University of Alberta

Reconstructing Individual and Population Diet at Fishergate House: Application of a New Microsampling Method for Stable Isotope Analysis

by

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Abstract

The stable isotope signature of childhood diet changes from a fetal signal (similar to the mother), to a breastfeeding signal, and finally to a weaned signal, which may or many not match the adult diet. The patterning of these changes can give insight into child feeding practices and parenting. A stable isotope microsampling method was created to allow the analysis of these diets in a single individual. Tooth dentine was used as once formed it does not remodel, as does human bone. The method was developed and tested on a modern sample of 33 teeth collected from Edmonton, Alberta. The results showed changing early childhood diet with some individuals being breastfed, while others were bottle fed. Despite the large variety of weaning foods available to modern families, the weaned child diet was surprisingly uniform and did not reflect the variation seen in Canadian adults.

Dentine analysis using the new microsampling technique, as well as rib stable isotope analysis, was used to reconstruct juvenile diet from the Fishergate House (14^{th} – 16^{th} century) York, UK. 62 juvenile samples and 11 adult female samples were collected. No previous dietary reconstructions of the children from this site have been run, so it was important to establish the time of weaning for the population during this critical period of early childhood that often results in infant death. The high level of mortality for four to six year olds at Fishergate House led previous researchers to believe weaning was taking place at this time. In contrast, the results of this work showed that weaning was complete by two years. By looking at individuals, it is possible to see variation in weaning practice that

reflects the individual choices of mothers and children at Fishergate House. The dietary information for Fishergate House was also compared with growth and pathological data from the site to look more closely at health. The results of this study show that by looking at weaning at a population and individual level it is possible to look at the overall early childhood feeding pattern as well as at deviation from that pattern.

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Chapter 1

Introduction

1.1 Introduction

The bioarchaeological study of human diets is a thriving area of research. While there are many ways to reconstruct past diets, the focus of this work is on the use of nitrogen and carbon stable isotope analysis. This robust form of analysis is possible due to the use of dietary components to create human tissues creating an isotopic record of what was eaten (Katzenberg, 2008; Lee-Thorp, 2008). The stable isotope analysis of collagen is used to provide information on the protein component of the diet rather than the whole diet. Teeth reconstruct the diet at the time of tooth formation, while bone values reconstruct the diet within years or months of the time of death based on the age of the individual (juvenile or adult) and the turnover rate of the particular bone sampled. Stable isotope analysis can reconstruct both adult and juvenile diets, in terms of both population patterns and individual diets.

Reconstructions of the diets of individual juveniles in the past, as well as the dietary pattern of an entire juvenile population, are presented in this study. To analyze an individual's changing diet, it is necessary to serially sample a set of remains (Clayton et al., 2006; Fuller et al., 2003). While previous studies have done some serial sampling, the goals of this research required the development of a new microsampling method to allow a more nuanced look at juvenile diet throughout early childhood and including fetal life. A new method of microsampling for stable isotope analysis was created using a modern sample of

deciduous teeth from Edmonton, Alberta. This dissertation also focuses on the lives of children from medieval (14^{th} – 16^{th} century) Fishergate House, York, UK. For a closer look at the lives of these individuals, this study uses a combination of dietary analysis and growth and health data.

1.2 Research Development and Dissertation Content

The initial research questions this dissertation is based on seemed simple: is it possible to analyze the small area of deciduous tooth that contains the isotopic signatures of fetal life? Would this signal allow a researcher a window into the mother's diet during pregnancy? A review of the literature on serial sampling of human teeth clearly showed that current methods would not be able to reconstruct this diet (Clayton et al., 2006; Fuller et al., 2003). To help answer these questions, a microsampling method was developed to allow the study of changing juvenile diet during early childhood using a modern sample of human deciduous teeth. While the modern sample is interesting in its own right, it was also desirable to test the method on an archaeological population.

Fishergate House is an ideal population for testing the microsampling method due to the large number of juveniles present, a lack of previous juvenile stable isotope data, and an interesting mortality pattern that could be better understood through understanding juvenile diet at the site. This methodology will not only provide a look at the population weaning pattern, but also allow for the reconstruction of individual diets from the fetal period through early childhood. The initial osteological investigation of Fishergate House suggests weaning at the

site completed between four to six years based on age of peak mortality (Holst, 2005). However, this does not match the expected weaning age based on historical data for Britain and medieval Europe (Fildes, 1986; Shahar, 1990). The historical accounts and stable isotope analysis from other sites during the late medieval period suggest that weaning completed around two years of age. This simple research question about weaning time has major implications for the juvenile experience at Fishergate House, as well as the health of these individuals.

As this is a paper based dissertation, the main chapters represent articles that deal with a set of specific research questions. Each of these research chapters represents an independent paper intended for publication. For ease of reading, Chapter 2 is composed of the combined background sections of all these papers. This chapter outlines the important historical, anthropological, and scientific background needed to understand and interpret the results of this research. Chapter 3 outlines the creation and details of the microsampling method as well as the modern stable isotope results. Chapter 4 presents the results of the rib stable isotope analysis and is the first stable isotope analysis conducted on the Fishergate House juveniles. This analysis reconstructs the overall juvenile dietary pattern at Fishergate House. Chapter 5 contains the results of the stable isotope analysis of the teeth using the microsampling method previously outlined. This chapter presents a reconstruction both weaning pattern and individual diets at Fishergate House. For a more complete view of diet at the site, the teeth and rib results are also analyzed together. Chapter 6 is different from the previous chapters, as it does not focus on dietary reconstruction. Instead, Chapter 6 combines the dietary

data with growth and pathology data to try to understand health in these children. Chapter 7 provides a summary of the research and focuses on themes found throughout the research. This concluding chapter also contains a discussion of the future of this research.

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Chapter 2

Background

2.1 Biology of Breastfeeding and Weaning

Breastfeeding is a key aspect of being a mammal; however, there is a lot of variability in the practice. There are three main functions of breastfeeding that are shared by mammals: immune protection and reduced contact with dietary pathogens, a supply of energy and nutrients specific to an infant's needs, and fertility regulation (Sellen, 2009). Breastfeeding practices vary greatly in humans between cultures and over time due to the cultural component of breastfeeding in our species (Bogin, 1997; Dettwyler, 1995; Fouts, 2004; Sellen, 2007; Sellen, 2009; Stuart-Macadam, 1995; Van Esterik, 1988). Humans have a more flexible breastfeeding pattern than other mammals, which allows humans to adapt to environments where it is more difficult to balance maternal and infant needs. This also means that this vitally important period of human development will vary widely between cultures and sometimes does not truly meet the needs of the infant.

Before proceeding, it is important to define the term weaning, which many authors in the literature use variably. For this study, weaning is the process of switching a child from breast milk to supplementary foods. Once a child is no longer consuming breast milk it is considered fully weaned. Weaning can be a long or a quick process involving different kinds of supplementary foods (Bogin, 1997; Dettwyler, 1995; Fouts, 2004; Sellen 2001; Sellen, 2007; Sellen, 2009; Stuart-Macadam, 1995, Van Esterik, 1988). The introduction of supplementary

foods is also important to the understanding of weaning. Caretakers may give supplementary foods to infants early in life before they can chew and digest it, but often this is a way to include the child in meal times and not considered as a source of food (Dettwyler, 1995; Fouts, 2004; Stuart-Macadam, 1995; Sellen, 2009 Van Esterik, 1988; Van Esterik, 2008; Winikoff and Laukaran, 1988). For this study, weaning is considered to begin when supplementary foods start to make up a large component of the protein in an individual's diet, allowing weaning to be detectable using stable isotope analysis and making it visible to this study. The amount of supplementary foods needed to be visible with isotopic analysis will vary by child and types of weaning foods. The increase in supplementary foods should correspond with a relative decrease in the consumption of breast milk and eventually the full cessation of breast milk consumption. A fully weaned child would then eat either a child specific diet or a similar diet to its parents.

Not all human early childhood feeding strategies are equally successful, with many resulting in poor infant health. Specifically some strategies can result in poor growth, delayed development, and increased morbidity and mortality (Bogin, 1997; Fouts, 2004; Sellen, 2009 Stuart-Macadam, 1995; Van Esterik, 2008). The resulting health problems can be quite severe and last into adulthood. Early childhood feeding practices that negatively affect a child include lack of breastfeeding, irregular breastfeeding, early cessation of breastfeeding, and the use of nutritionally poor or contaminated supplementary foods (Bogin, 1997; Lewis, 2007; Sellen, 2009; Stuart-Macadam, 1995; Van Esterik, 1988; Van

Esterik, 2008; Winikoff and Laukaran, 1988). Contaminated supplementary foods, which increase the chances of illness and disease, were a major risk in the past. This is particularly true when there is no refrigeration, resulting in the consumption of spoiled foods, or where untreated water is used. Poor water quality can be a factor of the natural environment, though often human habitation and poor waste removal make water quality even more dangerous. These issues would have been very common in archaeological populations around the world.

The definition of early cessation of breastfeeding is controversial because the biologically optimal age of weaning is not known. There does not appear to be an upper limit to when breastfeeding is beneficial to a child, so the decision to wean always involves tradeoffs between maternal and child health and socioeconomic pressures (Bogin, 2009; Sellen, 2007). No human group bases breastfeeding and weaning practices purely on physiological factors. The median weaning age in human groups without manufactured infant food (baby formula or the equivalent) is between 30 – 36 months or about 2.8 years (Bogin, 1997; Bogin, 2009; Dettwyler, 1995; Sellen, 2007). Again this is an estimate with many individuals within these societies being weaned earlier or later. Different preferred weaning times are found in many societies, which illustrates that what people consider proper weaning behavior is constantly changing and can follow trends. In the present day and historically, the advice of knowledgeable practitioners influenced most mothers directly or indirectly, but they did what worked best for their own lifestyle and what seemed best for their child. It is clear that breastfeeding and weaning practices will have a major impact on child health

along with socioeconomic background and environmental factors that are often the focus of bioarchaeological studies. By understanding infant and childhood feeding practices in the past it is possible to better understand the culture as a whole and the tradeoffs mothers are making between health and necessity.

2.2 Stable Isotopes, Breastfeeding, and Weaning

Many aspects of past human diets can be reconstructed using stable carbon and nitrogen isotope analysis of bone and dentine collagen (Katzenberg, 2008; Lee-Thorp, 2008). Both $\delta^{15}N$ and $\delta^{13}C$ values reflect dietary protein, but they are incorporated into the body differently. Carbon primarily gives information on the kinds of plant foods eaten and marine resource dependence, while nitrogen provides information about where an animal is in the local food web. Marine resources can be indentified in past populations by combining $\delta^{15}N$ and $\delta^{13}C$ analysis. These isotopes can be used to reconstruct adult and juvenile diets. This study utilizes collagen from tooth dentine and ribs. Although bone collagen analysis is more commonly used, it requires a large sample with a fairly even age distribution through early childhood to reconstruct breastfeeding and weaning (Katzenberg, 2008; Lee-Thorp, 2008). The dentine in teeth forms during early childhood and does not remodel, so it will preserve early diet even as the child matures. In the interest of brevity and due to the excellent quality of isotope reviews in the literature, this background will not directly examine the details of specific stable isotope processes such as isotope fractionation and mass spectrometer measurements, but will focus more on the specific background

needed for the isotopic analysis done for this research. For more details on the basics of stable isotope analysis, please see Katzenberg (2008) or Lee-Thorp (2008).

Variability in the $\delta^{13}C$ values of human foods begins with plants, which incorporate atmospheric or aquatic carbon using the C_3 and C_4 photosynthetic pathways (Bender et al., 1981; Smith and Epstein, 1971). Differential fractionation during this process creates distinctive $\delta^{13}C$ groups in land plants, with C_3 plants such as wheat and oats ranging from about -20‰ to -34‰ and C_4 plants such as maize and millet ranging approximately between -9‰ and -16‰ (Bender et al., 1981; Deines 1980). Between plants, herbivores and subsequent consumers a whole-body trophic level effect of approximately +1‰ is seen, with individual tissue values varying according to their composition and formation pathway (DeNiro and Epstein, 1978). Under many conditions, bone collagen is enriched approximately 5‰ over dietary protein (Ambrose and Norr 1993; Lee-Thorp, 2008). Marine resource consumption also strongly affects $\delta^{13}C$ values. The main source of carbon in the marine environment is dissolved carbonate, which has a $\delta^{13}C$ value of 0‰ (Chisholm et al., 1982; Katzenberg, 2008; Schoeninger and DeNiro, 1984). This is much higher than the terrestrial source, atmospheric CO_2, which has a $\delta^{13}C$ value of -7‰. This difference is found in the animals eating in these different ecosystems, meaning that populations eating significant quantities of marine resources will have higher $\delta^{13}C$. This can be confusing in regions with high C_4 plant consumption, as the $\delta^{13}C$ ranges will overlap (Chisholm et al., 1982; Schoeninger and DeNiro, 1984; van Klinken et al., 2002;

Walker and DeNiro, 1986). When C_4 plants are limited, such as in medieval Europe, enriched $\delta^{13}C$ values are more likely due to marine resources than maize or sugarcane (Müldner and Richards, 2007a; 2007b; van Klinken et al., 2002). Marine resource consumption will also affect $\delta^{15}N$ values, which is not seen with C_4 plant consumption. The effect on nitrogen will be discussed in the following section.

Animals acquire nitrogen through dietary proteins. In the course of protein digestion and amino acid metabolism, the animal's tissues become enriched in ^{15}N relative to dietary protein because ^{14}N is preferentially excreted (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Schoeninger and Deniro, 1984). This results in a trophic level effect in which the tissue $\delta^{15}N$ values of organisms increase by roughly 3‰ to 5‰ relative to their diets, with the increases varying by species and living conditions (Bocherens and Drucker, 2003; Hedges and Reynard, 2007). The marine environment is composed of very long trophic chains, as almost all fish eaten by human are themselves carnivores. This means that diets rich in marine resources will have high $\delta^{15}N$ values (Minagawa and Wada, 1984; Müldner and Richards, 2007a; 2007b; Schoeninger and Deniro, 1984; Walker and DeNiro, 1986). Populations dependent on marine resources have higher $\delta^{15}N$ than those dependent on terrestrial animals. Marine consumption also increases $\delta^{13}C$ values. When $\delta^{13}C$ and $\delta^{15}N$ are analyzed together, it is possible to determine if marine resources are being utilized.

The trophic level effect also occurs in the nursing young of some species including humans, with a stronger effect seen in $\delta^{15}N$. Fingernail and hair samples

have clearly demonstrated this in human mothers and infants (Fogel et al., 1989; Fuller et al., 2006a; Katzenberg and Pfeiffer, 1995; Katzenberg et al., 1996). The regularity of this effect allows researchers to reconstruct the length of breastfeeding and the time of weaning due to changes in $\delta^{15}N$. At birth, an infant has a similar nitrogen isotope signal to its mother. Its tissues will maintain this value for a variable postnatal period that depends on the infant's growth rate and tissue turnover before being replaced by an elevated breastfeeding signal (Fuller et al., 2006a; Katzenberg and Pfeiffer, 1995; Katzenberg et al., 1996; Kinaston et al., 2009; Richards et al., 2002). Generally, this transitional period lasts for no more than a couple of months. The trophic level elevation occurs because the infant is consuming its mother's milk, a bodily secretion with $\delta^{15}N$ similar to her tissues. Human infants show a $\delta^{15}N$ trophic level increase over their mothers of approximately 2‰ - 3‰ during peak breastfeeding (Fogel et al., 1989; Fuller et al., 2006b; Katzenberg and Pfeiffer, 1995; Katzenberg et al., 1996; Katzenberg, 2008; Schurr, 1998). Infants that are bottle fed only do not show this enrichment (Fuller et al., 2006a). The tissue isotope signal changes again as supplementary foods begin to be introduced. Supplementary foods depress overall dietary $\delta^{15}N$ because they introduce dietary protein sources other than breast milk which tend to have lower $\delta^{15}N$ similar to items in the mother's diet. In response, the child's tissue $\delta^{15}N$ values begin to trend downward and eventually stabilize at a new level after weaning has finished. This new value could reflect a child-specific diet or the general diet of a population. The shift to the new diet may be characterized by a very steep drop in $\delta^{15}N$ values or by a slow decent to new levels, indicating the

speed at which weaning is completed and length of a mixed feeding period. Fogel et al. (1989) found that the infants in their study had fingernail $\delta^{15}N$ values close to those of their mothers three to five months after weaning. This demonstrates how quickly the tissue turnover rate is and the speed at which new diets can be detected.

Although nitrogen isotopes are the most informative for the trophic level effect of breastfeeding, carbon isotope values are also affected by breastfeeding and weaning. Fuller et al. (2006a) found that infants that were exclusively breastfed had a $\delta^{13}C$ increase of around 1‰ over their mothers, while infants that were bottle fed only showed no $\delta^{13}C$ elevation. These observations imply the presence of a trophic effect for $\delta^{13}C$ analogous to that seen in $\delta^{15}N$, consistent with the general $\delta^{13}C$ elevation of organisms relative to their diets. Because the magnitude of this difference is low, it may be more difficult to identify in smaller groups of infants, especially for populations consuming foods with a wide range of $\delta^{13}C$ values (both C_3 and C_4 plants). As with $\delta^{15}N$, infant $\delta^{13}C$ elevation begins to decline when weaning commences. In some studies this decline is more rapid than that seen for $\delta^{15}N$, leading some authors to suggest that $\delta^{13}C$ is more sensitive than $\delta^{15}N$ to the introduction of weaning foods (Dupras et al., 2001; Fuller et al., 2006a; Richards et al., 2003; White et al., 2001). Fluctuations in diet caused by supplementary foods may therefore be more prevalent when analyzing carbon signals.

Many studies have examined breastfeeding and weaning in past populations using the distinctive stable isotope signatures of collagen laid down

during those periods (e.g. Fuller et al., 2006b; Katzenberg and Pfeiffer, 1995; Katzenberg et al., 1996; Katzenberg, 2008; Nitsch et al., 2011; Prowse et al., 2008; Tuross et al., 1988). Most studies rely primarily on nitrogen, with age-related shifts in $\delta^{15}N$ values of juvenile skeletal remains used to estimate the length of breastfeeding in past populations, to suggest when weaning foods were introduced, and when weaning was normally completed. Carbon has also been used, with shifts in $\delta^{13}C$ values compared to shifts in $\delta^{15}N$ values to track the introduction of particular solid foods in the diet and $\delta^{15}N$ levels used to estimate the duration of breast milk consumption.

2.3 Sampling for Stable Isotope Analysis

In young juveniles, collagen samples from bones such as ribs likely reconstruct diet in the few months prior to death due to rapid bone remodeling during this stage of life (Fuller et al., 2006b; Jay, 2008; Nitsch et al., 2011). Dentine, which does not remodel, can be used to recover dietary signals from earlier periods in life that have been preserved within the teeth. In many archaeological weaning studies, diet is reconstructed by analyzing diet by analyzing bone samples from a large number of juveniles and seriating the values by estimated age at death. This methodology was the earliest to be developed in the literature and is still often used, with the most commonly sampled element being the rib (e.g. Jay, 2008; Mays et al., 2002; Nitsch et al., 2011; Richards et al., 2002). Another potential approach is to analyze the dentine of whole teeth from multiple individuals, using the $\delta^{13}C$ and $\delta^{15}N$ values for each tooth position as

indicators of diet in the age range at which that tooth typically forms. Dupras and Tocheri (2007) analyzed 297 deciduous and permanent teeth from Roman period Kellis, Egypt. For each tooth, all dentine was processed as a single sample. Mean dentine $\delta^{13}C$ and $\delta^{15}N$ values were then generated for each tooth position. By sampling multiple teeth in this way from several individuals, diet can be reconstructed for roughly the first 20 years of life, including the breastfeeding and weaning period. This method can generate useful results; Dupras and Tocheri (2007) found statistically significant differences between the deciduous and permanent teeth at Kellis, reflecting the different diets associated with these ages. However, it requires a large sample of teeth and by homogenizing so much dentine, potential information is lost.

Serial dentine sampling within a single individual is a way to produce a more detailed look at diet. The common methodology for studies of this sort is to homogenize dentine from a tooth region, for instance a tooth crown or the tooth root. The results of studies like these are stable isotope values that are the average for the age range of development for that tooth section. Previous studies have shown that serial dentine sampling can detect changes in diet over time (Clayton et al., 2006; Fuller et al., 2003). These studies have used relatively large dentine samples, consisting of an entire tooth or a major portion such as the crown. Clayton et al. studied weaning age at Matjes River Rock Shelter in South Africa (2006). This was primarily a bone study, but due to underrepresentation of two to four year olds in the Matjes sample, the root tips of deciduous canines and deciduous molars were also used. The roots of these teeth complete their

formation between two to four years. By using them as proxies for the two to four year olds missing from the sample, Clayton et al. (2006) were able to make the series complete enough to properly interpret.

Serial sampling was a focus of Fuller et al.'s (2003) study, which investigated weaning times at medieval Wharram Percy. Twenty-one deciduous second molars, eight permanent canines, and eight permanent third molars were used in the study. Each tooth was sampled into three large sections: crown, cervical root half, and apical root half. Samples were taken horizontally; the authors cautioned that this was a known limitation of their study as that is not how dentine forms (see section 2.4 for more on tooth formation). Despite this limitation, the results clearly showed changing diet through the breastfeeding and weaning period. This sectioning method generalized diet from large periods of time, because the crown was not subsampled, this strategy was not able to reconstruct a fetal life value. Fuller et al. (2003) remarked that their method could be improved by sectioning along the lines of growth, which previous studies had also not done. The problem with the current strategies of serial sampling described here is that areas, such as the deciduous tooth crown, reflect more than just the early childhood diet they are used to represent (Clayton et al., 2006; Fuller et al., 2003). While these serial studies do provide a look at an individual's changing diet, it should be possible to get results that are even more specific through microsampling, which should be more flexible and precise in sampling location.

Eerkens et al. (2011) recently published a human microsampling method that utilizes smaller serial cross-sectional cuts than those analyzed in earlier work, though larger ones than used in this study (see Chapter 3). The sample contained the permanent first molars from five individuals and the first, second, and third molars from a single individual. All individuals were from the Marsh Creek site in California. Enamel and cementum were removed from the teeth leaving the dentine, which were then fully demineralized using a dilute HCl soak. The demineralized collagen models were then sliced horizontally into five to ten 1-2 mm parallel samples. Eerkens et al. (2011) report that they could detect isotopic changes attributable to weaning, but that again some clarity was lost due to horizontal sectioning of the teeth, which, as reviewed in section 2.4, form in parabolic increments. Because this method used permanent molar teeth rather than deciduous teeth, there was no opportunity to examine dentine forming prior to birth for potential fetal $\delta^{13}C$ and $\delta^{15}N$ values.

Faunal teeth have also been used for dentine microsampling (Balasse et al., 2001; Kirsanow et al., 2008). Although these methods are not directly applicable to the analysis of human teeth due to differences in size, shape, and development, they are still of interest here. Balasse et al. (2001) looked at dietary changes in carbon and nitrogen stable isotopes in the dentine of cattle. The molars of five steers from an experimental farm were demineralized and sliced into 4mm sections (these can be considered microsamples for cattle teeth, which are significantly larger than human teeth). Using this method, the authors were able to detect isotopic shifts corresponding to the known pattern of weaning in the

cattle. Kirsanow et al. (2008) microsampled at an even more precise level as their study focused on determining seasonal variation in dentine collagen $\delta^{18}O$ and δD values of sheep and goats. The teeth were demineralized in EDTA solution and 1mm diameter microsamples were taken in a longitudinal series moving down the molars using a punch and creating truly tiny microsamples. The samples in this study were still quite large due to the large size of these animal teeth (resulting in greater sample depth), and no issues in sufficient sample weight for mass spectrometry were found. This strategy is sufficient when sampling animal teeth that are forming in horizontal layers, but would not be applicable to human teeth. To accurately microsample human teeth the difference in formation, size, weight, and ratio of carbon and nitrogen found in the collagen would have to be overcome. Chapter 3 outlines how microsampling in accordance with how teeth grow allows increased precision in the sampling of human teeth, while maintaining a sample weight sufficient to reconstruct diet. Histological sectioning of teeth to ensure that samples are taken from known locations that relate to important life stages rather then a set sampling spacing also enhanced sampling precision.

2.4 Human Tooth Formation

Presented here is a method is based on the layered, parabolic pattern of human dentine formation and which utilizes the histological identification of the neonatal line as a marker of birth. It also takes advantage of the fact that a portion of human deciduous tooth dentine is laid down prior to birth (Scheuer and Black,

2004; Van der Linden, 1983; Zaslansky, 2008), allowing *in utero* values to be studied in addition to values reflecting breastfeeding and weaning. Consideration of how teeth develop is an important aspect of this method. To understand why the method works, it is important to understand how human teeth form.

