	1	2
4C-03-01-B77	40	0			1	1	2
4C-03-01-B78	65	0			1	1	2
4C-03-01-B80	43	1	3	1	0		
4C-03-01-B81	45	1	3	1	1	1	2
4C-03-01-B82	50	0			1	1	1
4C-03-01-B83	34	1	3	1	1	1	2
4C-03-01-B84	75	1	2	3	1	1	2
4C-03-01-B85	42	1	3	3	1	1	1
4C-03-02-B01	24	0			1	2	2
4C-03-02-B02	42	1	3	1	1	1	2
4C-03-02-B03	40	0			1	2	2
4C-03-02-B04	75	1	3	1	1	1	2
4C-03-02-B06	27	0			1	1	2

4C-03-02-B07	68	1	3	2	1	1	1
4C-03-02-B08	26	0			1	2	2
4C-03-02-B09	50	1	2	1	1	1	2
4C-03-02-B10	42	1	3	1	1	2	2
4C-03-02-B11	30	1	3	2	1	2	2
4C-03-02-B13	27	0			1	1	2
4C-03-02-B15	50	0			1	1	1
4C-03-02-B16	28	1	3	1	1	1	1
4C-03-02-B17	23	0			1	1	2

APPENDIX F

RAW DATA FOR CHAPTER 3 (ADULTS: EH, CSI, MEASUREMENTS)

Burial	EH			CSI	Measurements			
	Presence	MinLEH	MNSE		FML	FHD	CI	BI
4C-03-01-B01	1	3.4	1	3	43.5	3.95	0.86	0.75
4C-03-01-B02	1	2.3	2	3	45.2	4.47	0.85	0.79
4C-03-01-B03	1	6.2	1	2	41	3.71	0.82	
4C-03-01-B04	0		0	1	46.8	4.79	0.85	0.79
4C-03-01-B05	1	2.5	1	3	48	4.03	0.86	0.78
4C-03-01-B06	0		0	2		4.82		
4C-03-01-B07	0	2.8	2	2	43.4	4.09	0.83	0.78
4C-03-01-B08	1	4.4	2	3	43.6	4.15	0.89	0.75
4C-03-01-B09	1	1.9	3	3	40.2	3.57	0.87	0.81
4C-03-01-B13	1	5.9	2	2	44.8	4.75	0.84	0.79
4C-03-01-B14	1	1	4	3	41.6	4.06	0.87	0.82
4C-03-01-B16	1	2.6	1	3	36.7		0.87	0.82
4C-03-01-B17	1	5	2	3	45	4.59	0.84	0.78
4C-03-01-B18	1	4.2	2	2	45	3.94	0.87	0.81
4C-03-01-B19	1	4.8	1	3	42.3	4.01	0.85	0.8
4C-03-01-B20	1	3.5	3	3	43.2	4.42	0.88	0.81
4C-03-01-B21	0		0	1	45.6	4.29	0.87	0.8
4C-03-01-B22	0		2	2	42.2	4.03	0.85	0.78
4C-03-01-B23	0		0	1	47.6	4.77	0.83	0.79
4C-03-01-B26	1	2.6	3	3	42.3	3.71	0.88	0.82
4C-03-01-B27	1	4.9	1	1	42	4.23		0.83
4C-03-01-B29	1	4.3	2	2	42.3	4.21	0.85	0.8
4C-03-01-B30	1	5.8	2	2	46.1	4.25	0.89	0.81
4C-03-01-B33	1	4	1	2	46.3	4.56	0.86	
4C-03-01-B34	1	1.8	4	3	44.1	4.09	0.84	0.75
4C-03-01-B35	1	5.1	1	3	47.02	4.47	0.85	
4C-03-01-B36	1	2.7	2	2	41.4	3.83	0.81	0.77
4C-03-01-B37	1	2.3	3	2	43.2	4.62	0.86	0.81
4C-03-01-B38	1		2	3	46.2	4.68	0.82	0.78
4C-03-01-B39	1	4.9	1	3	43.9	3.92	0.85	0.75
4C-03-01-B42	1	2.2	1	3	43.6	4.47	0.87	0.8
4C-03-01-B43	1	3.2	3	3				
4C-03-01-B44	1	3.9	2	2	46	4.5	0.86	0.8
4C-03-01-B45	1	4.5	1	3	48.1	4.58		0.77