Human teeth begin forming with the development of the dental lamina approximately six weeks after conception. The appearance and early development of the tooth germs that develop along this lamina is broken down into three stages: bud stage, cap stage, and bell stage (Hillson, 1996; Ruch, 1984; Scheuer and Black, 2004; Van der Linden, 1983). Matrix secretion and mineralization begin in the late bell stage. This process is the same for both deciduous and permanent teeth, though the timing is different.

Matrix secretion initiates at the dentinoenamel junction, with enamel formation proceeding outward from this boundary while dentine formation proceeds inward toward the future location of the pulp cavity. Both enamel and dentine are laid down in incremental layers. Formation is in two phases, the first of which involves the deposition of an organic matrix and the second of which is the mineralization of the tissue. Odontoblasts are the cells that secrete dentine, and are responsible for the formation of its organic matrix, or predentine (Hillson, 1996; Linde, 1989; Van der Linden, 1983). This matrix is formed mainly of collagen (approximately 90%) and other proteins (Hao et al., 2004; Mjör, 1984). The first layers of predentine laid down at the dentinoenamel junction will form mantle dentine, which contains less collagen (Mjör, 1984; Zaslansky, 2008). After this dentine is secreted, normal dentine production begins and forms the bulk of

the crown dentine. As the predentine is laid down, mineralization begins and follows quickly behind in a wavelike pattern of development. The mineral precipitated during mineralization does not replace the original organic matrix, but is secreted within it (Jones and Boyde, 1984; Mjör, 1984; Van der Linden, 1983; Zaslansky, 2008). This is important, as a portion of the organic matrix of the deciduous teeth forms during fetal development and should preserve a record of collagen stable isotope values at that time.

The dentine in deciduous teeth begins forming in the early weeks of prenatal life with timing as follows (Hillson, 1996; Ruch, 1984; Scheuer and Black, 2004; Van der Linden, 1983). Deciduous central incisors begin forming 13 – 16 weeks after fertilization, followed by deciduous lateral incisors at approximately 15 – 17 weeks and deciduous canines at 15 – 18 weeks. Molar formation times are reported with the most variation, but deciduous first molars begin forming around 15 – 17 weeks after fertilization and deciduous second molars begin at 16 – 24 weeks. Clearly, dentine development is ongoing in all teeth for a sizable portion of the fetal period. Mineralization begins immediately after matrix formation, approximately two weeks after the matrix begins for all teeth (Hillson, 1996; Van Der Linden, 1983). The closeness of this timing means that literature estimates of the ages of formation of the teeth, which are based on mineralization, will be reasonably accurate estimates of the ages of the collagen formation in their dentine. A tooth is considered fully formed when the apical tip of the root has finished forming and is fully mature in appearance. For the deciduous central incisor, lateral incisor, and first molar this happens at

approximately 1.5 to two years of age (Hillson, 1996; Scheuer and Black, 2004; Van der Linden, 1983: 168). For the deciduous canine and second molar this happens around three years of age. Liversidge and Molleson (2004) found these estimates to be slightly early, but still very close to their own longitudinal study of tooth formation using radiographs. Their estimates place root closure at half a year to a full year later than previous estimates. Population differences in tooth formation timing are also possible (Liversidge and Molleson, 2004; Scheuer and Black, 2004).

The enamel portion of the crown forms simultaneously with the dentine (Hillson, 1996, 2005; Van der Linden, 1983). Figure 2-1 shows a simplified diagram of the incremental formation of both enamel and dentine. Enamel formation also begins with matrix secretion. The initial matrix secreted by the ameloblasts has a large organic component, but during the mineralization process of enamel this organic component is broken down leaving dental enamel composed almost completely of mineral. The incremental organization of enamel established during development is not destroyed by this replacement process and is preserved in the mature enamel. Examination of postnatal enamel with a microscope reveals incremental lines that represent its formation over regular intervals of time. The neonatal line is the first of these lines that can be observed clearly in the enamel.

The neonatal line results from tooth formation disruption at birth. In the enamel, this line extends from the dentinoenamel junction (DEJ) to intersect the enamel surface of the tooth (Hillson, 1996, 2005; Norén et al., 1978; Van der

Linden, 1983). Given that dentine is also laid down in layers and also shows incremental patterning after birth, theoretically a line should also form in the dentine at this point. However, the neonatal line varies in prominence in enamel and is even more difficult to visualize in dentine (Hillson, 1996, 2005; Norén et al., 1978; Sabel et al., 2008; Skinner and Dupras, 1993). Because the enamel and dentine should be forming at a similar rate, the neonatal line in the dentine should extend upward into the dentine from the same point on the DEJ, and at a similar angle. For this study, the neonatal line was examined and measured in the enamel and extrapolated in the dentine because it is difficult to visualize in dentine. Further details on visualization of the neonatal line and its relationship to the sampling method used here are in the methodology section of Chapter 3.

The long period of tooth formation spanning the time from shortly after conception to between two and three years after birth make it likely that stable isotope studies of deciduous dentine will be able to pick up dietary signals from many different important life stages, including fetal life (the maternal diet), breastfeeding, and (depending on weaning age) weaning. While some previous studies assumed that all dentine of the deciduous teeth would be from the breastfeeding period (Dupras and Tocheri, 2007), it is clear that the early dentine found before the neonatal line should represent fetal life. This dentine is not accessible through bulk tooth sampling or from large serial samples of the entire crown (Clayton et al., 2006; Dupras and Tocheri, 2007; Fuller et al., 2003). However, microsampling offers a way to get at this small preserved record of fetal life. The neonatal line forms in the enamel at birth and provides a visible

microstructure demarcation between the portion of the tooth formed *in utero* and that which formed after birth, providing a potential marker to identify the portion of the dentine laid down prenatally.

2.5 Background on Fishergate House and Medieval York

Fishergate House is an archaeological site in York, UK excavated between 2000 and 2002 (Spall and Toop, 2005). The remains excavated from the site represent a medieval suburb of York located on the banks of the River Ouse (Fig. 2-2). The neighborhood is located at a distance from the historic core of York and the people living there were mainly of the working poor. While there was Roman and early medieval occupation of the suburb as a habitation site, the most intensive funerary use occurred in the mid to late medieval period. A total of 244 individuals were excavated from the site in good to moderate condition (Holst, 2005). These remains were found primarily in a narrow linear cemetery located south of the monastic site of St Andrew's. During this period, different cemeteries would have individuals from different backgrounds, so identifying the church associated with a cemetery is advantageous to the proper interpretation of remains (Lewis, 2007).

During the 11th and 12th centuries, several churches were founded in York – St George, St Andrews, St Helen, and All Saints – though most fell out of use during the medieval period. When the medieval cemetery at Fishergate House was found, it was unclear to which church it belonged (Spall and Toop, 2005). All evidence indicates that this is a lay cemetery, though it was located just south

of the Gilbertine priory of St Andrew's. Archaeological excavation showed that a wall separated the priory from the cemetery, establishing it as a separate complex. The narrow cemetery runs east-west from the Fishergate to the river Ouse. Based on the sparse historical evidence, it is believed that the cemetery located during the excavation belongs to the church of St Helen. St Helen was established just prior to the late 11th century and was abandoned in the 16th century. The pottery found mixed in with the cemetery sediments suggests a date of peak use between the mid-14th to mid-15th century. Most of the remains are believed to be from this period.

The archaeology of the cemetery indicates that individuals were probably interred in small groups (Spall and Toop, 2005). Children were discovered throughout the cemetery, with a greater concentration in the northern part of the site. The southeastern area of the site had the fewest children. This distribution is important to understanding the cemetery as in many cemeteries young children, particularly infants, are buried separately from adults (Lewis, 2007). It is believed that these kinds of burial choices indicate that these children were seen as relating differently to their communities then did the adults. In this case, there is no indication that young children are being treated differently than adults.

All individuals were buried with their heads to the west and feet to the east. No grave markers survived in the cemetery and it appears that while a few individuals were buried in coffins, the majority was wrapped in shrouds. The excavation recovered only three grave goods: a scallop shell indicating pilgrimage to Santiago del Compostello, a buckle, and a ring (Spall and Toop, 2005). Overall,

the lack of grave goods and the style of burial imply that the individuals at Fishergate House were of a low socioeconomic class. St Helens was taxed the least of any church in the area, further supporting their low socioeconomic standing (Dryer, 1989; Wilson and Mee 1998). All of the historical evidence indicates that these individuals would have been part of the working poor. The individuals in the cemetery likely had very similar economic resources, and wide socioeconomic divisions within the Fishergate House sample are not expected.

Throughout the medieval period, York was an important political, clerical, and financial center of England. As the second largest city in the country and one of the largest international trading centers in England, York had a large and thriving work force (Gillingham and Griffiths, 2000). In the mid to late medieval period (14^{th} – 18^{th} century) many women entered the workforce as the demand for workers grew. There was a general rise in the standard of living for many individuals in the increasingly urban environment. During this period, women still earned less than their male counterparts and had less reliable incomes (Gillingham and Griffiths, 2000; Jewel, 2007). The increase of women in the workforce meant increased pressure to wean children younger and to use methods such as bottle feeding or wet nursing to free mothers to work long hours away from the home. Mothers often either left their young children at home or brought them to work with them (Hanawalt, 1977, Jewel, 2007). The records suggest that children would have had little supervision in either environment increasing the likelihood of accidents and exposure to contaminants.

The living conditions in York would have been rough compared to modern western standards with people and animals living in tight proximity. This would increase the likelihood of household accidents and zoonoses. There would be little sanitation and most human and animal waste would have gone into the river Ouse, which was also the main water supply for the city (Grauer, 1989). All of these factors would lead to the risk of epidemics and generally difficult living conditions for the people living in medieval York. This is particularly true of the Fishergate House individuals who were not only buried near the river Ouse, but likely lived near it as well. Not only would the children consume the contaminated river water, they would also play in it. This could result in drowning, but a less obvious danger would be the exposure to many water borne parasites and other pathogens. Typhoid is one such pathogen that can be found in water contaminated with feces and has resulted in numerous epidemics (Grumbkow et al., 2011; Lewis, 2002; Luckin, 1980; Roberts and Manchester, 2007). Many potentially hazardous environmental factors could have affected the lives of children in general during this period, and those buried at Fishergate House in particular.

2.6 Food in Medieval York

While more limited than modern markets, medieval British markets would have had a variety of foodstuffs available. Many foods would have been seasonal, but preserving methods like smoking, salting, drying, and pickling were used to allow the consumption of seasonally or locally unavailable foods. Common

staples in Britain were grain, legumes, vegetables, fruits, dairy products, eggs, meat, and fish (Adamson, 2004; O'Connor, 2000; Roberts and Cox, 2003). Spices, salt, honey, and nuts such as walnuts and chestnuts would also be available in smaller quantities. Wheat would be the most plentiful grain, but barley, rye, and oats would be available. Vegetables and legumes such as beans, peas, onions, leeks, spinach, cabbage, and parsnips as well as other local leafy greens and root vegetables would have been widely utilized. Common fruits would have been apples, pears, and peaches (from the 13th century onward), as well as local berries (Adamson, 2004; Roberts and Cox, 2003). Meat would come from pigs, cows, lamb, and chicken (or other fowl both domesticated and wild). Fresh water and marine fish would also be widely eaten during this period. Shellfish would have been less commonly consumed, particularly among the lower classes. Ale would be the most widely available beverage other than water, which was not recommended for drinking.

Local farmers would supply food to the surrounding area, but trade of foodstuffs across Britain was common (Adamson, 2004; Hall, 2000; Rycraft, 2000). Britain also had extensive commerce with the European continent during this period and trade for foods not found in Britain was possible. Foods coming from the continent would be more expensive and more likely to be high status items finding their way only to the affluent. Some trade goods would be inexpensive and widely available, such as pickled or salted cod or herring (Adamson, 2004; Barrett et al., 2004). The wide availability of fish was linked to

increased demand as the number of religious fasting days grew during the Middle Ages.

The people of York would have had access to a diverse range of food products. The historical and archaeological evidence indicate that most foods were not as highly separated by social class as one might expect (Hanawalt, 1977; Müldner and Richards, 2005). Many foods believed to be essential dietary components were regulated to allow the poor to purchase them, such as ale. Due to the variation in supply and price of food from the countryside, many individuals kept animals and grew their own food. Grains, particularly wheat, meat such as pork and fish, dairy products, and vegetables would be widely available for all socioeconomic classes, though in varying degrees of quality and freshness. The historical records indicate that although many products were traded in the city, York authorities did not set the prices or market for meat and grains being brought into the city from the surrounding countryside, the local farmers did (O'Connor, 2000). This could result in lower quality goods being sold at higher prices, which encouraged many city inhabitants to grow their own food as much as possible. All available space around homes in the city would be used for this purpose. Most local food would be produced in city suburbs such as Fishergate House, which were not as densely populated as the city centre.

Grains were transported from the countryside where C_3 grains such as wheat, rye, oats, and barley dominated although millet, a C_4 plant, was also known. Local wheat and rye would be the major staple grains due to their dominance in bread making at the time. Some vegetables were also brought in

from rural areas, but historical sources indicate that a substantial quantity of vegetables would have been grown in small plots in the city itself (Hall, 2000; Rycraft, 2000). Fruit would be available in smaller quantities, as would other expensive sugary items. Some fruits, such as apples and pears, could be brought in from the local countryside or even grown in the city (Rycraft, 2000). More exotic fruits were transported from farther away. Sugary products other than fruit, such as sugarcane, would not have been widespread even in the very high socioeconomic classes. Sugarcane is the only other C_4 plant that could be bought in medieval Britain and would be very unlikely to be consumed by the urban poor even in a large city like York (Adamson, 2004; Hall, 2000; Roberts and Cox, 2003; Rycraft, 2000).

People ate eat beef, pork, and mutton throughout the medieval period (Hanawalt, 1977; Müldner and Richards, 2005). Beef, while quite prominent in the historical accounts due to the number of butchers listed in the records, would have been one of the more expensive meat options. The beef bought in York would have come from the surrounding countryside (O'Conner, 2000; Rycraft, 2000). Many if not most of the inhabitants of York, on the other hand, kept pigs. There is far less evidence for the sale of pork, but much legal mention of the responsibilities of urban pig owners. Eggs would also be a more common food, as domestic fowl were kept in the city as well (Rycraft, 2000). Dairy products were another important foodstuff sold in the city, but produced in the local countryside.

The population of York, as a major trading hub for marine food being transported to inland cities, would have benefited from available marine food

(O'Connor, 200; Rycraft, 2000). Many varieties of salted fish would be available, but fresh was also available. Fishmongers were highly regulated to ensure their stock was fresh and suitable for consumption by the city inhabitants. As York is a distance from the sea fresh fish was likely much more expensive than the salted or otherwise preserved fish. Increased pious devotion during the period would have increased the levels of marine resources being utilized by all classes, not just the clergy or nobility (Barrett et al., 2004; Hanawalt, 1977; Müldner and Richards, 2005; 2007a; 2007b). Barrett et al. (2004), in their study of fishing during the medieval period in York, discovered that fresh water fish were depleted by the late medieval period, which increased the demand and reliance on marine fish such as cod and herring.

The dependence on C_3 grains such as wheat, barley, and oats and higher trophic level proteins such as pig and marine fish has been supported by stable isotope analysis. Müldner and Richards (2007a; 2007b) have conducted two large studies of diet in York, one focusing on the late medieval period and the other looking at York from the Roman period to the early 19th century. These studies showed that diet in the city did change from the Roman period to the 19th century. One important shift occurred during the late medieval period when intense marine resource use emerged. They found that there were no significant dietary differences between males and females in the medieval period. While Müldner and Richards suspected socioeconomic differences were playing a part in the range of their results, they did not have clear indication of this based on cemetery affiliations. Socioeconomic stratification is often assumed to be the cause of

dietary differences in medieval populations as this was a major point of differentiation between groups drawn by medieval authors and often modern historians. Müldner and Richards (2007b) also found evidence that pigs were an important source of protein in medieval York. As was discussed above, pigs are well established as a major source of meat by historical accounts of the city.

The documentary evidence suggests that even very low status individuals would likely show signs of a marine/meat rich diet due to widespread availability in York through trade and animal husbandry in the suburbs. Müldner and Richards (2007a; 2007b) examine diet in many communities in York, but they do not cover the burials at Fishergate House, nor do they look at the diets of juvenile individuals. Thus, stable isotope analyses conducted to date on samples from York have only considered higher social status individuals and the middle classes. Due to potential differences in diet due to socioeconomic status, it is important to continue to explore diet at York through the Fishergate House sample, which is made up of the urban working poor. A full reconstruction of juvenile diet looking at breastfeeding, weaning, and the eventual child diet that may or may not match that of the adults will also be valuable. No previous work in York during the late medieval period investigates early childhood diet.

2.7 Written Accounts and Stable Isotope Studies of Weaning in Britain

It is well documented that life during the medieval period was difficult both for adults and for children. Reports of mortality rates from 16th century England estimated that 27% of juveniles died before age one and that in London

during the non-plague years, 36% of juveniles died under the age of six years (Lewis, 2007). It is speculated that many juvenile deaths after one year of age were the result of weaning stress that could easily be linked to poor weaning foods and practices that lead to poor nutrition, infection, and death (Fildes, 1986; Fildes, 1995; Schofield, 2006; Waldron, 2006). Many sources have made it clear that medieval parents were often doing what they thought best based on the medical and common knowledge on childrearing available at the time. Unfortunately, many of the common childrearing practices were not beneficial to the child.

Supplementary foods such as animal milk or gruels might be introduced right after birth. Feeding newborns supplementary foods rather than breast milk was usually done out of the fear of poor quality breast milk (Fildes, 1986; 1995; MacLehose, 1996; Shahar, 1990). Early inclusion of supplementary foods was not done in all cases, but was suggested by the medical profession at the time if poor quality milk was suspected. Poor quality milk was seen as very dangerous for the child, more dangerous than animal milk substitutes. Colostrum in particular was considered bad for a newborn because it looked different compared to breast milk and was suspected of being unhealthy, this is in direct opposition to what is now known about the importance of colostrum for long-term child health (Cunningham, 1995; Fildes, 1986; 1995; Heywood, 2001; Stuart-Macadam, 1995). Colostrum helps transfer a mother's immunities to the child and builds a strong immune system. It is not known how many mothers may have avoided feeding their baby colostrum or even have fasted their newborns for a day before

beginning breastfeeding. Varied practices would be expected during the first couple of days of life, but following this breastfeeding by the mother was the norm.

A wet-nurse might be used during the late medieval period, initially by the nobility and then extensively by the middle class as well (Fildes, 1986; 1995; Green, 2001; Heywood, 2001; MacLehose, 1996; Shahar, 1990). Wet-nurses were seen as a way to protect delicate ladies and preserve their figures. The prevalence of the use of wet-nursing varied by region and by socioeconomic status, though popularity in Europe seems to have peaked between 1500 and 1800 (Fildes, 1986; 1995). Fildes' (1995) sources indicate that wet nursing was less prevalent in Britain than in the rest of Europe during this period. It would not have been common for lower class women to send their children to be wet-nursed, though many might have been employed as wet-nurses. The use of wet-nurses would likely not be detectible using stable isotope analysis. The breastfed infant would express the expected pattern of a trophic level increase regardless of whether the milk was provided by its mother or another woman. It is possible that the children of wet-nurses may have been weaned earlier, though the evidence suggests that all infants from this period were weaned quite young.

From a health standpoint, wet nurses were preferable to methods of artificial feeding available at the time. By the late 15th and 16th century in Britain, many types of artificial feeding methods were available (Fildes, 1986; 1995; Lewis 2007). Children could be fed cow or goat milk from suckling horns or small suckling pots or bottles. These method would be used if the mother died

during the breastfeeding period or her milk dried up before weaning, but also if the mother needed to be away from the child for long period of time. Use of these artificial methods increased even more during the eighteenth century with increased industrialization. It is possible, even during the medieval period, that a child would not breastfed or only be partially breastfed, which could result in nutritional stress. A mix of breastfeeding and artificial feeding was believed to be used by working people during the medieval period due to mothers working out of the home (Fildes, 1986; Schofield, 2006). This would be increasingly common in Britain through the late medieval period to the early modern period as the economy continued to grow, particularly for individuals of lower socioeconomic status who would have more opportunities for wage earning (Schofield, 2006). Historical sources alone cannot illuminate this trend. Significant mixed feeding would be visible using stable isotope analysis, though it is not expected in this population. Bottle feeding was still time consuming and early weaning of children was more common than prolonged bottle feeding in lower class individuals.

There are not extensive historical records on weaning practices in Britain during the late medieval period, though there are a few key resources. Records from the medieval period suggest that the preferred or proper time to wean a child was around the age of two for medieval Europe as a whole (Fildes, 1986; Shahar, 1990). The justification given for this at the time and by later researchers is the presence of the child's complete deciduous dentition, indicating the ability to eat solid foods. Fildes (1995) proposes more variation in weaning practice in medieval Europe, with the age of cessation of breastfeeding ranging from nine to

twelve months in some areas and from two to three years in others. The age at which physicians said children were to be weaned during the 16th century seems to agree with the age at which the samples of children in the historical record studied by Fildes were actually weaned (1986). Following the medieval period, mothers appear to be weaning children earlier than medically recommended at both that time and today due to increased pressures of industrialization and urbanization (Fildes, 1995). During later centuries, the medically recommended age of weaning changed so that it was more similar to the actual practice of the people, showing that there was interplay between actual practice and medical suggestion.

In Britain, there was a long-term trend toward earlier weaning (Fildes, 1986; 1995; Heywood, 2001). The median age of weaning in the early 16th century was around 18 months, but this changed to around seven months during the late 18th century (Fildes, 1995; Heywood, 2001). These ages were collected from historical accounts of the time and compiled by modern historians. Weaning foods were generally soft foods often macerated in some way to make them easier to chew (Fildes, 1986; 1995; Green, 2001; Heywood, 2001; Lewis, 2007; Shahar, 1990). Honey was often suggested as a proper food, as were light gruels, meat broths, pap, and panada. Pap is a very thick gruel made with ground grain, while panada is a kind of bread soup that is made of bread boiled in milk, broth or water. Most solid foods such as meat would be introduced later. Only wealthier children would have been given fresh fruits and vegetables regularly.

The historical sources alone will not provide answers on what weaning and breastfeeding practices were carried out in the past. Children and family life, particularly lower class life, were not a priority for medieval writers who were primarily high status males. Stable isotope studies of weaning provide a way to get at the actual weaning practices of different groups, rather than the ideal practices that were more likely to be written down. Historical writers often overlooked the lives of children, which make it even more important for current researchers to attempt to reconstruct this important part of childhood.

Fuller et al. (2006a) used stable isotope analysis to look at breastfeeding and weaning practices in Late/Sub-Roman Britain. The subadults for their study were from the Queenford Farm site in Oxfordshire. Both carbon and nitrogen stable isotope analysis were performed on rib samples and a few femur samples. There were not enough individuals in the zero to 1.5 year age range to exactly pinpoint the introduction of weaning foods in this population. However, the $\delta^{15}N$ values gradually decline after age two until around age four. The results indicate the cessation of breastfeeding by three to four years. Both the $\delta^{15}N$ values and the $\delta^{13}C$ values indicate a different diet for children during the weaning years with stabilization at an adult normal value after this point. This weaning age matches what Holst (2005) suggested for the Fishergate House sample. However, this study does not directly apply to the Fishergate House sample, since it is from a much earlier time period.

Most work on breastfeeding and weaning in Medieval Britain (10^{th} to 16^{th} century) has been conducted on samples from the Wharram Percy site (Fuller et

al., 2003; Mays et al., 2002; Richards et al., 2002). The findings from these show general agreement, but they do vary a bit in the details of their findings. Mays et al. (2002) used nitrogen stable isotope analysis to examine weaning age using collagen extracted from ribs. The results showed that $\delta^{15}N$ values of the infants were elevated over the adult norm as expected with the peak at one year of age. The levels then dropped and resembled the adult norms by around age two. This would indicate that weaning occurred between the ages of one and two years with weaning ending around age two. This finding was supported by another study using both carbon and nitrogen values of collagen extracted from rib samples (Richards et al., 2002). A later study by Fuller et al. (2003) confirmed the earlier studies, but focused on dietary differences between individuals who survived the weaning period and those who did not, to determine if there was a difference in the weaning pattern. They found no differences between the groups and believe that completion of weaning by age two should be considered normal for the Wharram Percy site. It is interesting to see that the later Wharram Percy site actually has an earlier weaning age than the Queenford Farm site (Fuller et al., 2006a). This matches what the historic accounts tell us of the weaning pattern in medieval Britain and makes a strong case for expecting the Fishergate House individuals to have a weaning age of around two years (Fuller et al., 2003; Mays et al., 2002; Richards et al., 2002). These studies leave room for more weaning studies in Britain that focus on different locations and socioeconomic groups.

2.8 Studying Health Using Diet, Growth, and Pathology

Previous sections have outlined the fact that the weaning period is particularly stressful and important to understanding early childhood health. Diet in particular is linked to juvenile nutrition, which is directly linked to growth and illness susceptibility during early childhood (King and Mascie-Taylor, 2002; May et al., 1993; Schroeder et al., 1995). The follow sections outline the links between diet and nutritional state as well as the resulting impact on growth and illness. By looking at these factors together, it is possible to start to understand health in past populations.

2.8.1 Nutrition and Diet

Many infant feeding and weaning practices can result in malnutrition. Parental choices that limit the intake of breast milk and which often use nutritionally poor or contaminated supplementary foods can lead to illness, poor nutritional health, and faltering growth (Lewis, 2007; Sellen, 2009; Stuart-Macadam, 1995; Van Esterik, 1988; 2008; Winikoff and Laukaran, 1988). Early weaning, which is known to have been the norm in medieval Britain, would be negatively affecting childhood health during this period. Completion of weaning time in Britain had fallen to two years of age by the late medieval period; this trend is seen both in the historic literature and in stable isotope reconstructions of weaning from Britain (Fildes, 1986; Fuller et al., 2003; Mays et al., 2002; Richards et al., 2002; Shahar, 1990). Contaminated weaning foods would also be a major contributor to poor health during the medieval period due to untreated

water and the lack of refrigeration. Clearly, understanding weaning practices is crucial to understanding health during the early childhood period. When peak mortality does not align with weaning something must be happening to put a different segment of the population at greater risk.

Modern studies show a statistical difference in the survival rates of infants with different levels of nutrition due to poor infant feeding practices with malnourished individuals being less likely to survive. May et al. (1993) looked at the effect of nutritional supplementation on tooth and bone mineralization of malnourished Guatemalan children. The supplemented children did show some improvement in bone mineralization. Despite supplementation, however, malnourishment was detrimental to growth, with even supplemented children showing growth delays and non-specific stress indicators including linear enamel hypoplasia. The malnourished children in the study appeared to have dual problems with a synergistic loop of malnutrition and illness that was affecting this development.

Schroeder et al. (1995) also looked at the effect of nutritional supplementation on the growth and health of Guatemalan children. The authors found a similar pattern of improved bone mineralization with supplementation to that reported by May et al. (1993), but also found that the period in which supplementation had a significant effect on mineralization is limited. After age three, supplementation had no effect on growth, so malnutrition appears to have the greatest effect on growth in the early childhood period. Schroeder et al. (1995) conclude that proper early nutrition is very important to growth in body length.

The authors also found that malnourished children suffered from more gastrointestinal illness and generally poorer health; diarrheal disease was a particularly frequent and severe factor affecting health.

King and Mascie-Taylor (2002) studied faltering growth in children from Papua New Guinea. The authors discovered that socioeconomic factors were an important determinant of body size (both height and weight) with stunting being a result of poor nutrition. King and Mascie-Taylor (2002) found a large decline in growth after six months of age and equate this to greater levels of infection, as well as the late introduction of solid food resulting in inadequate nutrient intake from breast milk alone. When looking at diet and weaning patterns in modern groups, it is possible to determine the source of poor nutrition (for example, poor food sources and feeding strategies or physical stressors resulting in poor nutrition). This is more difficult in past populations, though by looking at diet and growth, which can be studied in skeletal populations, it is possible to start to understand the nutrition and health of these individuals.

2.8.2 Growth and Health

Health is not something that can be directly studied using human skeletal elements, but health remains an important topic in bioarchaeology as it speaks to the living conditions of archaeological populations. Many researchers have noted that growth, while genetically regulated, is also greatly affected by health status (Cardoso, 2007; Demirjian and Goldstein, 1976; Hoppa, 1992; Humphrey, 2000; Lewis, 2007; Roberts and Manchester, 2007). Health is easier to study in living

populations where it is possible to directly study nutrition and generational impacts of poor health and growth. In archaeological studies the effect of poor health on growth is most strongly seen in bones, though dental development is also affected by poor health, as with dental enamel hypoplasia. The evaluation of bone development and growth indicators is one method of looking at health. To understand growth, differences between skeletal growth and dental maturity can be examined. Bone growth and development are more affected by poor health and stress than is dental development, meaning that unhealthy or stressed children's skeletal growth will lag behind their dental development (Cardoso, 2007; Lewis, 2002; Lewis, 2007; Mays et al., 2008; Roberts and Manchester, 2007; Saunders, 2008; Ubelaker, 1989). These differences indicate growth disparities that may reflect health problems.

Accurately calculating stature is difficult in archaeological populations. When looking at growth in archeological populations, it is preferable to use long bone length as a proxy for stature. The femur and tibia are preferred for these studies as their length are the most directly linked to stature and they are the most likely to show signs of stress due to their quick growth (Eveleth and Tanner, 1990, Lewis, 2002; Mays et al., 2008; Roberts and Manchester, 2007). Juvenile long bone length can also be looked at as a percentage of adult long bone length, estimating the percentage of adult stature attained. This comparison is particularly important when comparing two or more populations that likely had different mean adult statures. By doing this, we can compare children from the groups in terms of achieved growth rather than stature. By comparing an individual's femur length

and dental age to create a skeletal growth profile, one can locate apparent disparities between skeletal and dental development (Cardoso, 2007; Cardoso and Garcia, 2009; Humphery, 2000; Lewis, 2002; Humphery, 2003; Lewis, 2007; Manchester, 2007; Mays et al., 2008; Roberts and Saunders, 2008). Although a portion of such disparities may be due to error, some sort of stressor is also often involved that is affecting growth. These stressors will vary by age group, culture, and environment.

Catch up growth is an important complicating factor to consider when examining growth in the past. Catch up growth is a commonly used term to refer to accelerated or prolonged growth making up for an earlier lack of growth. An adult may attain normal stature due to catch up growth (Cameron and Demerath, 2002; Cardoso and Garcia, 2009; Clark et al., 1986; Humphrey, 2000; Lewis, 2007). The reason why catch up growth appears to occur in some situations and not in others is not well understood (Cameron and Demerath, 2002; Saunders and Hoppa, 1993). Once normal growth patterns are attained, many authors assume that individuals are healthy. However, the epidemiological evidence seems to suggest that stress during critical periods will have lasting effects on growth and health (Cameron and Demerath, 2002; Saunders and Hoppa, 1993). Therefore, individuals who have caught up in their growth may appear to be healthy, but are actually at high risk for disease. Saunders and Hoppa (1993) report that the time from birth to three years is a crucial age with high nutritional demands, which if they are not met, can lead to stunting. Even before this time, poor maternal health can affect the health and growth of a neonate. This early childhood period is

crucial for understanding population health. If only adults are compared, catch up growth might obscure earlier periods of poor growth that could have a lasting effect on overall health.

Comparisons of dental age to skeletal age have been used to great effect when looking for potential signs of poor health in past populations (Cardoso, 2007; Cardoso and Garcia, 2009; Lewis, 2002; 2007; Mays et al., 2008). However, caution is warranted in the use of this kind of data. Hoppa (1992) found in his comparison of growth between widely different populations that differential skeletal growth is most useful as an indicator of health disparities within a population, rather than between them. Environmental factors such as malnutrition and disease will stunt an individual's growth potential, but different groups of people may have different growth potential due to different genetic composition (Cardoso and Garcia, 2009; Hoppa, 1992; Lewis, 2007; Nyati et al., 2006; Ribot and Roberts, 1996). It is important to pick appropriate comparative samples when attempting to compare samples or to study growth within a single sample. This study uses Wharram Percy as a comparative sample due to the close geographic and temporal relationship (background on this site can be found in Chapter 6).

2.8.3 Other Stress Indicators and Health

Illness is another important stressor that can also greatly affect health and growth. Although illness is often linked to malnourishment from an incomplete diet, many diseases strike the strong and weak alike. The fact that not all illness will have a visible effect on growth or be linked to long term stress must be taken

under consideration when using growth data (Buikstra and Cook, 1980; Goodman et al., 1988; Goodman and Armelagos, 1989; Ribot and Roberts, 1996; Saunders and Hoppa, 1993). One way illness can be measured in past populations is by studying non-specific stress indicators. Non-specific stress indicators do not have an exact etiology and are not caused by a known disease. They simply indicate stress severe enough to affect the skeleton (Goodman et al., 1988; Goodman and Armelagos, 1989; Saunders and Hoppa, 1993). The pattern of non-specific stress indicators is not considered an accurate representation of stress in living populations as it often indicates past or juvenile stress and not the current nutritional state of the individual (Larson, 1997; Lewis, 2002; 2007; Ribot and Roberts, 1996; Saunders and Hoppa 1993). However, it has been shown to indicate differences in health and survivorship in past populations.

Non-specific stress indicators are assumed to indicate a nutritional stress, but studies using them usually do not look at dietary differences (Larson, 1997; Lewis, 2002; Lewis, 2007; Ribot and Roberts, 1996; Saunders and Hoppa 1993). That is why this study will combine these non-specific stress indicators with dietary analysis and growth profiles. All of these conditions indicate stress, but stress that was often survivable, making them ideal for looking at ongoing stress in a population that likely affected survivors and non-survivors alike. Stress indicators pertinent to this study are cribra orbitalia, dental enamel hypoplasias (DEH), sinusitis, and non-specific bone infection. These indicators were analyzed separately in this dissertation to try to understand the effects of their different etiology as much as possible.

Cribra orbitalia is the term for porosity found in the orbital roof (Angel, 1966; Carlson et al., 1974; Holland and O'Brien, 1997; Steinbock, 1976; Stuart-Macadam, 1985; Stuart-Macadam, 1989). The prevalence of cribra orbitalia in populations is argued to indicate nutritional stress in archaeological populations. The primary etiology of cribra orbitalia cited by many researchers is that of iron deficiency anemia (Holland and O'Brien, 1997; Oxenham and Cavill, 2010; Steinbock, 1976; Stuart-Macadam, 1985; Stuart-Macadam, 1989; Sullivan, 2005). However, recently there has been debate on the reliability of that diagnosis (Oxenham and Cavill, 2010; Walker et al., 2009 Wapler et al., 2004). Walker (2009) believes that the clinical literature shows that the skeletal changes seen with cribra orbitalia should be diagnosed as hemolytic or megaloblastic anemias. These anemias are due to deficiencies in B_{12} or folate, rather than iron. Oxenham and Cavill (2010) re-review the clinical literature and show that while hemolytic and megaloblastic anemias are possible conditions, iron deficiency anemia remains a possible etiology in the differential diagnosis of cribra orbitalia. It is plausible that all three forms of anemia were present in past populations (Oxenham and Cavill, 2010; Sullivan, 2005). In a recent study, Murphy et al. (2002: 412, Fig. 8.1) found that iron deficiency anemia affects 30% of the world's population. Iron deficiency anemia was likely as great if not a greater issue in the past, making it a likely candidate for the cause of cribra orbitalia in past populations (Facchini et al., 2004; Roberts and Manchester, 2007; Sullivan, 2005). All of these anemias are caused by deficiencies due to nutrients lacking in the diet, malabsorption of nutrients, or loss of nutrients. Common causes of the

anemias are poor diet, diarrheal disease, infection, and parasitic infection (Facchini et al., 2004; Roberts and Manchester, 2007; Sullivan, 2005; Walker et al., 2009). Determining which nutrient was missing in past populations can be more difficult. Regardless of its specific cause, the prevalence of cribra orbitalia in past populations is an excellent way to access nutrition in past populations.

Improper enamel matrix secretion can cause dental enamel hypoplasias (DEH), which are deficiencies in enamel thickness seen as disruptions on the crown surface (Goodman and Rose, 1990; Hillson, 1996; 2005; Hillson and Bond, 1997; King et al., 2002). This improper formation results in abnormally thin enamel or areas where enamel is completely lacking. It is possible to identify and score many types of DEH, however this study uses simple presence and absence of any recorded lesion. In most instances, the specific cause of these defects is not known, but they do indicate difficult living conditions and poor health in a population. Some examples of stressors linked to DEH are infection, parasites, and nutrition deficiencies (Berbesque and Doran, 2008; Boldsen, 2007; Goodman and Rose, 1990; Hillson, 1996; 2005; Hillson and Bond, 1997; King et al., 2002; King et al., 2005; Palubeckaite et al., 2002). Early developing and severe hypoplasias are often linked to higher mortality rates in archaeological populations (Berbesque and Doran, 2008; Boldsen, 2007; King et al., 2005; Palubeckaite et al., 2002). The cause is believed to be either continued exposure to the stress event that caused the DEH or by a weakening of the immune system that would affect these individuals for their entire lives. As teeth are more

protected from insult than the skeleton, DEH are thought to indicate a greater level of stress (Hillson, 2005; King et al., 2005; Larsen, 1997).

Maxillary sinusitis is an ongoing ailment that is believed to be caused by poor air quality, upper respiratory tract infections, dental disease, and allergies (Brooks, 2009, Dobbs, 2009; Lewis et al., 1995, Roberts, 2007; Roberts and Manchester, 2007). People with this condition would experience the symptoms of pain and congestion in their maxillary sinus, headaches, and fever (Brook, 2009, Dobbs, 2009; Roberts, 2007). While the condition is not normally life threatening, it will compromise the immune system and is a good indication of poor health or stress in populations. Diagnosis of sinusitis in skeletal remains depends on identifying bone growth in the sinus (seen as spicules of bone and pitting in the floor of the sinus), so in intact remains it can only be diagnosed using an endoscope. Only chronic sinusitis can be identified in skeletal populations as the bone reaction occurs due to long term (at least a number of weeks) irritation of the sinus (Lewis et al., 1995; Ortner and Putschar, 1981, Roberts, 2007, Roberts and Manchester, 2007). While individuals may be congenitally susceptible to sinusitis, the more likely etiology in medieval populations is environmental conditions or systematic susceptibility: that is, poor air quality or asthma. Children under two years of age are more susceptible to the condition, as are children in daycare or close contact with other children (Brook, 2009, Dobbs, 2009). Medieval children from areas such as Fishergate House would be at high risk for the illness as risk factors for the condition was rampant in their overcrowded, damp, urban environment. They would continue to be at high risk throughout their lives, as

sinusitis is a common ailment in adults as well. Studies comparing medieval rural and urban populations have found sinusitis to be more prevalent in urban populations (Lewis et al., 1995, Roberts, 2007). The suggested cause of this difference is the poor air quality of urban centers due to density and manufacturing in those locations.

While sinusitis is an infection with a known cause and a limited number of etiologies, the etiology of non-specific bone infection is not well understood due to the overabundance of possible causes. Non-specific infections seen in bone include osteitis, osteomyelitis, and periostitis (Larsen, 1997; Lewis, 2002; Roberts and Manchester, 2007). These conditions result in additional/abnormal bone growth in children and adults affected with the conditions, although there is no identifiable specific disease process (such as tuberculosis) taking place. These pathological changes are thought to be due to bacteria or other agents that cannot be specifically identified in archaeological populations (Larsen, 1997; Lewis 2002; Roberts and Manchester, 2007). While the underlying cause is not known in most cases, non-specific infections do suggest some kind of chronic stress on the population that may have been linked to malnourishment and poor environmental conditions. By analyzing non-specific infection along with the other non-specific stress markers and conditions discussed above, it is possible to get a sense of the stress on populations, and to begin to analyze health and to speculate on its links to growth and diet.

Health is not directly analyzable in the past as it is more than just the symptoms and conditions that affect the skeleton. However, health is a key aspect

of human life, making it important to try to reconstruct even approximately. Diet, nutrition, growth, and illness are all aspects of health that can be studied, though not always completely, in past populations. By linking as many of these elements together as possible it is hoped that more can be learned about living conditions and individual health experiences of Fishergate House juveniles during the early childhood period.

Figure 2-1: Diagram shows incremental growth of dentine and enamel, which begin forming at the same time (Modified from Hillson, 1996). A: indicates the enamel of the tooth, which forms incrementally starting from the crown of the tooth to the root. B: indicates the dentine, which also begins forming incrementally from the crown down to the root.

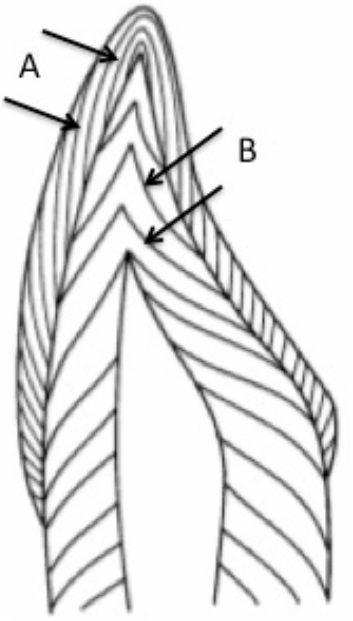
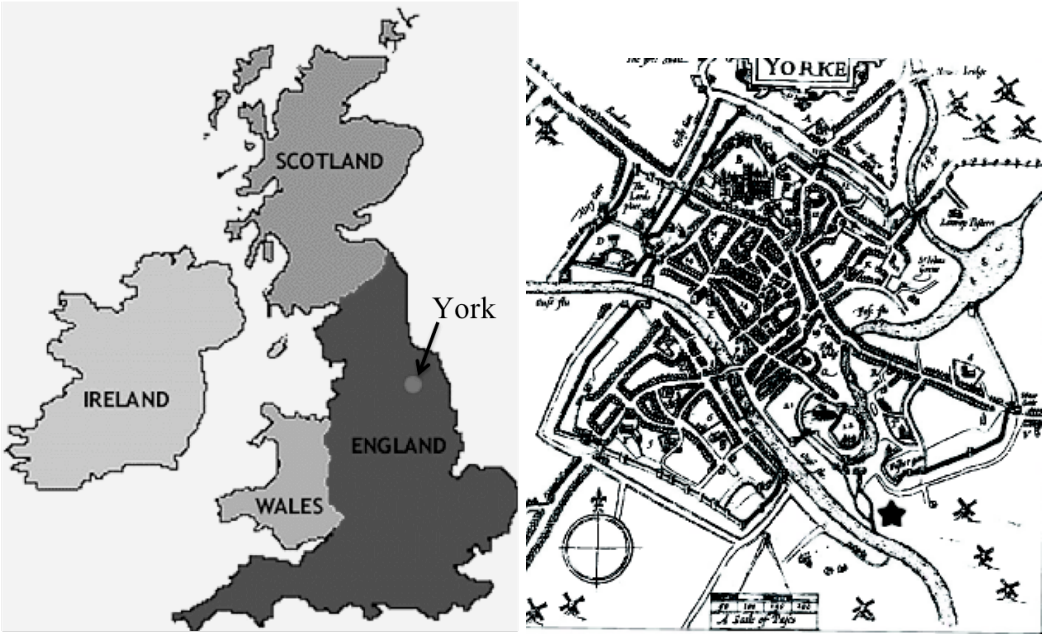


Figure 2-2: Maps of medieval York. Arrow indicates York. Star indicates Fishergate House site within York (White, 2000).



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Chapter 3

A New Method of Dentine Microsampling of Deciduous Teeth for Stable Isotope Analysis[1]

3.1 Introduction

Although a number of stable isotope researchers have microsampled human tooth enamel, few have attempted to microsample human dentine (Eerkens et al., 2011). Here we propose a novel microsampling method that uses smaller human dentine samples than those described in the literature to date and attempts to reconstruct diet around known life stages based specifically on how human teeth grow. The method identifies a specific life event – birth – from the neonatal line of deciduous teeth and uses that demarcation to define specific areas of the tooth to microsample. This study has two goals. The first is to improve the precision and range of dentine-based dietary reconstructions to allow for the study of more specific age related diets. Here we look at two specific postnatal life stages, namely the period shortly after birth (assumed here to represent a breastfeeding diet) and the time when the tooth completed formation (assumed to reflect a weaning diet). The second goal is to examine dentine from apical to the neonatal line in an attempt to extend analyses to the period before birth. This would allow the study of a life stage previously almost entirely unstudied: fetal life. Outside of work on archaeological fetal remains, which are rare, and a few modern human studies, very little has been done with this life stage using stable isotope analysis (Dupras and Tocheri, 2007; Fuller et al., 2006). The ability to

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recover stable isotope signals from the uterine environment would allow researchers to address novel and interesting questions about past populations including relationships between maternal nutrition and infant mortality. *For more background, please see Chapter 2.*

3.2 Materials and Methods

A sample of 35 modern deciduous teeth from children between five and twelve years of age was collected in collaboration with the Department of Pediatric Dentistry, University of Alberta. These teeth were the result of medically necessary extractions carried out at university-run dental clinics. The parents, who had been made aware of the nature of the study and gave their informed consent, donated extracted teeth; where age permitted, consent of the child was also given (University of Alberta ASL REB Ethics Approval #2120). For this preliminary study, no personal data were collected from the children so sex, place of birth and dietary history are unknown. Given study goals the ideal sampling strategy was to collect incisors, which begin forming first and are the most likely to show an in-utero signal. However, to maximize sample size and investigate the utility of the procedure on other teeth, molars and canines were also collected. Of the 35 teeth donated, two were rendered unusable by caries or prior dental work and were excluded from analysis. This left a sample set of 33 teeth, some of which provided limited results due to extreme wear, caries or root resorption (Table 3-1).

3.3 Sectioning Methods and Neonatal Line Identification Procedures

The microsampling process begins with the sectioning of the teeth, production of a histological slide, and the identification of the neonatal line. Intact teeth were sonicated in distilled water and cut into half longitudinally with a diamond dental wheel (AXIS Dental Corporation Flex Double Sided Diamond Dental Wheel), using a Dremel tool placed in a stabilizing stand designed and created by the author. This stand secured the Dremel in a horizontal position using adjustable metal zip ties allowing the blade to be raised and lowered in a controlled fashion. Teeth were secured in the proper orientation for cutting using a small vise positioned under the cutting wheel. A drill press vise was used, its clamps padded with adhesive foam strips to protect the teeth. Incisors and canines were cut directly along their labial-lingual midline, creating equal mesial and distal halves; molars were cut along their buccolingual midline (when possible given damage and decay), creating equal buccal and lingual halves. One half of each tooth was used for isotopic analysis as described in 2.1. The other half was sectioned to create microscope slides, which were used for identification of the neonatal line.

To create the slides, a 1-2 mm thick section was cut from one half of the tooth using the same set up used to longitudinally section the teeth. The sections were then mounted on a microscope slide and ground down to thin sections using a mechanical slide polisher. Completed slides were examined using a polarized light microscope to determine the location of the neonatal line. Polarized light

was chosen because this offers the best chance of identifying the neonatal line (Norén, 1983; Rythén et al., 2008).

The position of the neonatal line in the enamel was measured directly from the slide using a microscope ruler under polarized light. Measurements were taken of the distance from the occlusal surface of the tooth to the point where the neonatal line intersects the DEJ and the distance from the DEJ to the intersection of the neonatal line with the occlusal surface. The measurements from the enamel were used to estimate the area of antenatal dentine formation on the non-mounted half of the tooth to facilitate microsampling (Figure 3-1**)**.

3.4 Microsampling and Stable Isotope Processing

Microsampling has been conducted in previous studies using animal teeth; the idea of microsampling was adapted here for use on human deciduous teeth (Balasse et al., 2001; Kirsanow et al., 2008). These adaptations account for the different shape, size, and dentine thickness of human deciduous teeth, as well as their different growth pattern. The microsamples were also much smaller than those previously used on human teeth (Eerkens et al., 2011). The microsamples were prepared for collagen stable isotope analysis using standard procedures modified for very small samples (Katzenberg, 2008; Lee-Thorp et al., 1989; Tuross et al., 1980; Tuross et al., 1988). The modifications to these procedures were primarily in equipment and in the quantity of chemicals used.