4C-03-01-B48	0	2.5	2	2	44.5	4.07	0.86	0.79
4C-03-01-B49			0	2	44	3.91	0.85	0.78
4C-03-01-B50	1	2	3	3	48.2	4.85		
4C-03-01-B51	0	3	2	2	47.3	3.98	0.85	0.83
4C-03-01-B52	1			2	47	4.21	0.87	0.91
4C-03-01-B54	0	1	2	2	47.1	4.67	0.84	
4C-03-01-B56	1	3.9	2	2	45.4	5.02		0.77
4C-03-01-B57			0	1		3.9		
4C-03-01-B60	1	3	2	3	40.5	3.3	0.85	0.74
4C-03-01-B61	1	3.6	2	3	48.7	4.72	0.88	0.81
4C-03-01-B67	1	1.3	3	3	44.9	4.46	0.88	0.83
4C-03-01-B69	1	4	1	1	40.7	3.77	0.83	0.8
4C-03-01-B71	0	2.6	1	2	41	3.57	0.83	0.77
4C-03-01-B72	1	4.3	1	1	45.3	4.1	0.87	0.79
4C-03-01-B73	1	3.8	1	3	50.6	5.15	0.87	0.78
4C-03-01-B75	1	3.1	1	3	44.3	4.01	0.85	0.79
4C-03-01-B77	0	4.6	1	1	41.4	3.88	0.83	
4C-03-01-B78	1	4.3	1	1		3.57		
4C-03-01-B80	0	5.9	1	1	45.2	4.37		0.78
4C-03-01-B81	1	1.1	1	3	46.9	4.24	0.84	
4C-03-01-B82	1	5	2	2	47.1	5	0.83	
4C-03-01-B83	1	5.2	1	3	39.9	4.5	0.82	0.81
4C-03-01-B84	1	3.6	3	2		3.85		0.73
4C-03-01-B85	1	3.7	1	3	46.6	4.55	0.86	
4C-03-02-B01	1	2.3	2	2	51.8	4.66		
4C-03-02-B02	0			2		4.57		
4C-03-02-B03	1	1.6	2	2	46.3	4.58	0.85	
4C-03-02-B04	1	3.5	1	2		4.15		
4C-03-02-B06	1	2.2	2	1		4.71		
4C-03-02-B07	1	2.7	2	3	45.3	4.83	0.87	0.78
4C-03-02-B08	1	2.4	3	2		4.45		0.83
4C-03-02-B09	1	4.5	1	2				
4C-03-02-B10	0		0	2				
4C-03-02-B11	0	5.4	1	2	43.7		0.84	0.82
4C-03-02-B13	0		0	1		4.85		
4C-03-02-B15	0			1		4.57		

4C-03-02-B16	0		0	2		4.07		0.81
4C-03-02-B17	1	3.6	1	2		4.12		

APPENDIX G

RAW DATA FOR CHAPTER 4

Burial #	Period	Sex	Age[1]	C:N	δ^{15}N‰	$\delta^{13}C_{COLL}$‰	$\delta^{13}C_{AP}$‰	$\delta^{13}C_{AP-COLL}$‰	CO / PH	CO Activity
4C-03-01-B01	C	F	25.0	3.0	11.6	-11.4	-8.4	3.0	B	Mixed
4C-03-01-B03	PM	F	35.0	2.9	13.2	-8.8	-10.2	1.4	PH	
4C-03-01-B04	PM	M	31.0	3.0	12.0	-7.9	-6.8	1.1	PH	
4C-03-01-B07	C	F	41.5	3.0	11.9	-12.0	-7.5	4.5	B	Healed
4C-03-01-B09	C	F	50.0	3.0	12.2	-12.1	-10.6	1.5	B	Healed
4C-03-01-B11	C	I	6.6	3.0	10.8	-14.5	-9.9	4.6	B	Mixed
4C-03-01-B13	PM	M	60.0	3.0	12.7	-8.2	-12.2	4.0	PH	
4C-03-01-B14	PM	M	18.0	3.3	13.0	-8.5	-9.3	0.8	B	Healed
4C-03-01-B17	C	M	50.0	3.0	10.5	-13.1	-7.2	6.0	B	Healed
4C-03-01-B18	PM	F	24.0	2.9	11.0	-9.2	-4.8	4.4	PH	
4C-03-01-B19	C	F	60.0	3.0	10.2	-12.9	-10.3	2.6	B	Healed
4C-03-01-B20	C	F	53.0	3.0	11.2	-13.1	-4.1	9.0	B	Healed
4C-03-01-B21	C	M	40.0	2.9	11.1	-11.9	-4.5	7.5	CO	Healed
4C-03-01-B22	C	F	43.0	2.9	11.2	-11.1	-7.6	3.5	B	Healed
4C-03-01-B23	PM	M	53.0	3.0	11.8	-10.6	-9.4	1.2	PH	
4C-03-01-B24	C	I	1.7	***4.7***			-5.9		CO	Mixed
4C-03-01-B25	C	I	1.0	***2.7***			-8.7		B	Healed
4C-03-01-B26	PM	F	40.0	2.9	11.6	-8.8	-9.8	0.9	B	Healed
4C-03-01-B27	LM-PM	M	45.0	2.9	11.9	-8.2	-8.1	0.1	A	
4C-03-01-B28	C	I	3.3	3.0	12.5	-14.0	-9.0	5.0	CO	Mixed
4C-03-01-B29	C	M	30.0	2.9	10.7	-13.0	-6.9	6.1	B	Mixed
4C-03-01-B33	PM	M	17.5	2.9	11.1	-7.8	-3.9	3.9	PH	
4C-03-01-B34	C	F	23.0	2.9	9.9	-17.8	-3.4	14.3	B	Mixed