The half of the tooth destined for stable isotope analysis was treated with a six hour diethyl ether soak for lipid extraction (Dobush et al., 1985; Garvie-Lok,

2001; Riccas et al., 2007). After soaking in distilled water, tooth halves were placed in 2 ml microvials for a 1% HCl soak (Katzenberg, 2008; Lee-Thorp et al., 1989; Tuross et al., 1980; Tuross et al., 1988). Because of the small amount of HCl that the microvials could hold, the solution had to be refreshed every day. When the dentine of a tooth half was judged to be roughly 50% to 75% demineralized based on texture and color of the dentine, it was microsampled using 1.0 mm and 0.75 mm Harris Uni-core FTIR cardpunches. These punches take a tiny plug of dentine out of the tooth that can then be ejected into a vial for further processing and testing. Using a dental caliper, the measurements made on the slide of the other half of the tooth were used to sample dentine along the approximate location of the neonatal line. Microsamples were taken occlusal and apical to the neonatal line (Figure 3-1). Occlusal to the neonatal line space was restricted, so the .75mm punch was used. Multiple punches were taken in the area if possible. Apical to the neonatal line, multiple punches were taken using either the .75mm or 1.0mm punch depending on the area available. Depending on the wear pattern of the tooth, samples were taken from both the lingual and labial sides of the tooth to increase the sample weight. The most apical portion of the tooth was also sampled. For teeth with complete roots this sample was taken at the apical tip of the root. If the root was incompletely formed or partially resorbed, the sample was taken at the most apical preserved edge. The partially demineralized tooth halves were retained in case further sampling was necessary. In a few cases, sampling along the neonatal line could not be conducted with punches because the estimated area of antenatal dentine was extremely small due

to occlusal wear or because the dentine had become fragile in the HCl, flaking apart along its depositional layers. In these cases, a scalpel was used to cut or peel off the approximate area of antenatal dentine.

Once the microsamples were taken, they were placed in microvials and soaked in daily changes of 1% HCl until demineralization was judged to be complete. After this, lipid extraction was completed using a second ether soak of two hours followed by a rinse with distilled water and a 20 hour soak in 0.125 M NaOH (Katzenberg, 2008; Lee-Thorp et al., 1989; Tuross et al., 1980; Tuross et al., 1988). After processing was complete, samples were again rinsed with distilled water and frozen. Samples were then freeze-dried, weighed and packed for analysis. Stable isotope analysis was conducted at the Biogeochemical Analytical Laboratory of the Department of Biology, University of Alberta (director Dr. Mingsheng Ma) using a EuropEA Elemental Analyzer coupled with an Isoprime Mass Spectrometer.

3.5 Results and Discussion

3.5.1 Sectioning and Sample Preparation

The sectioning protocol developed for this study worked well and allowed for precise sectioning of the deciduous teeth. All sampling was completed with readily available and inexpensive equipment. While many of the teeth used in this sample were decayed and worn, there was no issues with the teeth crumbling when being put in the vice or cut with the Dremel. The slides were quick and easy to make, but still allowed the neonatal line to be viewed. Although there was some variation, when present the line was usually quite dark and obvious. Wear

on the occlusal surface of the teeth affected the neonatal line measurements the most and caused the greatest variation in sampling locations between teeth.

Although at least one other study successfully collected and analyzed faunal dentine using punches of similar size to the ones used in this study, the previous work analyzed different stable isotopes (Kirsanow et al., 2008). Dentine microsampling of the kind presented here had not been undertaken before, and given the extremely small size of the collagen samples taken it was important to determine the typical sample weight that would be produced and the minimum collagen weight required to produce reliable stable isotope results with the equipment in use at the Biogeochemical Analytical Laboratory. For accurate measurement, a minimum sample weight is required, in part because more regularity in the weights within a run produces better results (A. Kwan, personal communication 2010).

After freeze-drying, samples were weighed using a microbalance. The distribution of weights after the first sampling attempt ranged fairly evenly from a minimum of .092 mg to a maximum of .839 mg. Prior to this experiment, collagen stable isotope analysis at the Biogeochemical Analytical Laboratory had typically used a sample weight of 1.000 mg. A small preliminary analytical run suggested that although acceptable $\delta^{15}N$ results could be obtained at all weights in the range, good simultaneous measurement of $\delta^{15}N$ and $\delta^{13}C$ was only seen at weights above the 0.3 mg - 0.4 mg range. Accordingly, additional microsampling was carried out on some tooth halves in order to bring the smaller samples into this weight range. This was not possible for all teeth due to the small size of some target areas. After

this the final analytical run was conducted. This second run showed that reliable simultaneous $\delta^{15}N$ and $\delta^{13}C$ results could be produced with samples weighing as little as .293 mg, and that sample weights of .320 mg and above produced consistently good results. While a few samples could not be brought into this weight range due to fragility of the tooth or small size of the sampling area, most teeth could be analyzed, showing that the method produces reliable simultaneous dentine $\delta^{15}N$ and $\delta^{13}C$ results even at these small weights.

Isotopic results, C:N ratios, and details on sampled teeth are presented in Table 3-1. The results of the second (adjusted weight) run are given whenever possible. Sample C:N ratios are within the normal range 2.9 to 3.6 (Ambrose, 1990; DeNiro, 1985; Schoeninger et al., 1998). No demographic information was collected as part of this study. It is unknown whether they were bottle fed, breastfed, or received a combination of these feeding methods, and time of weaning is unknown. Additionally, there are no data on family diet for comparison, which is likely an issue as given community demographics individuals likely came from diverse cultural backgrounds. In modern industrialized nations a great variety of diets are followed and these can result in diverse tissue isotopic signatures (O'Connell and Hedges, 1999). Despite these limitations, the stable isotope results can still be discussed in the general context of modern Canadian diets.

3.5.2 Evaluating the Microsampling Method

The stable isotope results for all individuals in the sample are presented in Figures 3-2 and 3-3. In both figures, the estimated ages assigned to the samples are based on a combination of relationship to the neonatal line and clinical data on tooth formation times (Hillson, 1996; Moorrees et al., 1963; Scheuer and Black, 2004). For samples collected occlusal to the estimated position of the neonatal line (hereafter pre-neonatal line samples) the average age of initial matrix formation for each tooth type was used, given as time in months prior to birth. An age of one month after birth was assigned to samples collected directly apical to the estimated position of the neonatal line (hereafter post-neonatal line). This age was estimated as the approximate time of formation for the samples taken very close to the neonatal line. This is not an exact age and some samples could represent a slightly older period of development. For samples collected at the preserved apical edge of the tooth, the age assigned is based on the average estimated age of formation of that particular portion of the tooth (Hillson, 1996; Moorrees et al., 1963; Scheuer and Black, 2004).

The initial impression from both figures is one of great diversity in the pre-neonatal line and post-neonatal line samples. The samples formed at later ages show less variation. As we discuss below, the large number of possible adult diets and post birth feeding methods for this sample could explain this patterning. However, another potential reason for the high variability and overlap of the pre-neonatal line and post-neonatal line values that must be discussed is error in sampling relative to the estimated position of the neonatal line. If some of the

punches that were intended to sample pre-neonatal line dentine actually sampled post-neonatal line dentine and vice versa, this could result in increased variability and overlap in the two groups because both included some samples with dentine formed before birth and some with dentine formed after birth. Although we concede that some sampling error may be present, there is good reason to believe that it is not the major cause of the patterning seen. Each prenatal sample typically represents a number of individual punches, most of which were placed as close as possible to the dentinoenamel junction rather than immediately along the estimated position of the neonatal line. Even if some of the pre-neonatal line punches along the estimated neonatal line actually represent dentine formed after birth this would likely have little effect on the overall result for the sample, as the entire estimated pre-birth area was sampled and only a small amount of post-birth dentine would have been mixed in. In the case of post-neonatal line samples, it is likely that some of the variation is due to the time needed for the nursing elevation to be fully established in the infant's tissues (Fuller et al., 2006a; Katzenberg and Pfeiffer, 1995; Katzenberg et al., 1996; Kinaston et al., 2009; Richards et al., 2002). Hair and fingernail studies indicate that it takes a variable amount of time for the infant's tissues to rise to their full nursing elevation. For future studies, post-neonatal line samples will be collected farther from the estimated neonatal line position. This should eliminate this potential source of error and ensure a distinct signal change between the neonatal and breastfeeding periods.

One good indication that the method is indeed detecting pre- and post-birth signals is that when the stable isotope patterns are considered by individual rather than collectively it becomes clear that diet is changing over the border of the neonatal line. Some individuals show a more enriched value after birth, as would be expected with breastfeeding, and others a less enriched signal, as might occur with bottle feeding. As we discuss below, this agrees with the pattern expected for pre- and post-birth values in a modern random sample of children who were fed in a variety of ways.

3.5.3 Nitrogen Patterning

There is tremendous variation in $\delta^{15}N$ values, which range from 7.4‰ to 15.3‰, with both extremes found in values around the neonatal line (Figure 3-2). Each age category is discussed separately to try to understand the large differences in nitrogen values. The pre-neonatal line values are the most diverse. *In utero* values should be linked to the mother's values during pregnancy, though slightly changed by the process of being incorporated into the fetus' body (Fuller, 2006a). Fuller (2006a) did not find the variation between mother and child to be systematic, and further found that fetal $\delta^{15}N$ values often decreased near the time of birth. The author hypothesized that the decline was linked to the growth process and differences in nitrogen metabolism. Nitrogen demands are increased in a pregnant female compared to the normal demands of a woman's body, putting the woman into positive nitrogen balance (Duggleby and Jackson, 2002; Fuller et al., 2004; Williams et al., 2011). This metabolic change appears to result

in a reduction of $\delta^{15}N$ values in the woman relative to her diet. It is likely that these metabolic changes will also affect the fetus' stable isotope signature. Work on the effects of metabolism on the $\delta^{15}N$ values of mothers and fetuses are quite recent and requires further study to be fully understood. A natural variation between maternal and fetal signals caused by differences in nitrogen metabolism may account for some of the variation of the pre-neonatal line values seen in this study. Such differences would also explain why the values are not a good fit for the adult female values at the site. The fact that the fetal signals in this study are enriched relative to adult females rather than reduced is interesting given previous work (Fuller et al., 2004). While metabolism is likely an important factor in the results, it is possible that other factors are affecting the nitrogen values.

Another important factor is likely variation in maternal diets. Diets in modern industrialized nations can vary to extremes based on choices including vegetarianism, omnivory and veganism as well as personal preferences for marine resources and other foods. These dietary choices have an impact on tissue stable nitrogen isotope values. For example, O'Connell and Hedges (1999) found that among modern Oxford residents, vegans had $\delta^{15}N$ values of 6.3‰ to 7.5‰, vegetarians had $\delta^{15}N$ values of 8.1‰ to 9.4‰, and omnivores had $\delta^{15}N$ values of 8.0‰ to 9.6‰. The range of 7.9‰ to 15.3‰ seen in the pre-neonatal line values is substantially larger than this. However, given the varied regional origins typical of the population served by the clinic, the distortion expected when comparing fetal to maternal values and the potential that some mothers were eating

idiosyncratic diets during pregnancy that differed from their normal diets, variation of this magnitude is not unreasonable.

Post-neonatal line samples also show a wide range of $\delta^{15}N$ values, with a range from 7.4‰ to 14.9‰. Each individual has three possible diets early in infancy. One is being exclusively breastfed, which would raise the $\delta^{15}N$ value by 3-5‰ from the maternal value. The infant could be bottle fed, which would not increase the $\delta^{15}N$ values and could lower them if the formula did not have the same nitrogen level as the mother. The third option is a mixture of the two, which would result in intermediate $\delta^{15}N$ values or fluctuating values if the two methods were used in alteration. Although there is potential variation in diet to determine what the population on a whole is doing, it is intriguing that the post-neonatal line samples appear to sort into two $\delta^{15}N$ groups (see Figure 3-4). This may reflect the presence of two distinctive feeding patterns, breastfed and bottle fed, in the group.

The apical tooth edge samples represent estimated formation ages ranging from 4.5 to 32 months. These do not show a clear decline that would allow a specific age of weaning to be determined. This is not surprising, as individual weaning histories presumably varied greatly and many individuals may have an elongated weaning/mixed feeding period obscuring this transition. In many individual cases, there is not much change in the $\delta^{15}N$ values from the post-birth value to approximately two years. It is possible that some of these individuals were not fully weaned by two years, although they were presumably given a variety of supplementary foods as modern physicians suggest (Dettwyler, 1995; Stuart-Macedam, 1995). Although there may not be a clear weaning shift, there is

a change to a more uniform diet at older ages. In samples with estimated formation ages over 12 months, the range of $\delta^{15}N$ values is between 10.7‰ and 13.7‰, with most values clustering around 11‰. This suggests a change from a diverse group of diets to a more uniform diet utilized by almost all children. The result is surprising given the high variability around the age of birth, and has interesting implications for perceptions of appropriate foods for young children in this modern community. Allowing for the typical 0.9‰ $\delta^{15}N$ elevation of collagen relative to hair (O'Connell et al. 2001), the dentine $\delta^{15}N$ values of these children fall reasonably close to the mean hair $\delta^{15}N$ values of 8.8‰ to 9.9‰ reported for modern Europeans and North Americans with omnivorous diets (Thompson et al. 2009).

Arranging the results by tooth type produces similar results. Again, the wide range of values in the pre-neonatal line samples is clear (Figures 3-5, 3-6, and 3-7). The molar results are confusing and the most difficult to interpret with very little variation in nitrogen values (Figure 3-7). The molar values may not be as reliable as the other teeth due to the difficulty in removing enamel from the molar crowns. For this reason some caution is needed when interpreting the results for this tooth category. The post-neonatal line values show some reduction in $\delta^{15}N$ range. This trend continues, with values of dentine formed around two years of age suggesting almost no dietary variation. Dentine formed past two years of age shows a 0.6‰ spread in $\delta^{15}N$ for incisors, a 1.3‰ spread in $\delta^{15}N$ for canines, and a 3.0‰ spread in $\delta^{15}N$ for molars. The results indicate that while there is a lot of variation in weaning practices, children's diets later become

surprisingly uniform. This transition can be seen in all tooth types by at least one year of age.

A look at each individual in the sample shows that some exhibit a $\delta^{15}N$ increase after birth and others a decrease. The post-neonatal line $\delta^{15}N$ elevation seen in some individuals is likely a sign of the elevated trophic level effect of breastfeeding, though of course not all individuals would be breastfed. Lack of $\delta^{15}N$ elevation, or a decline, may reflect bottle-feeding.

3.5.4 Carbon Stable Isotope Results

As with the nitrogen analysis there is variation in stable isotope values in young individuals, although the complete range is narrower than the nitrogen results (Figure 3-3). Carbon exhibits a smaller trophic level effect than nitrogen, making the potential stable isotope effects of nursing and weaning smaller. This may be why less dramatic variation is seen in the $\delta^{13}C$ results than in the nitrogen values during the breastfeeding period. The pre-neonatal line $\delta^{13}C$ values range between -16.6‰ to -19.5‰. In comparison, O'Connell and Hedges (1999) found $\delta^{13}C$ values between -19.6‰ to -21.6‰ for their Oxford sample, with little difference between the different diet types (vegetarian, omnivore, and vegan). The wider variation and higher average value in this study may be in part the result of the change in stable isotope signals between the actual maternal diet and the fetal signal as discussed by Fuller (2006a). However, it more likely reflects maize products and maize-fed animal products in some mothers' diets, a known factor in modern human $\delta^{13}C$ values from the Americas (Thompson et al. 2009). The post-

neonatal line values show a larger range, which could be due in part to some individuals having the small 1‰ trophic level increase expected with breastfeeding. As with nitrogen, apical edge values display less variation, with most clustering around -18‰; allowing for the offset between collagen, hair and fingernails (O'Connell et al. 2001), this is similar to results found for other modern groups from the Americas (Thompson et al. 2009). The presence of isolated outliers at -13‰ to -14‰ may reflect the inclusion of teeth from some children who grew up outside Canada, which is not unexpected for the community that contributed the sample.

Unfortunately, the carbon stable isotope results could not be obtained for many individuals in the sample and often for only part of an individual's development. Because of this, the carbon data cannot be discussed by tooth type and individual, as was the nitrogen data. However, it is clearly possible to get carbon results, and given that subsequent studies will begin with the sample weight needed to get accurate carbon results known, more carbon values will be gathered in the future.

3.5.5 Nitrogen and Carbon Results

When the $\delta^{13}C$ and $\delta^{15}N$ results are considered together it becomes even clearer that the samples from the apical edge of the tooth, which represent ages at which children would be weaning or fully weaned, are much more regular and clump together in a tight mass with only a couple of outliers (Figure 3-4). The nitrogen values are particularly tightly grouped. This suggests a relatively regular

early childhood diet for the whole sample. Both the pre-neonatal line values and the post-neonatal line values are much more dispersed. Variation in maternal diets and the use of many different infant feeding methods for the early months of life is likely the cause of this pattern. There seems to be somewhat less variation in the $\delta^{13}C$ results at these ages, as would be expected given the smaller trophic level effect. The three groups do not separate easily into three different diets due to population variation, but it is possible to see dietary groupings within the sample. A clear age of weaning cannot be determined, which is to be expected with a modern Canadian sample.

3.6 Conclusions

The purpose of this pilot study was to determine the feasibility of microsampling human deciduous teeth for stable isotope analysis. The preparation method described here works very well, and the results show that dentine microsampling is possible. The method allows accurate results that can be linked to different life stages: fetal life, early infancy, and weaning or toddler diet. The results themselves are difficult to interpret in terms of breastfeeding and weaning practices due to the unknown variables of diet and cultural weaning practices in the families of the children who provided the teeth. Examples of both breastfeeding and bottle feeding appear to be present in the sample resulting in a large range of $\delta^{15}N$ and $\delta^{13}C$ values for these age ranges and two distinct groups. There is also evidence of more uniform values in dentine formed at older ages, possibly indicating a uniform toddler diet across the sample.

Some caution is needed when using the method, as many stages of analysis are delicate. It is very important to longitudinally section the teeth as close to the midline as possible. A Dremel stand system was used in this study, but other tools might also be used. Although the sections prepared for microscopy are thicker than those normally used to study microstructure, they were found to be adequate for visualizing the neonatal line. More structures could be identified for even more nuanced microsampling if more sophisticated slides were produced. The demineralization procedure normally used for larger bone and dentine samples had to be changed very little for use in this study, and any lab currently doing stable isotope analysis would be able to follow it. Microsampling went smoothly when the tooth halves were well on their way to demineralization. However, delamination of the dentine during sampling became a problem in teeth that were left in solution for more than two weeks before microsampling. While sampling was still possible, it was much more difficult. Because instrumentation varies across laboratories, it will be necessary for researchers using this method to try to maximize sample weight by taking multiple microsamples in the region of interest, and to verify the minimum weight required for their own analytical equipment.

Table 3-1 Summary information for each individual. This includes sample number, tooth type, sample location, sample weight, ^{13}C (‰) values, $\delta^{15}N$ (‰) values, and C/N (atomic) values. POSTN is post-neonatal line and PREN is pre-neonatal line

Sample #	Individual	Tooth Type	Sample Location	Sample Weight (mg)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C/N (atomic)
BN1c	1	canine	PREN	0.515	-17.4	13.4	3.26
AN1c	1	canine	POSTN	0.118	-26.7	7.4	3.46
RE1c	1	canine	tooth edge	0.791	-17.9	10.8	3.24
BN2c	2	canine	PREN	0.506	-17.2	15.3	3.23
AN2c	2	canine	POSTN	0.480	-17.8	13.4	3.29
RE2c	2	canine	tooth edge	0.331	-17.6	11.3	3.18
BN4c	4	canine	PREN	0.403	-16.6	11.2	3.25
AN4c	4	canine	POSTN	0.863	-15.5	10.4	3.35
RE4c	4	canine	tooth edge	0.175	-14.6	12.4	3.24
BN5c	5	canine	PREN	0.349	-18.0	13.8	3.40
AN5c	5	canine	POSTN	0.607	-17.8	13.9	3.25
RE5c	5	canine	tooth edge	0.544	-18.1	10.8	3.46
BN6c	6	canine	PREN	0.119	-27.9	7.9	3.42
AN6c	6	canine	POSTN	0.448	-18.7	10.8	3.33
RE6c	6	canine	tooth edge	0.929	-18.2	11.3	3.18
BN7c	7	canine	PREN	0.555	-19.5	12.9	3.30
AN7c	7	canine	POSTN	0.133	-19.3	12.1	3.44
RE7c	7	canine	tooth edge	0.777	-18.4	11.0	3.22
BN8m	8	molar	PREN	0.420	-17.9	12.4	3.29
AN8m	8	molar	POSTN	0.203	-17.7	12.3	3.24
RE8m	8	molar	tooth edge	0.122	-17.9	11.0	3.45
BN9m	9	molar	PREN	0.839	-17.5	13.6	3.24
AN9m	9	molar	POSTN	1.049	-17.7	14.9	3.20
RE9m	9	molar	tooth edge	0.394	-17.9	13.7	3.27
BN10m	10	molar	PREN	0.366	-17.5	12.6	3.25
AN10m	10	molar	POSTN	0.980	-18.1	11.1	3.17
RE10m	10	molar	tooth edge	1.078	-17.5	11.4	3.21
AN11m	11	molar	POSTN	0.097	-22.1	6.5	3.50
BN12i	12	incisor	PREN	0.188	-18.1	14.1	3.38
AN12i	12	incisor	POSTN	0.305	-10.6	11.3	3.28
RE12i	12	incisor	tooth edge	0.770	-13.3	11.4	3.22
BN13m	13	molar	PREN	0.266	-16.5	12.5	3.24
AN13m	13	molar	POSTN	1.186	-17.7	8.4	3.24
BN14i	14	incisor	PREN	0.270	-16.0	11.6	3.36
AN14i	14	incisor	POST	0.537	-16.0	11.1	3.29
RE14i	14	incisor	tooth edge	0.698	-18.0	10.9	3.23
BN15m	15	molar	PREN	1.109	-17.1	10.9	3.22
AN15m	15	molar	POST	0.162	-18.2	11.3	3.39
RE15m	15	molar	tooth edge	1.101	-17.7	11.5	3.17
BN17m	17	molar	PREN	0.261	-13.5	13.6	3.30
AN17m	17	molar	POSTN	0.308	-13.5	11.4	3.29
RE17m	17	molar	tooth edge	0.394	-14.0	11.2	3.23

BN18m	18	molar	PREN	0.595	-17.4	12.2	3.25
AN18m	18	molar	POSTN	0.148	-17.4	10.9	3.46
RE18m	18	molar	tooth edge	0.409	-17.6	11.0	3.29
BN20m	20	molar	PREN	0.667	-18.1	12.8	3.27
AN20m	20	molar	POSTN	0.295	-17.9	11.1	3.33
AN22c	22	canine	POSTN	0.155	-18.8	11.3	3.35
RE22c	22	canine	tooth edge	0.554	-17.8	11.1	3.27
BN23c	23	canine	PREN	0.235	-17.6	12.2	3.28
AN23c	23	canine	POSTN	0.246	-17.6	11.2	3.34
BN19ia	19a	incisor	PREN	0.295	-16.5	12.5	3.36
AN19ia	19a	incisor	POSTN	0.407	-16.3	12.8	3.27
RE19Ia	19a	incisor	tooth edge	0.491	-15.9	13.0	3.47
BN19ib	19b	incisor	PREN	0.295	-16.3	11.9	3.37
AN19ib	19b	incisor	POSTN	0.217	-16.6	12.5	3.37
RE19ib	19b	incisor	tooth edge	0.370	-17.1	11.7	3.25
BN21ma	21a	molar	PREN	0.499	-18.1	13.4	3.27
AN21ma	21a	molar	POSTN	0.625	-18.3	13.4	3.24
RE21ma	21a	molar	tooth edge	0.625	-17.7	11.3	3.25
BN21mb	21b	molar	PREN	0.105	-18.4	8.8	3.50
AN21mb	21b	molar	POSTN	0.534	-18.1	13.9	3.26
RE21mb	21b	molar	tooth edge	1.186	-17.9	11.5	3.26
BN21ca	21a	canine	PREN	0.444	-17.8	13.6	3.22
AN21ca	21a	canine	POSTN	0.498	-18.1	13.9	3.29
RE21ca	21a	canine	tooth edge	0.198	-17.7	11.5	3.41
BN21cb	21b	canine	PREN	0.107	-26.8	10.5	3.55
AN21cb	21b	canine	POSTN	0.152	-18.0	14.1	3.40
RE21cb	21b	canine	tooth edge	1.101	-17.5	12.2	3.16
BN21cc	21c	canine	PREN	0.301	-18.0	13.7	3.34
AN21cc	21c	canine	POSTN	0.187	-16.4	11.2	3.41
RE21cc	21c	canine	tooth edge	0.223	-17.9	12.3	3.26
AN21mc	21c	molar	POSTN	0.195	-14.7	13.6	3.32
BN24ia	24a	incisor	PREN	0.138	-17.5	12.4	3.44
AN24ia	24a	incisor	POSTN	0.262	-16.8	11.1	3.33
RE24ia	24a	incisor	tooth edge	0.173	-17.2	10.0	3.48
BN3ia	3a	incisor	PREN	0.314	-16.9	8.5	3.47
AN3ia	3a	incisor	POSTN	0.320	-18.3	11.3	3.23
RE3ia	3a	incisor	tooth edge	0.866	-18.2	11.5	3.22
AN3ib	3b	incisor	POSTN	1.126	-18.8	11.0	3.24
RE3ib	3b	incisor	tooth edge	0.710	-18.1	11.3	3.22
AN3ma	3a	molar	POSTN	0.983	-18.0	11.1	3.25
RE3ma	3a	molar	tooth edge	0.293	-17.9	11.5	3.20
AN3ma	3a	molar	POSTN	0.893	-18.0	11.1	3.25
RE3ma	3a	molar	tooth edge	0.293	-17.9	11.5	3.20
BN3mb	3b	molar	PREN	0.229	-16.5	12.5	3.47
AN3mb	3b	molar	POSTN	0.333	-17.7	10.7	3.28
RE3mb	3b	molar	tooth edge	0.322	-18.6	10.7	3.30

Figure 3-1: Sampling location. The circles indicate the approximate locations of sampling. The circles occlusal to the neonatal line (indicated by arrows marked N in the enamel and mirrored by the grey line in the dentine) are the pre-neonatal line samples, apical to the line are the post-neonatal line sample, and the circle farthest from the neonatal line is the tooth edge sample.

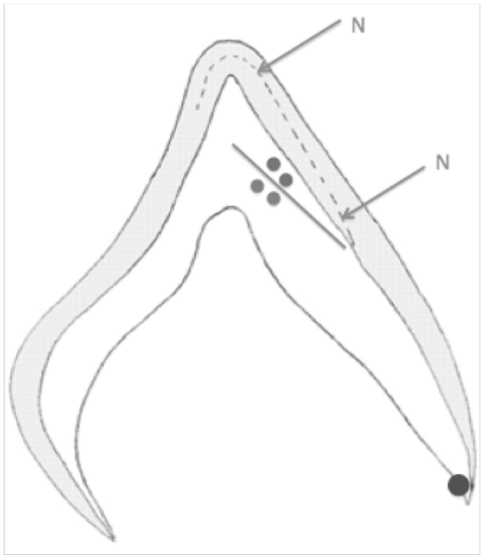


Figure 3-2: Nitrogen value by age. $\delta^{15}N$ (‰) values are on the y-axis, the x-axis is age in months. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details). Each diamond represents one individual.

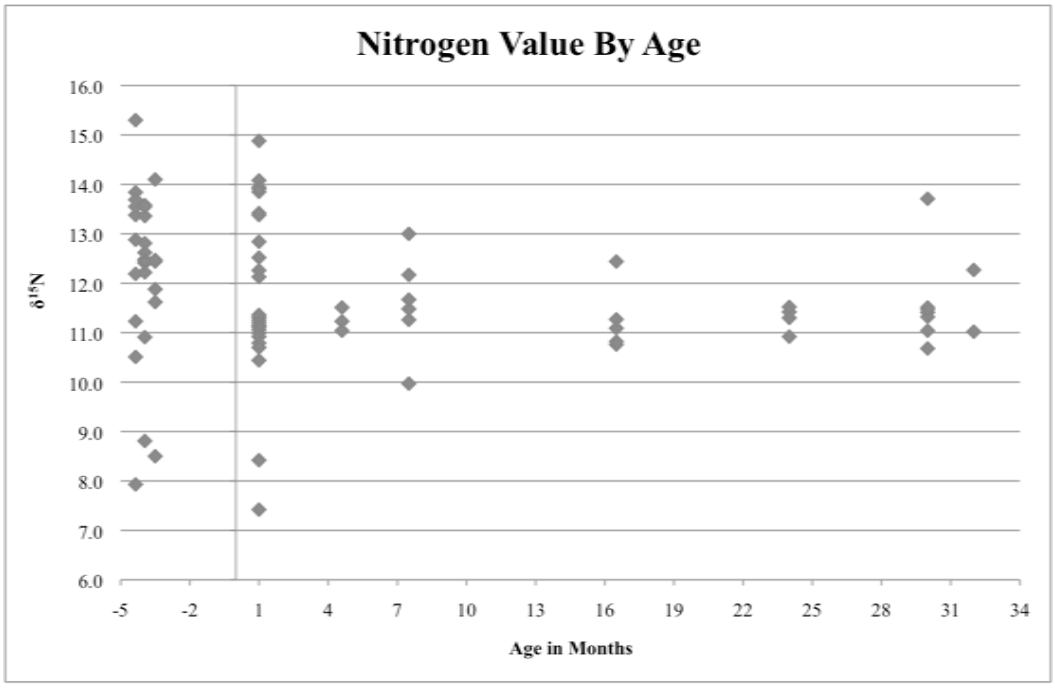


Figure 3-3: Carbon values by age. $\delta^{13}C$ (‰) values are on the y-axis, the x-axis is age in months. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details). Each diamond represents one individual.

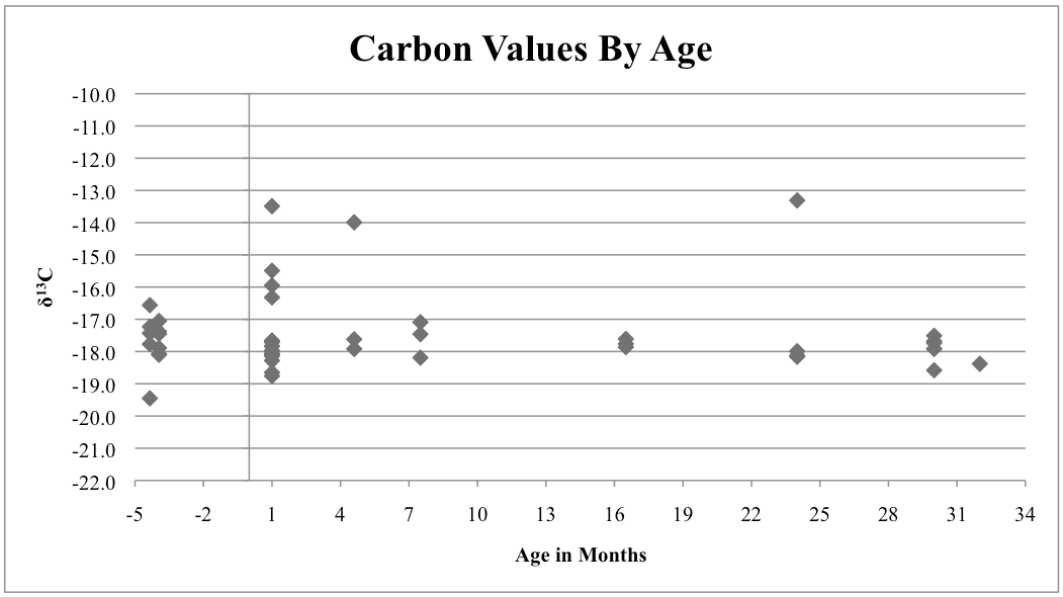


Figure 3-4: Nitrogen and carbon values by group. $\delta^{15}N$ (‰) values are on the y-axis and the $\delta^{13}C$ (‰) values are on the x-axis. Diamonds show in utero signals, squares are samples taken after the neonatal line, and triangles are samples from the tooth edge.

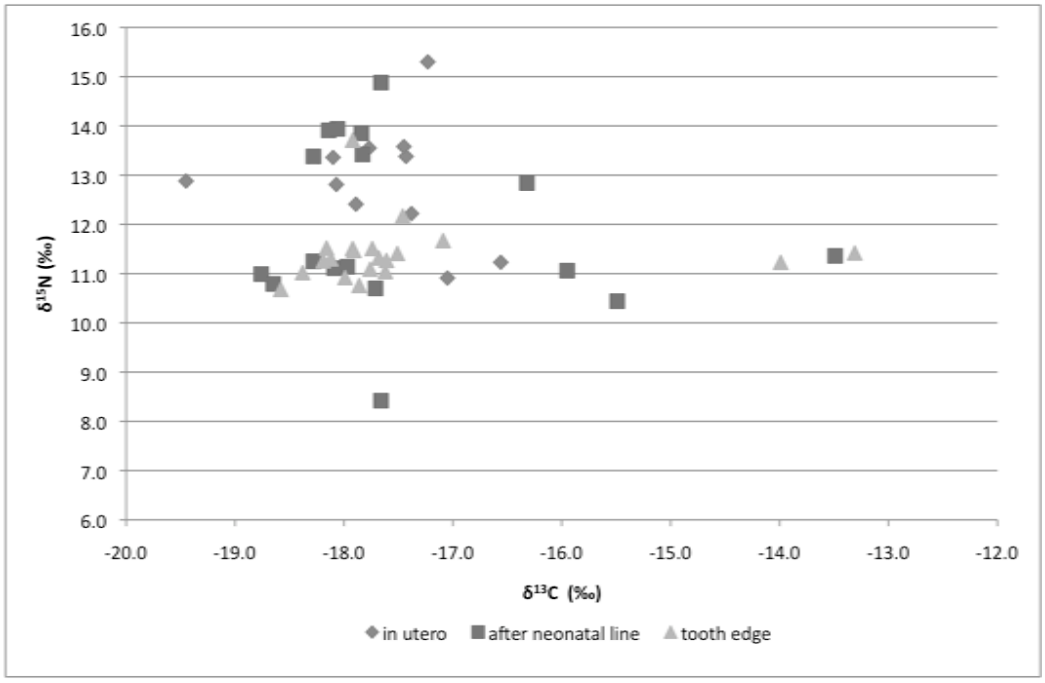


Figure 3-5: Incisor $\delta^{15}N$ (‰) values tracked by individual. Only individuals with at least two consecutive sampling areas are plotted. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details).

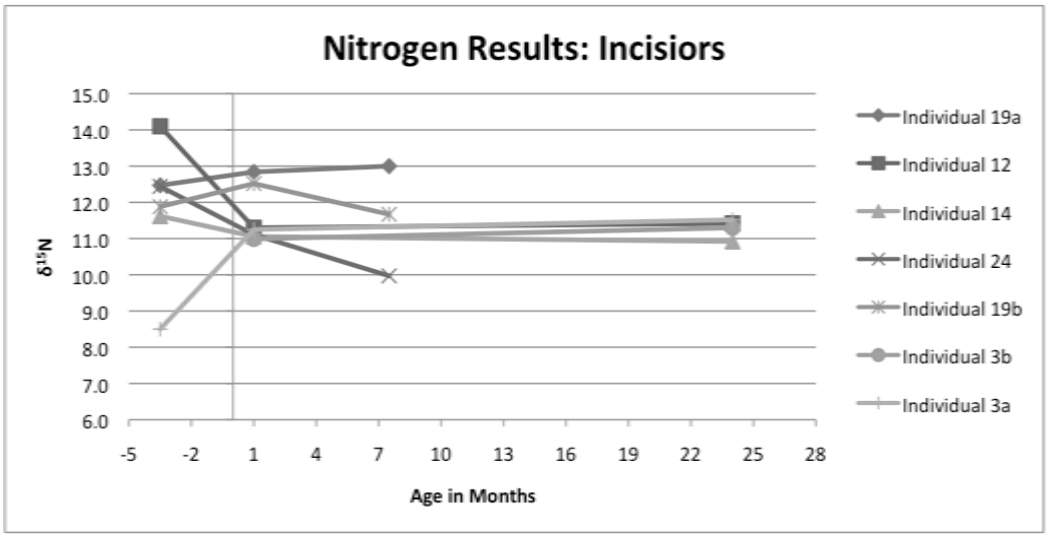


Figure 3-6: Canine $\delta^{15}N$ (‰) values tracked by individual. Only individuals with at least two consecutive sampling areas are plotted. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details).

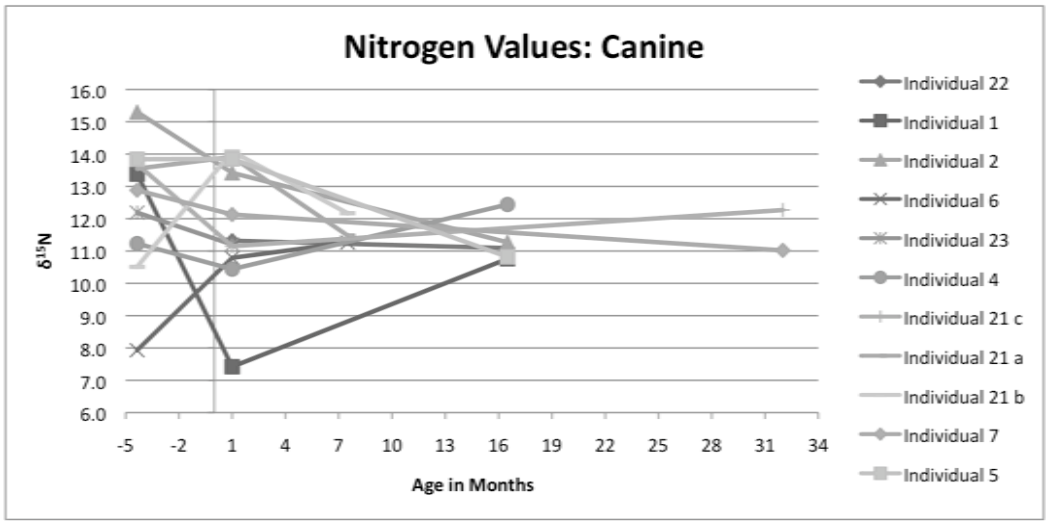
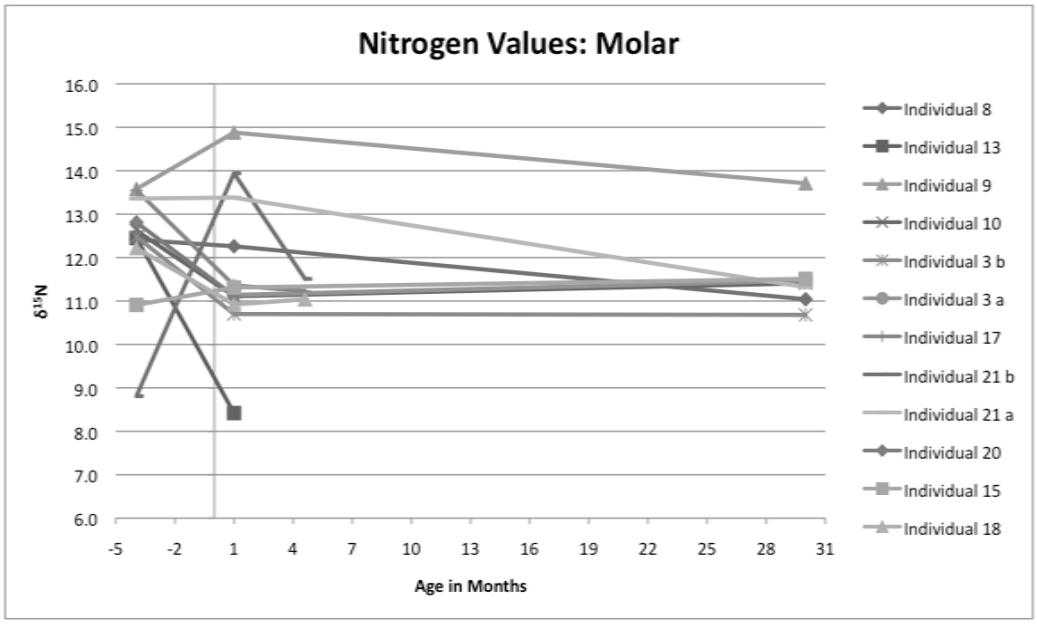


Figure 3-7: Molar $\delta^{15}N$ (‰) values tracked by individual. Only individuals with at least two consecutive sampling areas are plotted. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details).



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Chapter 4

Dietary Reconstruction of the Fishergate House Juveniles Using Carbon and Nitrogen Stable Isotope Analysis of Rib Collagen[2]

4.1 Introduction

The study of archaeological juveniles is often overlooked due to perceived difficulty in studying children or the idea that children are simply miniature adults with no specific culture or behavior of their own (Lewis, 2007). Children were an important part of life in the past, just as they are in the present, making the study of juveniles crucial to a proper understanding of daily life in past populations. This study reconstructs juvenile diet at Fishergate House using the stable isotope analysis of rib fragments from individuals who died between fetal age and five to six years old. The Fishergate House cemetery sample consists of remains from late medieval York, UK (Fig. 4-1). The purpose of this article is to develop a picture of juvenile life in this group by reconstructing juvenile diet and weaning age for this previously unstudied sample.

Nitrogen and carbon stable isotope analysis of bone collagen is a well-established method for dietary reconstruction in archaeological populations (Ambrose, 1990; Katzenberg, 2008). Using these stable isotopes to reconstruct patterns of breast feeding and weaning has also been well established in the literature (Katzenberg and Pfeiffer, 1995; Katzenberg et al., 1996; Kinaston et al., 2009; Richards et al., 2002). The typical method for studying weaning using bone collagen stable isotope analysis requires a series of age-seriated bone samples.

[2] A version of this chapter will be submitted to the American Journal of Physical Anthropology.

Ideally, such a series would include multiple representations of every age group from around birth to fully weaned subadults. The large number of juvenile remains recovered from Fishergate House makes this site ideal for such a study. This study uses rib collagen, which reflects very recent diet and allows a reconstruction of the diet of these children in the months prior to their death. Further study of the site is also ongoing in the form of serial study of the deciduous teeth from the same individuals, which will provide data on individual weaning histories as well as the population weaning pattern reported here.

Holst (2005) states in her initial osteological report on the Fishergate House remains that there is a particularly high mortality rate for individuals between the ages of birth and six years with the highest levels between the ages of four and six years. She postulates that the high mortality rate in this period is likely due to weaning stress. Weaning is generally considered to be the most stressful event of childhood, surpassing even birth (Cunningham, 1995; Fouts, 2004; Katzenberg and Pfeiffer, 1995; Katzenberg et al., 1996; Katzenberg, 2008; Lewis, 2007; Pearson et al., 2010; Schurr, 1998; Sellen, 2009, Stuart-Macadam, 1995; Van Esterik, 1988; Winikoff and Laukaran, 1988). However, based on prior stable isotope analyses reported for medieval Britain that suggest weaning was usually complete by two years of age, four to six years of age is substantially older (Fuller et al., 2003; Fuller et al., 2006b; Mays et al., 2002; Richards et al., 2002). The main goal of this study is to determine when the children of Fishergate House were weaned and whether that weaning stress might have contributed to their deaths. *For more background, see Chapter 2.*

4.2 Materials and Methods

The initial skeletal report for Fishergate House identified 104 adults and 144 subadults, with adults being all individuals over 18 years of age (Holst, 2005). The life expectancy tables created indicate that the mortality rate in the population was highest for individuals between one and six years, the peak mortality rate being between the ages of four and six. This is an unusual age period of peak mortality during the late medieval period (Fildes, 1986; 1995; Fuller et al., 2003; Fuller et al., 2006b; Heywood, 2001; Mays et al., 2002; Richards et al., 2002). Holst (2005) suggest that the high mortality rate for this age group may be due to weaning stress. The possibility of a link between peak juvenile mortality and weaning is well supported in the literature (Goodman and Armelagos 1989; Lewis, 2007; Roth, 1992; Sellen, 2009; Stuart-Macadam, 1995). These individuals did not exhibit signs of trauma, which increases the likelihood of poor health being responsible for the high mortality (Holst, 2005). This study focuses on individuals from fetal age to around five to six years of age to try to learn more about the unique pattern of mortality seen at this site through a reconstruction of diet. Holst (2005) carried out age estimates for all individuals using both dental and skeletal development. The median value of each individual's age range was used for individual age in the sample to allow the comparison of the stable isotope values.

A total of 62 ribs were collected from the Fishergate House collection for isotopic analysis (Table 4-1). Of these, ten were adult females of peak reproductive age, between 18 and 35 years of age. Females from this age range

were chosen to establish the typical female diet during the likely ages of pregnancy and breastfeeding. One additional adult female aged 45+ years was sampled as she was buried with infant c1092 and it is possible that this joint burial indicates a maternal or other close relationship between these individuals. The sample of juveniles ranged in estimated age from fetal (34 weeks) to 6.5 years. It is likely that both males and females are found in the sample. Due to the difficulties in sexing juvenile remains the sample was not divided in this way. All individuals, both juvenile and adult, were buried in a supine extended position. Although precise dating of these individuals is not possible, all are likely from the late medieval period.

Collagen was isolated using demineralization to a collagen model using 1% HCl (Sealy, 1986) followed by soaking the models in 0.125M NaOH for 20 hours to remove humic and fulvic acid contaminants (Katzenberg and Weber, 1999). Preservation of the collagen was determined using C:N ratios, and percent collagen yield (DeNiro, 1985; Ambrose, 1990). Samples were again rinsed with distilled water and frozen, after processing was completed. Samples were then freeze-dried, weighed (1 mg samples) and packed for analysis. Stable isotope analysis was conducted at the Biogeochemical Analytical Laboratory of the Department of Biology, University of Alberta (director Dr. Mingsheng Ma) using a EuropEA Elemental Analyzer coupled with an Isoprime Mass Spectrometer.

4.3 Results

The results of this analysis can be seen in Table 4-1; preservation was determined to be excellent for all samples. Precision was ± 0.1‰ for $\delta^{13}C$ and ± 0.2‰ for $\delta^{15}N$. The %C and %N values are not shown in the table, but percentages were not lower than the acceptable range specified by Ambrose (1990) for modern collagen. This paired with acceptable atomic C:N values indicates good preservation. The female adult rib values are shown in Figure 4-2, compared to means and standard deviation for animals local to York during the late medieval period adapted from Müldner and Richards (2007a; 2007b). All of these women but one, c1091 buried with c1092, was of reproductive age. These 11 individuals do not show much variation in either $\delta^{15}N$ or $\delta^{13}C$. The $\delta^{15}N$ values have a mean of 11.4‰ with a standard deviation of 1.1‰. The minimum and maximum $\delta^{15}N$ values are 9.8‰ and 13.1‰, with a range of 3.3‰. The $\delta^{13}C$ values have a mean of -19.4‰ with a standard deviation of 0.4‰. The minimum and maximum $\delta^{13}C$ values are -20.1‰ and -18.7‰, with a range of 1.4‰. This patterning suggests no major differences in diet within the group. It is clear that there is a reliance on C_3 grain and a high level of marine foods in the diet. The means found in this study are slightly lower than the female means found in previous studies of York (Müldner and Richards, 2007a; 2007b). This is likely due to sampling error from the small sample size used in this study, rather than a real difference in diet between the two samples. This point will be examined more fully in the discussion. The means and standard deviations for these 11 women

will be used as the range of maternal diet at Fishergate House when analyzing the juvenile rib values.

The stable isotope results for the juvenile ribs can be seen in Table 4-1. A graphic depiction of the juvenile $\delta^{15}N$ results is shown in Figure 4-3. The ages used in all figures are the midpoint for the age estimate of each individual as provided by Holst (2005). The $\delta^{15}N$ results for fetal remains show values slightly elevated relative to the adult average, though the values are close to the high end of the adult range. Following this period, there is then an interval from around five months to 1.5 years of age in which infants show a clear elevation of 2.1‰ to 7.0‰ above the adult female mean. This presumably indicates the breastfeeding period; when taking into account the upper and lower standard deviations of the female values this range fits well with the $\delta^{15}N$ trophic increase expected in breastfeeding infants. Values drop to at or near the adult female average by two years of age, suggesting that weaning occurred fairly rapidly and was complete by around two years. Some individuals do maintain a slight elevation over the female values during this period. It does not seem to indicate any kind of sustained mixed feeding in the two to six year period, but rather a slightly different diet than the one reconstructed for adult females. Previous studies of female diet in York during the high medieval period show mean $\delta^{15}N$ values higher than that of the small sample of 11 individuals used here (Müldner and Richards, 2007a; 2007b). This further strengthens the argument that the slightly higher values in children aged two to six years are not related to prolonged

weaning, but rather to a young childhood diet slightly different from that of adult woman sampled in this study.

A graph of the $\delta^{13}C$ results for the juvenile ribs can be seen in Figure 4-4. The pattern is a bit less clear for $\delta^{13}C$ values due to the smaller trophic effect seen with carbon, but the results do show the curve expected with breastfeeding and weaning. Again, the fetal values are slightly elevated relative to the adult average. There is a period of elevated $\delta^{13}C$ values of 1.4‰ to 2.4‰ above the adult female mean between the ages of five months and 1.5 years consistent with a breastfeeding period. The smaller magnitude of this trophic increase is expected for carbon values. $\delta^{13}C$ values then drop to near or slightly below the adult average by two years of age, again indicating a rapid weaning period at this time. It should be noted that while the carbon values are near or under the female values, the nitrogen values are elevated in the two to six year period over the adult females.