4C-03-01-B35	PM	M	42.0	3.0	12.7	-9.9	-8.2	1.8	B	Mixed
4C-03-01-B36	C	F	40.0	3.1	9.3	-14.0	-3.6	10.4	PH	
4C-03-01-B37	C	M	40.0	***5****			-3.2		PH	
4C-03-01-B38	LM-PM	M	21.0	***3.9****			-7.4		B	Mixed
4C-03-01-B39	C	F	22.0	3.0	12.0	-13.5	-4.6	8.9	B	Mixed
4C-03-01-B41	C	I	7.1	2.9	9.8	-12.4	-8.2	4.2	B	Healed
4C-03-01-B42	C	M	30.0	3.0	11.7	-8.1	-7.8	0.3	B	Healed
4C-03-01-B44	C	M	23.0	***4.4***			-6.7		PH	
4C-03-01-B45	C	M	22.0	2.9	13.6	-11.5	-4.2	7.3	B	Mixed
4C-03-01-B48	C	F	40.0	3.0	11.0	-12.6	-4.1	8.5	B	Healed
4C-03-01-B49	PM	F	70.0	***3****			-8.4		B	Healed
4C-03-01-B52	PM	M	16.5	***4.5***			-3.5			
4C-03-01-B53	C	I	3.3	3.1	11.4	-10.3	-5.8	4.5	CO	Mixed
4C-03-01-B54	C	M	33.0	3.0	12.7	-11.2	-7.9	3.2	B	Healed
4C-03-01-B55	C	I	1.4	***2****			-6.8		CO	Active
4C-03-01-B57	PM	F	40.0	3.4			-3.8		PH	
4C-03-01-B58	PM	I	14.7	***2.6***			-8.0		CO	Mixed
4C-03-01-B59	PM	I	6.4	3.0	10.4	-8.8	-3.4	5.4	B	Mixed
4C-03-01-B60	C	F	16.5	2.9	8.3	-13.8	-4.4	9.4	B	Mixed
4C-03-01-B61	LM-PM	M	30.0	***1.7****			-8.3		B	Mixed
4C-03-01-B62	C	I	2.5	3.0	11.6	-12.4	-7.9	4.6	CO	Mixed
4C-03-01-B64	C	I	4.8	3.0	10.1	-11.3	-5.9	5.5	CO	Mixed
4C-03-01-B65	C	I	2.2	3.0	10.9	-12.8	-7.4	5.5	CO	Mixed
4C-03-01-B67	C	M	30.0	2.9	10.9	-10.9	-7.9	3.0	B	Mixed
4C-03-01-B68	C	I	2.4	***2.4****			-6.1		CO	Mixed
4C-03-01-B69	C	F	70.0	3.0	10.2	-11.7	-3.4	8.3	CO	Healed

4C-03-01-B70	C	I	3.3	3.0	12.2	-10.8	-7.1	3.7	CO	Mixed
4C-03-01-B71	C	F	42.0	3.0	10.0	-11.9	-7.0	4.9	B	Healed
4C-03-01-B72	C	M	42.0	2.9	11.3	-10.2	-8.0	2.3	A	
4C-03-01-B74	C	I	10.3	2.9	10.4	-13.2	-7.3	5.8	B	Mixed
4C-03-01-B75	C	F	42.0	2.9	11.2	-11.7	-5.5	6.2	B	Healed
4C-03-01-B76	C	I	6.6	3.0	11.2	-15.0	-6.5	8.5	B	Healed
4C-03-01-B77	PM	F	40.0	**3.3***			-10.2		PH	
4C-03-01-B79	PM-C	I	5.9	2.9	10.9	-11.9	-7.3	4.6	CO	Mixed
4C-03-01-B81	PM	M	45.0	***4.6****			-4.4		B	Healed
4C-03-01-B85	PM	M	42.0	3.0	13.1	-9.2	-5.9	3.3	B	Healed
4C-03-01-B86	C	I	6.6	2.9	10.3	-12.0	-7.1	4.9	B	Active

1: In adults, age refers to median age. In preadults, age given is average dental age (see Chapter 2); Italics = C:N ratio is outside of 2.9-3.5 range; * = weight outside of calibration range