One outlying individual's (c1017) $\delta^{13}C$ value is well below the adult average at the age of 10.5 months. Though it does not appear to be an outlier for $\delta^{15}N$, this individual does have the lowest $\delta^{15}N$ of all individuals in its age range, at 13.5‰. It is possible that this individual was not breastfed at all or was weaned extremely early. This individual is considered an outlier from the regular pattern of breastfeeding and weaning seen at Fishergate House, but was not removed from the calculation of the means presented in Table 4-2.

The overall pattern of breastfeeding and weaning is very clear in these results with the $\delta^{13}C$ and $\delta^{15}N$ patterns matching exactly. As expected, the trophic

level increase is not visible until a few months after birth, which is consistent with the delay in the trophic level effect discussed earlier in this paper. It can be assumed that breastfeeding started at or very near to the time of birth, though it is only visible in these results at approximately five months of age. The apparent breastfeeding period continues until around 1.5 years of age. The abrupt decline in $\delta^{13}C$ and $\delta^{15}N$ at the end of this period suggests rapid transition to a fully weaned state at around two years of age. Mixed feeding is not believed to be a dietary factor after this point.

The dietary pattern outlined here was further tested using statistical analysis. The results were grouped into four age categories: fetal (34 weeks to birth), breastfeeding (birth to 24 months), weaned (24 months and older) and female adult. The age boundaries for each group were defined by the previous analysis. The nitrogen and carbon results were both analyzed using independent t-Tests after the distribution showed a normal distribution using a histogram of the data. The results of all t-Tests are presented in Table 4-2. The comparison between the fetal values and the breastfeeding values showed a statistically significant difference for $\delta^{15}N$ ($p<.05$), but not for $\delta^{13}C$. The fetal values also show a statistically significant difference in $\delta^{15}N$ from the adult female diets used in this study, though there is not a significant difference or $\delta^{13}C$. The comparison between the breastfeeding and weaned values showed a statistically significant difference for both $\delta^{15}N$ and $\delta^{13}C$ ($p<.05$). The comparison between the weaned values and the adult female values showed a significant difference for $\delta^{15}N$ ($p<.05$), but not for $\delta^{13}C$. This result was unexpected as weaned children are often

assumed to consume diets similar to those of the adult population. For this reason, the weaned values were compared to the $\delta^{15}N$ values of the larger medieval York sample reported by Müldner and Richards (2007a). No statistical difference was found between the weaned Fishergate House juveniles and this larger group ($p<.05$). The statistical analysis confirms the general interpretations of the Fishergate House sample. Further implications of this analysis are covered in the following section.

It should be noted that two juvenile individuals, 1356 and 1357, were buried together. Both sets of remains were aged at 34 weeks *in utero*. These individuals were thought to be twins (Holst, 2005). The isotopes support this conclusion as both individuals had almost identical stable isotope values. Both had $\delta^{15}N$ values of 13.7‰. The $\delta^{13}C$ values were -19.0‰ and -19.1‰ respectively. While these values could match by chance, it is more likely that the two individuals show the same values due to being twins and inhabiting the same *in utero* environment.

4.4 Discussion and Conclusions

The adult female results presented here are very close to other published results for York and northern England during the late medieval period, though their $\delta^{13}C$ and $\delta^{15}N$ values are on the low end when compared to these populations (Müldner and Richards, 2005; 2007a; 2007b). Variation is expected between study samples even if they are from the same location. Müldner and Richards (2007a) reported female means of -19.5‰ ± 0.5‰ for $\delta^{13}C$ and 12.1‰ ±

1.2‰ for $\delta^{15}N$ during the high medieval period in York. The means from Fishergate House are only marginally lower for $\delta^{13}C$ and $\delta^{15}N$, -19.4‰ ± 0.4‰ and 11.4‰ ± 1.1‰. This suggests consistency in female diet in York during the high medieval period. This consistency is particularly interesting as the Fishergate House sample is thought to be of lower socioeconomic status than the individuals used in previous studies of diet in York. It is important to note that prior studies at York showed female means were lower than male means, though the difference was not statistically significant (Müldner and Richards, 2007a; 2007b). A trend was seen for slight male elevation in $\delta^{13}C$ and $\delta^{15}N$, though some female individuals also exhibited elevated values. The authors believed some of these differences could be socioeconomic, though when compared to the small Fishergate House sample, socioeconomic status does not appear to greatly affect results. A larger sample of adults of both sexes from Fishergate House would need to be analyzed to better understand this relationship.

Although adult diet at Fishergate House was not a focus of this study, it is likely that a larger dietary reconstruction for this sample would closely mirror what has been found in other York samples during the high medieval period. The elevated $\delta^{13}C$ and $\delta^{15}N$ values in this population are evidence of a high level of marine resource use as part of a mixed diet of terrestrial plants and animals. Müldner and Richards (2007b) found that when looking at the general York population, the $\delta^{15}N$ values were high even given the presumed high marine consumption of the group. They explored many options and determined that the consumption of pigs was the likely cause of this extra enrichment seen in $\delta^{15}N$

and not in $\delta^{13}C$. This conclusion is partially based on the knowledge that the inhabitants of York kept pigs and that freshwater fish stocks were depleted by the high medieval period, making them unlikely as a major food source (Barret, 2004; Müldner and Richards, 2007b). A similar diet is likely, but not necessarily, present at Fishergate House. A larger study focused on the adults at Fishergate House would be interesting to determine if there are any differences to be found relative to the general diet of individuals from York. Müldner and Richards (2007a; 2007b) did speculate that it is possible that socioeconomic factors were creating more of the isotopic variation seen in late medieval York than was sex. The Fishergate House individuals were of a lower socioeconomic class than the majority of individuals used by Müldner and Richards in their studies of York and might shed some light on this possibility.

The Fishergate House fetal remains have a pattern of slight elevation over the presumed mean maternal values indicated by the female averages. This finding is consistent in magnitude with the slight differences Fuller (2003) found in his modern fingernail study of mother and infant pairs. However, the Fishergate House values do not appear to be exhibiting a non-patterned difference in values as was seen in Fuller. Rather, individuals seem to be uniformly slightly elevated over the maternal mean for both nitrogen and carbon. It is difficult to determine what this indicates at present, especially if the 11 women sampled here are not representative of the actual diet during pregnancy. Work on microsampling deciduous teeth from these same juveniles has been done and is likely to shed more light on this early period.

A trophic level increase of 3‰-5‰ for $\delta^{15}N$ and 1‰ for $\delta^{13}C$ can be seen in the juvenile remains by five months of age. This increase should indicate the breastfeeding period, which appears to extend to approximately 1.5 years of age before the $\delta^{15}N$ and $\delta^{13}C$ values begin rapidly approaching the adult means. This pattern indicates that breastfeeding likely terminated abruptly before the age of two years. From two years of age onward, the juveniles appear to have been fully weaned and consuming a diet that is near the adult female mean used in this study. There is no evidence of continued mixed feeding, just a different young children's diet than what is seen in the adult females. The findings indicate that the children, as well as the adults, were eating a mixed diet of terrestrial resources such as pigs and marine recourses such as cod and herring. The weaning pattern reported here is very regular and does not suggest a lot of difference between households or across what is likely a few hundred years of time. The same pattern of weaning was seen at Wharram Percy, a contemporary site (Fuller et al., 2003; Mays et al., 2002; Richards et al., 2002). This indicates a uniformity of weaning practices that seems to typify northern Britain during the late medieval period. There was a statistically significant difference found between the breastfeeding and weaned diets as defined by the 18 month boundary. This supports 18 months as the start of the transition to a young childhood diet. The abrupt shift that can be seen in the curve of the $\delta^{15}N$ and $\delta^{13}C$ results clearly indicates that there is no prolonged period of mixed feeding.

The young childhood diet does seem to be slightly different from the adult female diet. However, when the weaned individuals are plotted along with the

adult female population, the pattern suggests a regular offset with the juveniles shifted to the upper end of the adult female values (Fig. 4-5). The $\delta^{15}N$ and $\delta^{13}C$ means for the young children over 21 months, after weaning, are 12.4‰ ± 1.0‰ for $\delta^{15}N$ and -19.7‰ ± 0.5‰ for $\delta^{13}C$. This is very close to those of the adult females, who have a mean $\delta^{15}N$ of 11.4‰ ± 1.0‰ and mean $\delta^{13}C$ of -19.4‰ ± 0.4‰; at one standard deviation, these ranges overlap. The statistical analysis indicates a significant difference in the nitrogen values, but not in the carbon values. The patterning of the results does not suggest that this is a sign of mixed feeding; instead it may be an indication of a young childhood diet that is different from that of the adult female diet, with a higher $\delta^{15}N$ value. This could indicate a normal young childhood diet that is more similar to the more general diet of York, rather than the female-specific diet represented by the Fishergate House adult ribs (Müldner and Richards, 2007a; 2007b). Relative to the full population diet at York (Müldner and Richards, 2007a), the weaned childhood $\delta^{15}N$ values show no difference, suggesting that this diet was not significantly different from the general adult diet at York. If it is not simply the result of sampling error, the difference between the adult female diet at Fishergate House and the general York diet may be attributed to a greater consumption of marine resources, or possibly pigs, in the general population. This could also be the cause of the difference between the young childhood diet at Fishergate House and that of the adult females. It is possible the children were eating a diet intermediate between that of both parents, or that when high status food entered the household mothers put themselves last in consuming it. Further research that reconstructs the general diet

for all ages at Fishergate House specifically may help clarify the relationship of the weaned early childhood diet to the adult diet. It is an interesting finding given the assumed low status of children during this period.

Two other individuals used in this study were buried together, c1091 and c1092 (Table 4-1). This joint burial was speculated to indicate a close relationship between these individuals, possibly a mother-daughter relationship. The juvenile was 18 months old and the adult female was aged at what is generally considered older than reproductive age, 45+. Even if this individual is not the child's mother, she could still be a maternal relative. When the $\delta^{15}N$ and $\delta^{13}C$ values for these two individuals are compared, a clear elevation typical of breastfeeding can be seen. The child has $\delta^{15}N$ and $\delta^{13}C$ values of 14.4‰ and -18.8‰ while the adult female has $\delta^{15}N$ and $\delta^{13}C$ values of 12.3‰ and -19.4‰, a 2.1‰ difference in $\delta^{15}N$ and a 1.7‰ difference in $\delta^{13}C$. Based on diet alone, it is possible that c1091 is the mother of c1092. Due to the very similar results for all adult females, this is not a conclusive finding, but it certainly does not eliminate a maternal or other close familial relationship.

The demographic profile of the Fishergate House remains is unusual with the highest proportion of individuals being between four and six years old. Weaning is usually the greatest stress on infants and a leading cause of death (Fildes, 1986; 1995; Schofield, 2006; Waldron, 2006; Pearson et al., 2010). This led Holst (2005) to speculate that the Fishergate House individuals were being weaned at this age. However, the literature on weaning in Britain during the Late medieval period clearly indicates an earlier weaning age of two years or younger

(Fuller et al., 2003; Fuller et al., 2006b; Jay et al., 2008; Mays et al., 2002; Richards et al., 2002). The stable isotope results of this study clearly support completion of weaning at Fishergate House by around two years of age. Although this was expected given the general trend in Britain during this period, it leaves unresolved the question of why there is such a high prevalence of four to six year olds in this cemetery population. Clearly weaning stress alone cannot be responsible, though it is possible poor health developed at the time of weaning may have contributed to the later deaths of these young children. Further research is necessary on this before conclusions can be made. The next chapter presents the dental analysis that provides more information on the diet at Fishergate House.

Table 4-1 – Descriptive information for each individual. Both the age ranges (determined uisng dental aging) and the midpoint age in months used to graph the results are provided.

Context #	Age Ranges	Midpoint Age (months)	C/N (Atomic)	Collagen Yield (%)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
c1017	6-15 m	10.5	3.26	7.4	-20.4	13.5
c1023	5-6 yrs	66	3.26	3.7	-20.4	12.3
c1027	4.5-5.5 yrs	55	3.32	4.3	-20.4	10.6
c1029	2-3 yrs	30	3.23	11.9	-19.1	12.4
c1033	3-4yrs	42	3.27	5.4	-19.9	11.6
c1035	2-4yrs	36	3.26	4.1	-19.4	12.7
c1042	4-5 yrs	54	3.25	4.4	-20.2	11.9
c1059	3-5 yrs	48	3.26	5.0	-19.9	12.3
c1069	2.5-3 yrs	36	3.27	3.9	-19.5	12.8
c1071	1.5-2.5 yrs	24	3.33	4.9	-20.8	11.8
c1077	2.5-3.5 yrs	36	3.29	4.8	-20.2	13.3
c1089	2-3 yrs	30	3.23	4.7	-19.5	13.4
c1092	1-2 yrs	18	3.28	7.4	-18.8	14.4
c1111	2.5-3.5 yrs	36	3.22	13.3	-19.1	12.5
c1122	3-4 yrs	42	3.26	7.2	-19.5	14.2
c1124	2-3 yrs	30	3.25	9.5	-20.2	12.1
c1135	4.5-5.5 yrs	55	3.24	4.5	-19.8	11.1
c1157	2-3 yrs	30	3.20	9.1	-19.2	14.2
c1167	1.5-2.5 yrs	24	3.21	11.0	-19.0	13.9
c1178	5.5-6.5 yrs	72	3.14	5.6	-19.2	12.1
c1182	4.5-5.5 yrs	55	3.25	8.7	-18.9	13.3
c1216	1-2 yrs	18	3.22	7.1	-19.3	15.2
c1224	1-2 yrs	18	3.32	4.3	-18.8	13.1
c1226	6-9 m	7.5	3.23	5.5	-18.6	17.4
c1233	4.5-5.5 yrs	55	3.29	5.5	-19.3	13.8
c1265	3-9 m	6	3.23	6.9	-18.7	15.4
c1289	1.5-2 yrs	21	3.26	14.8	-19.4	12.7
c1290	3-4 yrs	42	3.23	4.1	-19.2	12.5
c1319	2-3 yrs	30	3.26	4.8	-19.1	13.2
c1324	38 wks	3 fetal	3.28	10.0	-18.9	12.9
c1336	4.5-6 yrs	60	3.16	9.1	-19.7	10.9
c1356	34 wks	2.8 fetal	3.27	9.3	-19.0	13.7
c1357	34 wks	2.8 fetal	3.30	9.1	-19.1	13.7
c1359	36 wks	3 fetal	3.31	7.3	-19.5	13.1

c1371	.5 - 1.5 yrs	12	3.25	8.4	-17.7	16.3
c1376	.8-18 m	9.4	3.21	11.5	-18.6	15.2
c1380	1-2 yrs	18	3.22	25.2	-19.4	15.5
c1386	3-9 m	6	3.21	11.8	-18.7	13.9
c1390	1-2 yrs	18	3.24	6.5	-19.5	13.9
c1414	4-5 yrs	54	3.23	3.6	-19.8	11.6
c1425	1-2 yrs	18	3.21	5.1	-20.0	11.1
c1427	1-2 yrs	18	3.27	5.1	-18.7	13.2
c1434	1-3 yrs	24	3.31	6.3	-20.1	13.2
c1443	0-1 yrs	6	3.42	11.7	-18.2	15.7
c1458	0-6 m	3	3.39	3.5	-19.7	12.2
c1463	5-6 yrs	66	3.33	8.1	-19.4	12.6
c1480	1-2 yrs	18	3.26	15.5	-19.5	16.3
c1492	4-6 yrs	60	3.14	8.1	-20.4	10.5
c1539	4-5 yrs	54	3.20	6.7	-20.0	11.2
c1545	3-4 yrs	42	3.23	8.1	-19.8	13.3
c1575	3-9 m	6	3.25	4.8	-18.5	16.0
c1585	4.5-5.5 yrs	60	3.21	7.7	-19.4	11.6
c1595	newborn	0	3.26	5.6	-19.2	12.9
c1055	22-25 yrs		3.46	5.0	-18.7	12.7
c1091	45+ yrs		3.28	6.6	-19.1	12.3
c1095	25-35 yrs		3.27	5.7	-19.1	11.4
c1155	25-35 yrs		3.19	13.7	-19.9	10.4
c1159	25-35 yrs		3.26	14.7	-18.9	13.1
c1214	25-35 yrs		3.32	4.7	-19.7	10.6
c1249	25-35 yrs		3.33	6.3	-19.5	10.3
c1251	25-35 yrs		3.17	13.7	-19.6	9.8
c1259	25-35 yrs		3.26	6.0	-20.1	11.9
c1277	18-20 yrs		3.33	4.2	-19.7	11.7
c1310	25-35 yrs		3.17	16.2	-19.5	11.1

Table 4-2 – General statistics and t-Test results for nitrogen and carbon.

Nitrogen General Statistics

Age Group	*N*	*Mean (‰)*	*Std*
Fetal	6	13.1	0.57
Breastfeeding	17	14.6	1.61
Weaning	30	12.4	1.02
Female Adult	11	11.4	1.05
York Adult*	134	12.8	1.27

*Data from Müldner and Richards (2007a)

Carbon General Statistics

Age Group	*N*	*Mean (‰)*	*Std*
Fetal	6	-19.2	0.31
Breastfeeding	17	-29.0	0.67
Weaning	30	-19.7	0.50
Female Adult	11	-19.4	0.43

Results of Independent Sample t Tests

Fetal vs. Breastfeeding	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std Error Difference*
$\delta^{15}N$ (‰)	-3.426	20.938	**.003**	-1.553	.453
$\delta^{13}C$ (‰)	-.858	21	.4	-.245	-.674
Breastfeeding vs. Weaned					
$\delta^{15}N$ (‰)	5.102	23.595	**.000**	2.205	.432
$\delta^{13}C$ (‰)	4.027	45	**.000**	.692	.172
Weaned vs. Female Adult					
$\delta^{15}N$ (‰)	2.845	39	**.007**	1.039	.365
$\delta^{13}C$ (‰)	-1.425	39	.162	-.243	.171
Weaned vs. York Adult					
$\delta^{15}N$ (‰)	-1.337	162	.182	-1.371	.395

Female Adult vs. Fetal					
$\delta^{15}N$ (‰)	3.605	15	**.003**	1.692	.470
$\delta^{13}C$ (‰)	1.009	15	.329	.203	.201

Figure 4-1 - Maps of medieval York. Arrow indicates York; star indicates Fishergate House site within York (White, 2000).

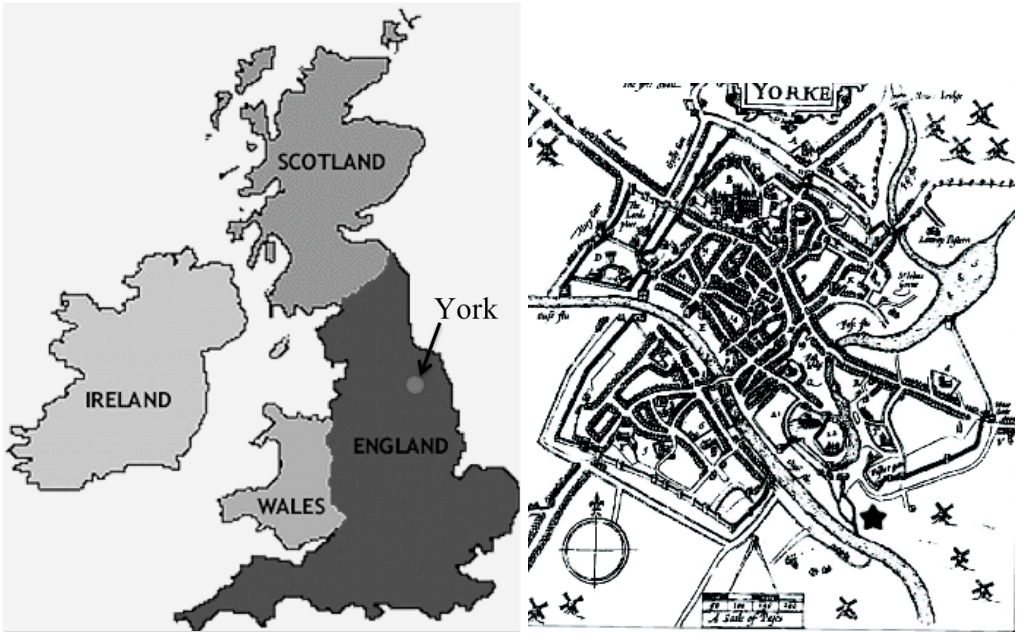


Figure 4-2 - Adult female $\delta^{15}N$ and $\delta^{13}C$ results for Fishergate House are the diamonds. Animal ranges are from Müldner and Richards (2007a, b) and show expected diet for the York area fauna. Adult females are of reproductive age.

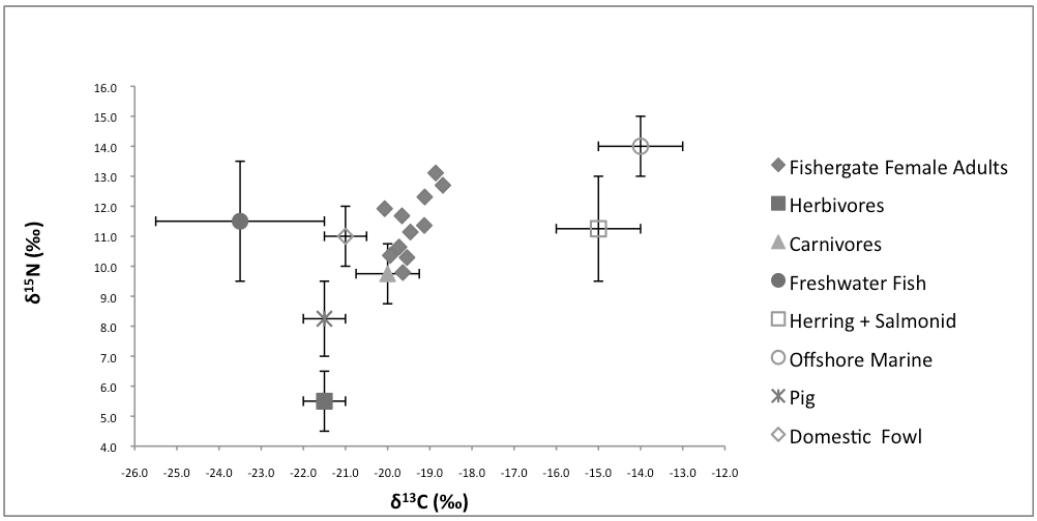


Figure 4-3 - Juvenile $\delta^{15}N$ values for Fishergate House. Juvenile values are shown as diamonds; the square box and error bars indicate adult female mean and standard deviation for Fishergate House. Juvenile ages are estimates of the midpoint of each age range (see text for details). All adult females are of reproductive age.

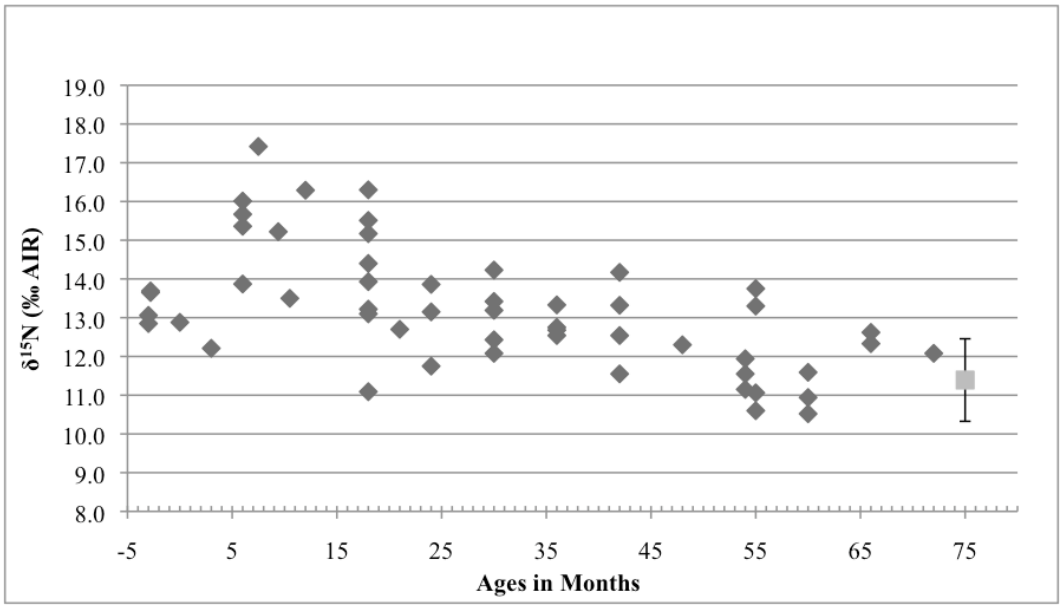


Figure 4-4 – Juvenile $\delta^{13}C$ values for Fishergate House. Juvenile values are shown as diamonds; the square box and error bars indicate adult female mean and standard deviation for Fishergate House. Juvenile ages are estimates of the midpoint of each age range (see text for details). All adult females are of reproductive age.

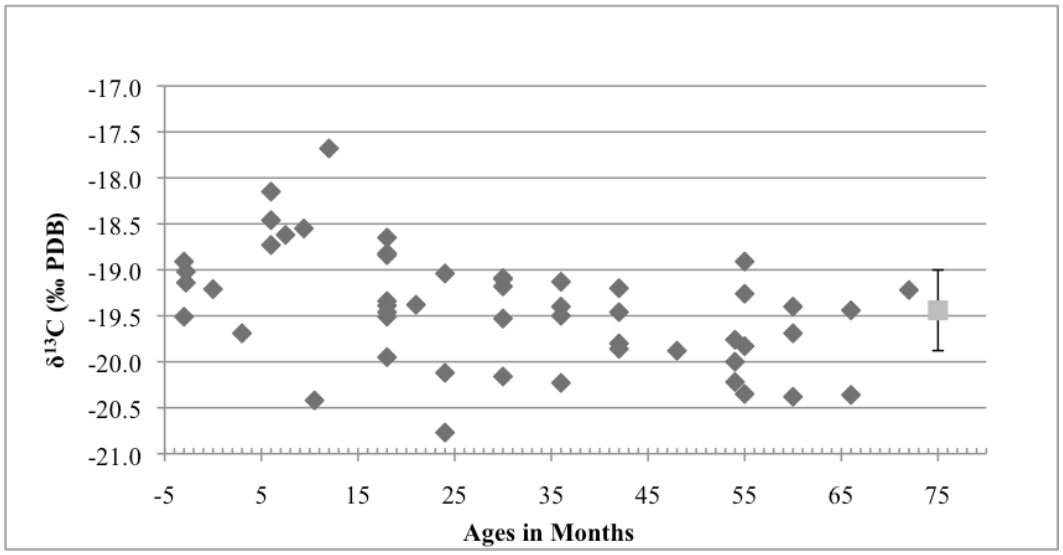
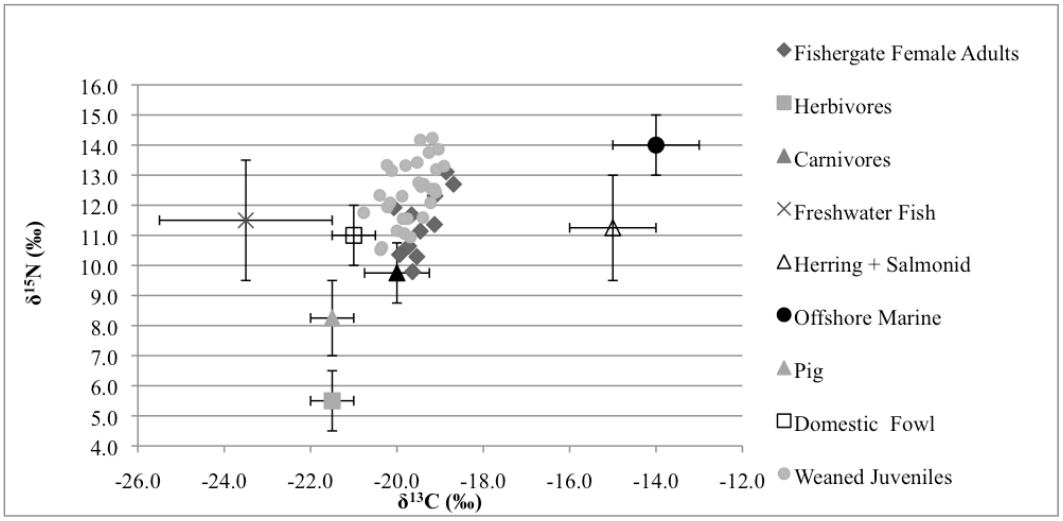


Figure 4-5 - Adult female $\delta^{15}N$ and $\delta^{13}C$ results for Fishergate House (diamonds) and weaned juvenile $\delta^{15}N$ and $\delta^{13}C$ results (grey circles). Animal ranges are from Müldner and Richards (2007a, b) and show expected diet for the York area fauna. Adult females are of reproductive age.



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Chapter 5

Dietary Reconstruction of the Fishergate House Juveniles Using a New Method of Dentine Microsampling for Stable Isotope Analysis

5.1 Introduction

Stable isotope analysis is used to reconstruct diet in past populations (Katzenberg, 2008; Lee-Thorp, 2008). While stable isotope analysis usually involves the use of bone collagen, this study focuses on collagen from tooth dentine. Dentine is laid down during fetal and childhood development and does not remodel after this period (Hillson, 1996; Scheuer and Black, 2004; Van der Linden, 1983: 168; Zaslansky, 2008). This makes dentine an excellent material for studying early childhood diet in the past. While many previous human dentine studies used whole teeth or large serial samples of teeth (Dupras and Tocheri, 2007; Fuller et al., 2003; Richards et al., 2002; Wright and Schwarcz, 1999), the focus of this study is microsampling. The serial nature of the analysis is designed to show any major changes in diet during different developmental periods for the subadults in a population as a whole. It will also make it possible to see the dietary trends within a single individual. Microsampling is a new methodology for stable isotope analysis that is just beginning to be used in human dentine studies. The microsamples used in this study, and described previously by the author (See Chapter 3), are the smallest currently being used on human dentine. This study will present the applicability of this method to archaeological samples.

The research presented here further examines the breastfeeding and weaning pattern of juvenile individuals from Fishergate House York, UK. Diet in this late medieval population has not been extensively studied. Chapter 4 details

stable isotope results for rib collagen from juveniles at the site, and this study is a continuation of that research intended to further examine maternal diet, breastfeeding and weaning diet, as well as weaning age in this population. The increased sample size afforded by microsampling will help to test a prior hypothesis regarding weaning time at Fishergate House. The initial osteological study of the Fishergate House remains (Holst, 2005) led to a suggestion that weaning occurred between four and six years of age based on the high level of mortality for this age group. However, rib collagen isotope analysis (Chapter 4) determined that weaning at Fishergate House was completed around two years of age, as is the case in most of northern Britain during this period (Fuller et al., 2003; Fuller et al., 2006b; Jay et al., 2008; Mays et al., 2002; Richards et al., 2002; Spall and Toop, 2005). One of the goals of using dental microsampling on the Fishergate House remains is to increase the number of isotopic data points for each age category, creating a fuller picture of juvenile diet by looking at the patterning of nitrogen and carbon throughout early childhood. Another focus is on looking at individual weaning trends at Fishergate House. This study is the first to test the dentine microsampling method on archaeological remains. *For more background on medieval diet, please see Chapter 2.*

5.2 MATERIALS

5.2.1 Fishergate House

Fishergate House is an archaeological site excavated by the York Archaeological Trust between 2000 and 2002 (Spall and Toop, 2005). The original Fishergate suburb was located in York near the Fishergate, some distance

from the city core. The site was identified as the cemetery for St Helen, which was established in the 11th century; it runs from Fishergate in a narrow band over to the banks of the river Ouse (Fig. 5-1). Peak cemetery usage was during the mid-14th to 15th centuries and was abandoned by the 16th century. Based on historical records, the individuals composing the Fishergate House sample are all members of the working poor (Dryer, 1998; Wilson and Mee 1998). These individuals were all buried east-west in a supine position, and all but a few were buried in shrouds rather than coffins. Burial style and goods give few signs of socioeconomic differences within the population. Most of the remains from the cemetery were in good to excellent condition, and they include a significant number of juveniles. *For a more detailed description of the site, see Chapter 2 or Spall and Toop (2005).*

5.2.2 Sample

Deciduous teeth from 42 subadult individuals were collected from the Fishergate House collection. All individuals between birth and six years were sampled if a tooth was available. The sample likely contains both males and females. Due to the difficult and unreliability of sexing juvenile remains the sample was not separated by sex. Photographs of all teeth were taken before processing to ensure that the level of development of the tooth could be recorded and to preserve a record of the tooth before destructive processing proceeded. Single rooted teeth, particularly incisors, were preferred for the study, but all tooth types are represented (Table 5-1). The teeth were in excellent condition with

little dental wear being present. Teeth without dental pathology were chosen preferentially, as were loose teeth. Rib samples were also collected for these individuals, and the full results of that isotopic research are presented in Chapter 4. Adult diet was established using eleven female adult ribs from the Fishergate House collection. The mean $\delta^{15}N$ and $\delta^{13}C$ values of those rib samples will be used as the Fishergate House adult averages for comparative purposes.

5.3 METHODS

The tooth microsampling method used in this study has been previously described elsewhere and will be described only briefly here (Chapter 3). Each tooth was longitudinally sectioned in a labial-lingual direction at the midline using a Dremel tool. One half of the tooth was used to make a slide on which the neonatal line was identified using polarized light microscopy. This feature was used to establish the approximate extent of dentine at the time of birth, locating the fetal dentine. The other half of the tooth was used for the dentine stable isotope analysis. The tooth was partially demineralized using standard stable isotope procedures adjusted for small sample size (Katzenberg, 2008; Lee-Thorp et al., 2008; Tuross et al., 1980; 1988). Sample demineralization was started using 1% HCl, and microsamples were taken after roughly 50%-75% demineralization using a dermal punch. Samples were taken from three areas: occlusal to the approximate location of the neonatal line, apical to the neonatal line (near the apical edge of the crown), and at the preserved apical edge of the tooth root. Care was taken to ensure that the enamel was completely removed from these samples.

As many microsamples as possible were taken from each of these locations without compromising the precision of the sampling. Previous findings on modern teeth had established the need to maximize sampling area to avoid extremely low sample weights (Chapter 3). It was assumed that even less collagen would be present in microsamples of archaeological teeth, making obtaining an adequate sample weight even more crucial. Tooth size was an important determinant of the number and size of microsamples available at each of the three sampling points. Each tooth, once sampled, contributed three different dietary signals, resulting in a total of 126 samples. After sampling, demineralization in 1% HCl was continued for all microsamples; after demineralization was complete, soil humic and fulvic contaminants were removed using a 20 hour soak in 0.125 M NaOH. Collagen $\delta^{15}N$ and $\delta^{13}C$ analysis was performed at the Biogeochemical Analytical Laboratory of the Department of Biology, University of Alberta (director Dr. Mingsheng Ma) using a EuropEA Elemental Analyzer coupled with an Isoprime Mass Spectrometer.

5.4 RESULTS AND DISCUSSION

5.4.1 Results and Discussion: Population

Three samples were run for each tooth for a total of 126 microsamples (neonatal, post-birth, and growing edge of the tooth). For the purposes of interpretation, the neonatal signal for each tooth was assigned the age of initial dentine formation for that tooth. The post-birth samples represent the apical edge of the crown and were assigned the age of crown completion for that tooth type.

Finally, the preserved apical edge of each tooth was assigned the age corresponding to the normal age of development for that region. In cases where the tooth was still in formation, this age corresponds to the point of formation reached at death (for example, root half formed). In cases where the root was completely formed, this age corresponds to the age of formation of the apical end of the root. These ages vary by tooth type and are based on known development patterns of deciduous teeth (Van der Linden, 1983; Hillson, 1996). Of the 126 samples, three neonatal samples were not large enough to generate reliable nitrogen or carbon results, valid nitrogen results were generated for all other samples. Of these 123 samples, 59 did not have a sufficient weight to generate dependable carbon results. Precision was ± 0.1‰ for $\delta^{13}C$ and ± 0.2‰ for $\delta^{15}N$. The %C and %N values are not shown in the table, but percentages were not lower than the acceptable range specified by Ambrose (1990) for modern collagen. This paired with acceptable atomic C:N values indicates good preservation. Isotopic results and C:N ratios are presented in Table 5-1 (for age at death please refer to Table 4-1). Sample C:N ratios are within the normal range for all valid sample weights. The $\delta^{15}N$ and $\delta^{13}C$ values for the molars do not show the regular patterning seen in other tooth types, indicating that distinct sampling locations could not be reliably maintained, presumably due to within-tooth variation. This is consistent with what was found when testing the method on modern teeth (see Chapter 3). The neonatal line is very difficult to locate in molars and it does not appear that the molars are producing accurate results for the target age categories. For this reason, the molar values were excluded from

further interpretation. This removes four individuals from consideration (1029, 1059, 1089, and 1427). *For further discussion of molars, see section 5.4.2.*

Figure 5-2 presents the nitrogen stable isotope results. The overall pattern is very clear; the neonatal values (mean $\delta^{15}N = 14.1‰$) are higher than the adult female values (mean $\delta^{15}N = 11.4‰$) from Fishergate House. The postnatal breastfeeding values (mean $\delta^{15}N = 14.8‰$) are higher than the fetal signals and reflect the expected breastfeeding elevation. The peak seen with breastfeeding then decreases rapidly starting around 1.5 years to the weaned signal (mean $\delta^{15}N = 12.4‰$). The pattern suggests that most individuals were fully weaned by two years. At its peak, the apparent breastfeeding signal is located the expected 2‰ to 3‰ above the fetal values. Although the patterning of the dentine values suggests that values representing roughly two years of age are weaned values, these values are still more enriched on average than the female adult rib value for the site. Rib values show a similar pattern (Chapter 4). The variation in $\delta^{15}N$ values seen around two years is likely caused by some individuals having a slightly accelerated weaning schedule (being completely weaned by two years) and others having a slightly slower weaning schedule (not showing full weaning until a bit after two years). The $\delta^{15}N$ values from the small set of dentine samples corresponding to three years of age are at the upper end of the adult female range for most individuals. Based on these values, there does not appear to be breastfeeding occurring in any of the individuals by three years of age.

Another view of the data is possible when the weaned $\delta^{15}N$ values are compared to the values obtained for the general medieval population of York,

rather than the few adult female Fishergate House values used here (Müldner and Richards, 2007a; 2007b). The dietary reconstruction for medieval York is based on remains from the same time period from the Gilbertine Priory cemetery on the other side of the wall from the Fishergate House cemetery. Possible issues with the representativeness of the adult female diet reconstructed for Fishergate House, the most likely being sample size, were outlined previously in the study of the juvenile ribs (Chapter 4). In that study, it was suggested that the $\delta^{15}N$ elevation of the young children over the adult females is likely due to a dietary difference between young juveniles and adult females, with the juveniles eating more high trophic level proteins like marine fish or pigs, which are known to be important foods at medieval York. Although the weaned diet differs from that of the adult females used in this study, it is more in fitting with the whole population of York as reconstructed by Müldner and Richards (2007a; 2007b). This could indicate that the children ate a diet reflective of both of their parents. For that reason, the weaned diets are compared to the adult female diets reconstructed for this study, but also to the total population diet for the statistical analysis. This comparison will also help clarify the unusual amount of high trophic level proteins apparently consumed by the weaned Fishergate House children.

The microsampling technique has provided a large sample of neonatal $\delta^{15}N$ data. The enriched fetal signal seen here may indicate that the maternal diet had a generally higher $\delta^{15}N$ value than did the general female diet of Fishergate House, and thus that it included protein of higher trophic level. A comparison to an adult female average is not the same as a comparison of a mother and her own

infant. With such a small adult female sample size, there is considerable uncertainty regarding maternal diet. Clearly, though, the fetal values are related to that child's maternal values in some way. It is possible that the fetal values are slightly enriched compared to maternal diet due to processing of the isotope from the diet. Fuller et al. (2006a) did not find a uniform difference in neonatal values as compared to maternal diets in his study of modern infants and mothers, but they did find differences between the values. Both the rib and tooth results from Fishergate House appear to indicate a slight increase in comparison to the maternal values, or very little difference (Chapters 4). While fetal values are higher than expected, this is not believed to be sampling error. Great care was taken to isolate the area of sampling and should the signal be mixed it would still be overwhelmingly fetal. Additionally, while there is some enrichment in the fetal values, they still do show the expected pattern (see section 5.4.2 on individual trends for a better representation of this pattern). It is also possible that the enriched fetal signals are the result of metabolic changes during pregnancy. This topic is just beginning to be explored in the literature (Duggleby and Jackson, 2002; Fuller et al., 2004; 2006a; Williams et al., 2011). It appears clear that there is a metabolic difference during pregnancy affecting the separation between pregnant women's diets and their tissue signals. It is likely that separation of fetal tissue isotope stable values from the maternal diet also differs from the usual trophic enrichment pattern. Fuller et al. (2004) found that maternal tissue $\delta^{15}N$ values were decreased near the time of birth when compared to diet due to altered metabolism of nitrogen during pregnancy. This is particularly interesting given

the findings of this study, with enrichment seen in the fetal signals relative to the adult female values. Further study is needed, but it may be possible to determine a regular metabolic effect on the stable isotope values of the fetus in relationship to maternal diet.

Figure 5-3 presents the carbon stable isotope results. The pattern is much less clear than that seen in the nitrogen results, so to help with the visualization the means of the breastfeeding and weaning periods are depicted connected with a trend line to show the overall difference between these values. The fetal and postnatal periods in particular have a lot of variation, much more than are seen in the adult females. This variation is difficult to link to a specific cause. Carbon shows a small 1‰ trophic increase during breastfeeding, and when coupled with variability in the weaning process, this makes archaeological infant $\delta^{13}C$ values difficult to interpret (Dupras et al., 2001; Fuller et al., 2006a; Richards et al., 2003; White et al., 2001). In this case, an outlier at 2.5 months (individual 1071, $\delta^{13}C$ is -20.5‰) appears to be obscuring the overall pattern. This individual shows an atypical pattern that is discussed in the section on individual values. When this very low value is taken out, the overall $\delta^{13}C$ pattern becomes slightly clearer though the range is still wide. When the mean values for the birth to 18 months and over 18 months are plotted, a clear drop in carbon values (0.3‰) can be seen between these periods (Fig 5-3). Though the pattern is almost non-existent in the carbon values when compared to the pattern seen in the nitrogen values, the carbon values do increase, consistent with a breastfeeding period spanning from birth to 1.5 yrs before falling to a level nearer to the female average by around

two years of age. The adult female range clearly overlaps with all of the values from every life stage. However, when looking at individuals in the next section the pattern of breastfeeding and weaning is a bit easier to see.

The apparent dietary groups discussed above were also tested using independent t-Tests; normality was first visually checked using histograms. Four age/dietary groups were tested: fetal, breastfeeding, weaned, and adult. Adult values were both the adult female rib values from Chapter 4 and the adults from later medieval York (Müldner and Richards, 2007a, 2007b). The fetal group contains all pre-birth values. Dentine samples formed between birth and roughly two years of age made up the breastfeeding group. The weaned group contains dentine samples estimated to have formed after two years of age.

Table 5-2 presents the t-Test results for nitrogen values. They show that there is a significant difference between the fetal values and the breastfeeding values ($p<.05$). The fetal values are also significantly different from the adult female values ($p<.01$). This suggests that some physiological process is causing the fetal values to be different from the female values, though it is possible that the adult female values do not accurately reflect diet during pregnancy. The breastfeeding and weaned means are significantly different ($p<.01$) as was expected based on the visible shift between these stages. There is also a significant difference between the weaned values and the adult female mean ($p<.05$). Due to the uncertainty of the accuracy of the mean of these 11 women for the general population, the weaned results were also compared to the total population values from later medieval York (Müldner and Richards, 2007a,

2007b). Interestingly, the weaned mean was not significantly different from the total population mean with a p-value = .05. These results indicate that the weaned diet followed after the age of roughly two years was distinct from the earlier breastfeeding diet. Though the test of the weaned diet relative to the adult female diet indicated by the 11 Fishergate House ribs showed a significant difference indicating a child specific diet, when compared to the whole York population as determined in other studies the weaning diet does not differ significantly from the adult diet. Again, this suggests what would be considered a high status diet for these juveniles.

Independent sample t-Tests were also run comparing carbon values for all four groups. The carbon means were all extremely close to each other, which makes comparing means difficult. No statistically significant differences were found between any categories. The breastfeeding and weaning patterns are not strong enough to be testable using basic statistics. The carbon sample also suffered from small sample size. These findings do not change the general trends seen with these values.

5.4.2 Results and Discussion: Individual Trends and Weaning at Fishergate House

The individual $\delta^{15}N$ results are arranged by tooth type and are presented in Figures 5-4a, 5-4b, 5-5, and 5-6. When considering the results on this scale it is clear that most individuals show an increase from fetal to postnatal dentine that is consistent with a trophic level increase from the fetal value, as proxy for maternal

tissue values, to breastfeeding. The values then drop again by the age of 20 - 25 months, presumably to the weaned value, which is close to the population mean and falls below the fetal signals. The fetal values are higher than the female average as reconstructed from the eleven adult female rib samples; as discussed above, this difference is statistically significant. Because the fetal values are so high the breastfeeding peaks look relatively modest. However, when the average value for breastfeeding-period dentine is compared to the average adult female rib value, a difference of roughly one trophic level (3 - 4‰) is seen. The unexpectedly high fetal values compared to Fishergate House adult females could be due to a number of factors. It is possible that the diet during pregnancy differed significantly from the normal adult female diet. It is also possible that with only eleven individuals represented, the sampled adult females of reproductive age are a skewed subset of women at Fishergate House. Further work on adults from the site may show an overall average closer to the fetal values and the population averages found in previous studies of medieval York. Even given the elevation of the fetal signals, when the values for each individual are plotted most adhere to the expected pattern of lower fetal $\delta^{15}N$ than breastfeeding $\delta^{15}N$. A few individuals' $\delta^{15}N$ values changed very little, yielding almost identical fetal and breastfeeding signals (individuals 1319, 1027, 1178, 1167, 1111, 1226, 1033). Rather than being a sampling error, this could be due to the fetal processing of nitrogen. Fuller et al., (2004; 2006a) believed that a possible reason for differences seen between the signals of pregnant women and their fetuses was differential processing of the isotopes from the diet. Since we do not know the

actual female diets during pregnancy and just have the fetal signals, it is difficult to determine if all of the fetal signals are elevated above the maternal diet or not. In cases where there are no fetal juveniles to be studied, or a limited number of fetal bones, it does appear that the fetal signal contained in teeth has a potential to be an adequate if not perfect proxy for maternal diet. More work must be done to determine if there is a systematic difference between the maternal and fetal values. It is clear from the individual graphs that most of the fetal signals are very close to the weaned signal for each individual. This implies there is a true relationship between the two diets where the signal from fetal life reflects the maternal diet, which will be close to that individual's weaned diet.

Figure 5-6 shows the individual patterns for the molars. In this view, it is clear that the sampling strategy was less effective for this tooth type. As mentioned above this is the reason these patterns are not specifically discussed here. In the future refinement to the sampling method may allow the microsampling of molar teeth.

Figure 5-7 presents the individual results for carbon. Looking at the graph, it is clear that the fetal signals group together closely with an overall range of 1.8‰. The validity of the fetal values as a proxy for maternal values is not clear due to the amount of overlap of the signals at different ages. A $\delta^{13}C$ increase attributable to a breastfeeding diet is also not clear, as it appears to occur in some individuals and not others making the overall pattern difficult to interpret. Some of the individuals that can be followed through the breastfeeding and weaning periods suggested by $\delta^{15}N$ analysis show the expected pattern of a drop in $\delta^{13}C$

over time. When this is present, the difference is in the 0.5‰ range, reasonable given the 1‰ trophic $\delta^{13}C$ elevation associated with nursing. However, two individuals do not show this decrease (1071, 1380). These two cases will be discussed separately in the following section. The small set of weaned $\delta^{13}C$ values are close to the adult female rib mean of -19.4‰, implying that these values are reflecting a diet similar to that of adult females and not necessarily a completely different early childhood diet.

5.4.3 *Results and Discussion: Unusual Individual Trends and Health*

Individual 1380 shows a $\delta^{15}N$ increase between the fetal and postnatal samples, but at 18 months there is no sign of a decrease in nitrogen values. At nine months dentine $\delta^{15}N$ is 15.7‰, and at 18 months, it is essentially unchanged at 15.9‰. It appears that this individual may have been breastfeeding for a somewhat longer period than some others in the group may. It is also possible that at this point fewer weaning foods had been introduced, so that a greater proportion of the protein was being drawn from breast milk. The rib value for this individual also represents an age around 18 months, the estimated age at death. It is 15.5‰ (Chapter 4), a very small decrease relative to the dentine. A prolonged weaning period is also suggested by the carbon values. At nine months the $\delta^{13}C$ value is -19‰; at 18 months the $\delta^{13}C$ value is -18.7‰ and the rib value is -19.4‰. Again, this indicates that weaning may not have begun for this individual even at 18 months of age. Holst (2005) determined that this individual had a possible case of hydrocephaly. The different feeding pattern seen here could

indicate an attempt to protect the health of the child. The specific reason for the deviation cannot be definitively known, but it does imply that feeding behaviors could be modified for sickly children.

Individual 1290 also shows an atypical weaning pattern with almost no change between the breastfeeding and root end values. A closer look at the nitrogen values does show a slow decline in values, indicating a prolonged breastfeeding period. At 2.5 months the $\delta^{15}N$ value is 13.7‰ and by 24 months it is 13.5‰. The rib value, representing an age of roughly 42 months, is 12.5‰; this suggests that tissue $\delta^{15}N$ values were slowly decreasing to approach the adult norm at the time of death. The postnatal sample for this individual did not produce a usable $\delta^{13}C$ value, so the $\delta^{13}C$ pattern cannot be traced in this individual. This individual shows no signs of pathology, so there is no obvious reason for a prolonged weaning period.

Again, individual 1545 shows a pattern of almost no $\delta^{15}N$ change between the postnatal signal and the tooth root signal. As with individuals 1380 and 1290, this likely indicates a prolonged breastfeeding period for this individual. At two months the $\delta^{15}N$ value is 14.0‰ and by 20.5 months the $\delta^{15}N$ value has only fallen to 13.7‰. The rib value at death (approximately 42 months) is 13.3‰, again showing only a slight decrease. In contrast, the $\delta^{13}C$ values appear to be decreasing in the expected way. This could indicate that complementary feeding with grain based gruel or a similar cereal was occurring that affected the carbon values, but was not a significant enough protein source to register in the nitrogen values. This individual has severe DEH, which could be a sign of serious stress

through the early childhood period. If this individual was struggling, this could be a reason for the longer than usual breastfeeding period. A limited number of weaning foods being used could result in the pattern of consistent stable nitrogen values from two months to 42 months.

Individual 1226 is an example of the overall pattern expected for an individual with a very young age of death. At two months the dentine $\delta^{15}N$ value is 16.3‰, and at five months, it increases to 18.7‰. The rib $\delta^{15}N$ (representing a time of death of approximately 7.5 months) is also very high at 17.4‰, the highest of all the rib $\delta^{15}N$ values. It is likely that as this person was so young, there were no weaning foods being introduced at this time and this represents the peak breastfeeding signal. Even given this, the $\delta^{15}N$ value is higher than those seen in the other breastfeeding infants. The fetal $\delta^{15}N$ value for this individual is the second highest in the study at 16.1‰. This could indicate that the mother's diet was more enriched than most female diets, which could explain the high breastfeeding $\delta^{15}N$ peak in the infant. However, it is also important to note that this individual exhibits periostitis on its skull and right radius. Periostitis is a non-specific infection affecting the skeletal system that is used as an indicator of stress in a population. This introduces the possibility that this individual was fed differently than most infants due to illness. Care was taken to only sample non-pathological bone and teeth, though it is still possible that the elevation was a general one caused by metabolic changes associated with illness (Katzenberg and Lovell, 1999). As with the previous individual, the carbon analysis for the

breastfeeding sample was not successful, so the $\delta^{13}C$ pattern cannot be followed in this individual.

Individual 1071 shows the expected pattern for $\delta^{15}N$ (13.6‰ at 2.5 months and 12‰ at 17 months), though its $\delta^{15}N$ values are some of the lowest in the study at both ages. However, the $\delta^{13}C$ values show an unusual pattern. At 2.5 months the $\delta^{13}C$ value is -20.5‰ and at 17 months it is -20.2‰, showing almost no change. The breastfeeding value from 2.5 months was excluded from the grouped analysis of $\delta^{13}C$ values as an extreme outlier. The rib values are consistent with this pattern. At death (approximately 24 months), the rib $\delta^{15}N$ value is 11.8‰, consistent with the 17 month dentine sample and once again fitting the normal weaning pattern. The rib $\delta^{13}C$ value is -20.8‰, consistent with the unusual dentine $\delta^{13}C$ values. Apart from an unusual diet, it is unclear what would cause the unusual carbon results without affecting the nitrogen values in a significant way. Harris lines, often used as non-specific stress indicators, are present in the individual, but there are no clear indicators of poor health.

5.4.4 Results and Discussion: Comparing Ribs and Teeth

Figure 5-8 shows the combined $\delta^{15}N$ results for this study and the previous study of the Fishergate House individuals using rib samples (Chapter 4). The overall pattern of breastfeeding indicated by the rib and dentine samples is the same. The breastfeeding period clearly extends to around two years of age, where there is a rapid decline to lower values. The few fetal rib signals available for Fishergate House do not seem to differ from the dentine signals. All fetal signals,

from both teeth and ribs, are elevated compared to the Fishergate House female mean, but fit better with the mean for the broader adult population from York, though there is still a difference. The mean $\delta^{15}N$ value for the total adult population in late medieval York is 12.8‰ with a standard deviation of 1.3‰ (Müldner and Richards, 2007a; 2007b). The rib mean for Fishergate House females is 11.4‰ with a standard deviation of 1.1‰ (Chapter 4). As was argued for the rib data alone (Chapter 4), the $\delta^{15}N$ elevation in weaned juveniles relative to the Fishergate House females is likely due to marine fish or pigs making up a larger portion of the children's diet; in other words, consumption of a diet similar to that eaten by adult males and females from the wider York population.

There are a number of possible reasons why the Fishergate House fetal values are not quite the same as Fishergate House adult female values. First, based on the reasoning outlined above it appears likely that the female mean calculated here is low and that the general population mean for late medieval York (St. Gilbertine Priory) determined by Müldner and Richards (2007a, 2007b) is actually a better model for adult female diets in the Fishergate House group. In addition to this, it may be that pregnant women ate a distinctive diet, with the normal pregnancy diet more abundant in higher trophic level resources compared to the general female diet. It is also possible that Fishergate House females, but not Fishergate House children, consumed a lower trophic level diet than the general York population. Fetal values might have an intrinsic enrichment over their mother's diet due to differences in fetal metabolism (Fuller et al, 2004;

2006a). Both of these processes could be at work concurrently. It is not clear why not all the fetal values are affected in the same way.

The diet of weaned children seems to have been enriched in higher trophic level resources relative to the female diet, but not relative to the population as a whole, which was demonstrated statistically for both teeth and rib values (Chapter 4). When the dental sample is examined together with the rib sample, it is clear that as children get older the $\delta^{15}N$ values do not get closer to the adult female-only diet. In a few cases, the $\delta^{15}N$ values do drop slightly, but overall the slight enrichment is maintained after two years of age. When individual lifetime shifts are looked at in terms of both their teeth and rib values, there is clear evidence that the $\delta^{15}N$ values decrease very little or stay the same as the child gets older (Fig 5-9a, 5-9b, and 5-10), this conforms to the expected pattern for early childhood (fetal, breastfeeding, weaning). The individual graphs show that some individuals were likely weaned after two years. These individuals could have been suffering from poor health that affected how they were weaned; although this is speculative given the limited number of individuals that can be examined. The majority of individual lifetime trends and the aggregate data clearly show that weaning after two years was not the normal pattern at Fishergate House.

Unfortunately, the $\delta^{13}C$ values for the teeth are not very clear, though the expected small 1‰ trophic elevation can be seen to some degree as demonstrated in the previous section. The effect is much clearer in the rib samples, and is more thoroughly discussed in Chapter 4. Combining the teeth and rib $\delta^{13}C$ values does not provide much more insight into the feeding patterns at Fishergate House (Fig

5-11). The variation in the teeth does begin to obscure the pattern seen in the ribs. However, it is possible to clearly see the elevation in the carbon values up until 25 months when the $\delta^{13}C$ values are suddenly all below -19‰. This indicates the end of the weaning period and a fully weaned diet by this time. Figure 12 shows the individual dentine $\delta^{13}C$ shifts, including the rib samples. Most individuals are seen to maintain their $\delta^{13}C$ value after roughly two years of age, as was seen with the $\delta^{15}N$ results. Two individuals, 1027 and 1071, continue to drop quite dramatically between their oldest-forming dentine sample and their rib sample. The $\delta^{13}C$ values of these individuals are also much lower than that seen for the adult females. These very low $\delta^{13}C$ values suggest that these individuals may not have been eating as many marine foods as the other children. C_3 plants may have been providing a greater portion of their protein during the weaning years. 1027 also has one of the lowest $\delta^{15}N$ values (10.6‰), supporting a diet low in marine protein for this individual. 1071 also has a fairly low $\delta^{15}N$ value (11.8‰), indicating that this individual may also have been weaned to a diet with less marine protein and more C_3 plants as the main protein source.

5.5 CONCLUSIONS

5.5.1 Microsampling Archaeological Remains

This was the first test of a newly developed dentine microsampling method (Chapter 3) on archaeological remains. Despite initial concerns over lower collagen weights from archaeological samples, both nitrogen and carbon stable isotope results were successfully obtained from deciduous tooth dentine.

The archaeological dentine did require the use of more microsamples than modern dentine to ensure suitable sample weights for runs. Only three samples out of 126 did not meet minimum weight requirements for $\delta^{15}N$ analysis, showing how promising this method is for analyzing archaeological remains. As with the initial study, getting valid simultaneous $\delta^{13}C$ and $\delta^{15}N$ results is more difficult than getting $\delta^{15}N$ results alone (Chapter 3). The method was not found to be reliable for molars and caution should be used for this tooth type. Eerkins et al. (2011) is a good alternative for the study of molars.

The microsampling method described here has many possible applications for future research. Kirsanow et al. (2008) microsampled cattle teeth in their study focusing on determining seasonal variation in tooth dentine collagen $\delta^{18}O$ and δD values of sheep and goats. Though the microsamples used here are smaller, it might be possible to do oxygen mobility or weaning studies using this method on human teeth. It is hoped that now that it has been proven effective with archaeological remains, more researchers will attempt dentine microsampling to look at individual human diets in the past as well as try to understand the fetal dentine $\delta^{15}N$ and $\delta^{13}C$ and their relationship to $\delta^{15}N$ and $\delta^{13}C$ in older children and adult females. Being able to reconstruct such a large number of fetal signals may allow an interesting look at changing early childhood diet and nutrition. Eventually it may be possible to estimate maternal diet during pregnancy from the fetal signals, but more work needs to be done on this.

5.5.2 Juvenile Diet at Fishergate House

The dentine stable isotope results agree with previous rib stable isotope results in terms of their implications for early childhood diet at Fishergate House. After birth came the breastfeeding period, which lasted in most individuals until approximately 1.5 years, at which point stable isotope values begin dropping quite rapidly. This suggests a relatively fast shift to a weaned diet, which was complete by about two years of age. The weaned early childhood diet seen after two years of age had statistically higher $\delta^{15}N$ than the female-only Fishergate House diet, but is not statistically different from the general diet at York during the same period (Chapter 4; Müldner and Richards, 2007a; 2007b). This could mean that the children were eating a diet more akin to that of both their parents rather than just the mothers, or that children were provided more high trophic level proteins then were other inhabitants of Fishergate House. A dietary reconstruction of the entire adult population at Fishergate House would help to answer this question.

The dentine results differ from the rib results in that they allow a glimpse into fetal life and individual dietary changes over time. The fetal results are difficult to interpret without knowing more about the relationship between fetal $\delta^{15}N$ and $\delta^{13}C$ values and maternal values. Further research in this area is needed as there is a possible regular enrichment of fetal values over maternal values (Fuller et al., 2004; 2006a). Even with this unknown factor, the fetal $\delta^{15}N$ and $\delta^{13}C$ values tell an interesting story of apparent dietary diversity. There is a wide range of fetal $\delta^{15}N$ and $\delta^{13}C$ values that are statistically different from adult female values. It is possible that the pregnancy diet typical of the Fishergate

House community was somehow different from the overall adult female diet, this seems likely even given the uncertainty over the relationship between maternal and fetal values, as the fetal values show much more $\delta^{15}N$ and $\delta^{13}C$ variation than the adult female group. Fetal values are closer to the range typical of the full adult sample from York, though still significantly different. At the individual level the variation in fetal diets can be seen very clearly with most individuals showing the expected $\delta^{15}N$ increase from a fetal to a breastfeeding signal, but some individuals do not.

Even with this confusing relationship, the individual results clearly show a distinct breastfeeding period that switches to a weaned diet by around two years of age. When looking at individuals, it is clear that some children were not weaned as quickly as their peers and had a slow or extended weaning period. In some cases, this prolonged weaning appears linked to distinct osteological signs of poor health. Other individuals have no skeletal signs, but it is quite possible they too were affected by illness. There is no documentary evidence of cultural variation in the mothers that could account for different weaning patterns (e.g. a pattern from a different homeland that could hypothetically prescribe longer or shorter weaning times).

The $\delta^{13}C$ values were not as clear as the $\delta^{15}N$ values, so the breastfeeding period could not be easily isolated. This could be the result of the type of weaning foods being used, though there is no reason to believe that C_4 plants like millet or sugarcane would be significant weaning foods in this area (Dupras et al., 2001; Richards et al., 2003; Fuller et al., 2006a; 2006b). With the presence of these

plants, the $\delta^{13}C$ values should be higher rather than lower, as we see during this period. Marine protein also leads to higher $\delta^{13}C$ values while a steady C_3 plant diet leads to lower values. The wide range of $\delta^{13}C$ values in the breast feeding period may indicate that while many mothers ate a mix of marine and C_3 plant protein, others ate less marine protein. The 1‰ enrichment seen during nursing would further increase the spread of these carbon values. It does not appear that a particular food could be causing the unusual lack of pattern we are seeing in carbon with the tooth samples, as the expect pattern was seen in the ribs. $\delta^{13}C$ values are known to react faster to supplementation than $\delta^{15}N$ values, which could mean that the tiny tooth samples are more susceptible to the rapidly changing diet during this period or dietary supplementation that does not present as readily in the large rib samples. The $\delta^{13}C$ pattern is difficult to interpret at an individual level as well. Only some of the individuals showed any signs of the expected pattern of elevated breastfeeding values followed by decreased weaning values. The $\delta^{13}C$ results found for the dentine were less clear than the Fishergate House rib $\delta^{13}C$ results, which did show the expected pattern (Chapter 4). Despite the above hypotheses, the reason for the diverse $\delta^{13}C$ results in this sample is difficult to explain. Further work on the microsampling method and early childhood diet at Fishergate House may provide clues to this issue.

Table 5-1 - Information on study sample.

Individual	Sample Location	Tooth Type	Age (months)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C:N Ratio (Atomic)
1017	A	upper right central incisor	3.5 in utero	-19.3	13.0	3.1
1017	B	upper right central incisor	2	-19.3	15.6	3.3
1017	C	upper right central incisor	8	-20.4	11.9	2.9
1023	A	lower left central incisor	3.5 in utero	-19.7	13.0	3.1
1023	B	lower left central incisor	2	-18.8	13.9	3.2
1023	C	lower left central incisor	18	-20.6	11.6	3.0
1027	A	lower left canine	4.35 in utero	-19.9	14.6	3.3
1027	B	lower left canine	9	-19.3	14.8	3.3
1027	C	lower left canine	36	-19.9	12.2	3.2
1033	A	lower left central incisor	3.5 in utero	-19.3	14.3	3.1
1033	B	lower left central incisor	2	-19.6	14.1	3.1
1033	C	lower left central incisor	18	-20.0	12.5	3.1
1035	B	upper left lateral incisor	2.5	-18.9	15.4	3.2
1035	C	upper left lateral incisor	24	-19.5	12.1	2.9
1042	A	lower right canine	4.35 in utero	-20.2	12.2	3.2
1042	B	lower right canine	9	-20.0	13.2	3.3
1069	B	lower right canine	9	-19.0	16.0	3.2
1069	C	lower right canine	36	-19.4	12.7	3.0
1071	A	lower right lateral incisor	3.5 in utero	-20.3	13.2	3.3
1071	B	lower right lateral incisor	2.5	-20.5	13.6	3.2
1071	C	lower right lateral incisor	17	-20.2	12.0	3.3
1077	A	lower left central incisor	3.5 in utero	-19.4	13.0	3.0
1077	B	lower left central incisor	2	-19.5	15.1	3.3
1077	C	lower left central incisor	13.5	-20.1	13.8	3.3
1092	B	lower right lateral incisor	2.5	-18.3	15.0	3.2

1111	A	upper right lateral incisor	3.5 in utero	-18.5	15.9	3.3
1111	B	upper right lateral incisor	2.5	-18.5	16.1	3.2
1111	C	upper right lateral incisor	24	-19.1	14.7	3.2
1122	A	lower right lateral incisor	3.5 in utero	-19.0	15.1	3.7
1122	B	lower right lateral incisor	2.5	-19.0	16.3	3.2
1122	C	lower right lateral incisor	24	-19.8	13.5	3.0
1124	A	upper left central incisor	3.5 in utero	-19.2	13.6	2.9
1124	B	upper left central incisor	2	-19.3	15.6	3.2
1124	C	upper left central incisor	18	-20.2	12.2	3.1
1135	A	lower right lateral incisor	3.5 in utero	-18.8	15.2	3.1
1135	B	lower right lateral incisor	2.5	-18.5	17.3	3.2
1135	C	lower right lateral incisor	24	-20.0	11.5	3.1
1157	A	upper left canine	4.35 in utero	-18.5	16.5	3.1
1157	B	upper left canine	9	-18.7	17.5	3.1
1157	C	upper left canine	24	-18.9	14.5	3.2
1167	A	lower left lateral incisor	3.5 in utero	-18.7	14.3	3.2
1167	B	lower left lateral incisor	2.5	-19.4	14.2	3.3
1167	C	lower left lateral incisor	24	-20.4	11.1	2.9
1178	A	lower left canine	4.35 in utero	-19.2	15.0	3.2
1178	B	lower left canine	9	-19.1	15.1	3.2
1178	C	lower left canine	22	-19.3	12.0	3.3
1182	A	upper left central incisor	3.5 in utero	-18.5	14.1	2.9
1182	B	upper left central incisor	2	-18.3	16.1	3.3
1182	C	upper left central incisor	18	-19.2	13.3	3.1
1216	A	upper right central incisor	3.5 in utero	-19.2	14.0	3.1
1216	B	upper right central incisor	2	-18.8	15.6	3.2
1216	C	upper right central incisor	18	-19.2	13.1	2.9
1224	A	upper left canine	4.35 in utero	-19.0	12.4	3.0

1224	B	upper left canine	9	-18.7	15.5	3.2
1224	C	upper left canine	22	-18.9	12.6	3.1
1226	A	upper right central incisor	3.5 in utero	-18.6	16.1	3.1
1226	B	upper right central incisor	2	-18.4	16.3	3.0
1226	C	upper right central incisor	5	-18.6	18.7	3.2
1233	A	upper right canine	4.35 in utero	-19.0	15.9	3.1
1233	B	upper right canine	9	-19.5	16.8	3.2
1233	C	upper right canine	24	-19.5	14.2	3.1
1289	A	upper left lateral incisor	3.5 in utero	-19.3	14.5	3.2
1289	B	upper left lateral incisor	2.5	-18.7	16.7	3.3
1289	C	upper left lateral incisor	24	-19.4	12.3	3.0
1290	A	upper left lateral incisor	3.5 in utero	-18.7	12.1	2.9
1290	B	upper left lateral incisor	2.5	-18.6	13.7	3.2
1319	A	upper left canine	4.35 in utero	-18.8	14.8	3.1
1319	B	upper left canine	9	-19.1	14.1	3.0
1319	C	upper left canine	24	-18.9	12.8	3.0
1336	B	lower right lateral incisor	2.5	-18.8	16.1	3.2
1336	C	lower right lateral incisor	24	-19.4	11.1	3.1
1376	A	lower right central incisor	3.5 in utero	-18.3	14.3	3.2
1376	B	lower right central incisor	2	-18.2	15.5	3.2
1376	C	lower right central incisor	6	-19.0	14.6	3.1
1380	A	lower right canine	4.35 in utero	-18.8	15.0	3.2
1380	B	lower right canine	9	-19.0	15.7	3.2
1380	C	lower right canine	22	-18.7	15.9	3.3
1390	B	upper right central incisor	2	-19.2	15.1	3.1
1390	C	upper right central incisor	15	-19.6	14.0	3.2
1414	A	upper left canine	4.35 in utero	-19.1	14.2	3.1
1414	B	upper left canine	9	-19.5	16.3	3.2
1414	C	upper left canine	36	-19.4	12.0	3.1
1425	A	upper right canine	4.35 in utero	-19.8	12.1	2.9
1425	B	upper right canine	9	-19.1	15.3	3.2

1425	C	upper right canine	22	-20.1	11.5	3.1
1434	A	upper right lateral incisor	3.5 in utero	-19.2	13.8	3.1
1434	B	upper right lateral incisor	2.5	-19.4	14.7	3.2
1436	C	upper right lateral incisor	24	-20.7	13.3	3.1
1463	A	lower right canine	4.35 in utero	-19.0	14.9	3.2
1463	B	lower right canine	9	-19.4	16.6	3.2
1463	C	lower right canine	36	-19.3	12.2	3.0
1480	A	upper right central incisor	3.5 in utero	-18.8	15.2	3.2
1480	B	upper right central incisor	2	-18.4	16.8	3.3
1480	C	upper right central incisor	15	-19.8	15.4	3.0
1492	A	lower left lateral incisor	3.5 in utero	-19.7	14.5	3.2
1492	B	lower left lateral incisor	2.5	-20.2	13.7	3.1
1492	C	lower left lateral incisor	24	-20.4	11.7	3.1
1539	A	lower left lateral incisor	3.5 in utero	-19.3	14.0	3.1
1539	B	lower left lateral incisor	2.5	-19.5	15.1	3.3
1539	C	lower left lateral incisor	24	-20.2	10.5	2.9
1545	A	lower left central incisor	3.5 in utero	-19.2	13.0	3.0
1545	B	lower left central incisor	2	-19.7	14.0	3.2
1545	C	lower left central incisor	20.5	-20.1	13.7	3.2
1575	A	lower left lateral incisor	3.5 in utero	-18.5	15.8	3.2
1575	B	lower left lateral incisor	2.5	-18.3	17.0	3.2
1575	C	lower left lateral incisor	6	-19.1	16.1	3.0
1029	A	lower left molar	3.95 in utero	-19.0	14.5	3.0
1029	B	lower left molar	6	-19.5	14.6	3.2
1029	C	lower left molar	30	-19.0	13.5	3.2
1059	A	lower left molar	3.95 in utero	-19.7	14.4	3.1
1059	B	lower left molar	6	-19.9	12.5	3.2
1059	C	lower left molar	36	-20.0	13.0	3.3
1089	A	upper right molar	3.95 in utero	-19.5	11.2	2.9
1089	B	upper right molar	6	-19.4	12.5	3.0

1089	C	upper right molar	18	-19.5	13.1	3.1
1427	A	upper left molar	3.95 in utero	-18.1	15.6	3.2
1427	B	upper left molar	6	-18.5	13.5	3.1
1427	C	upper left molar	16	-19.1	14.0	3.2

Table 5-2 - Descriptive statistics and t-Test Results

Nitrogen General Statistics

Age Group	*N*	*Mean ‰*	*Std*
Fetal	35	14.1	1.32
Breastfeeding	57	14.8	1.69
Weaned	19	12.4	1.29
Female Adult	11	11.4	1.05
York Adult*	134	12.8	1.27

*Data from Müldner and Richards (2007a)

Carbon General Statistics

Age Group	*N*	*Mean ‰*	*Std*
Fetal	19	-19.1	.57
Breastfeeding	36	-19.2	.61
Weaned	4	-19.3	.44
Female Adult	11	-19.4	.43

Results of Independent Sample t Tests

Fetal/ Breastfeeding	*t*	*df*	*Sig. (2-tailed)*	*Mean Difference*	*Std Error Difference*
$\delta^{15}N$ (‰)	-2.051	90	**.043**	-.686	.335
$\delta^{13}C$ (‰)	.497	53	.621	.085	.171
Breastfeeding /Weaned					

$\delta^{15}N$ (‰)	5.539	74	**.000**	2.346	.423
$\delta^{13}C$ (‰)	.270	38	.788	.086	.319
Weaned/ Female Adult					
$\delta^{15}N$ (‰)	2.256	28	**.032**	1.035	.459
$\delta^{13}C$ (‰)	.731	13	.477	.186	.255
Weaned/ York Adult					
$\delta^{15}N$ (‰)	-1.077	15	.283	-.336	.312
		1			
Female Adult/ Fetal					
$\delta^{15}N$ (‰)	6.158	44	**000**	2.693	.438

Figure 5-1 - Maps of medieval York. Arrow indicates York; star indicates Fishergate House site within York (White, 2000).

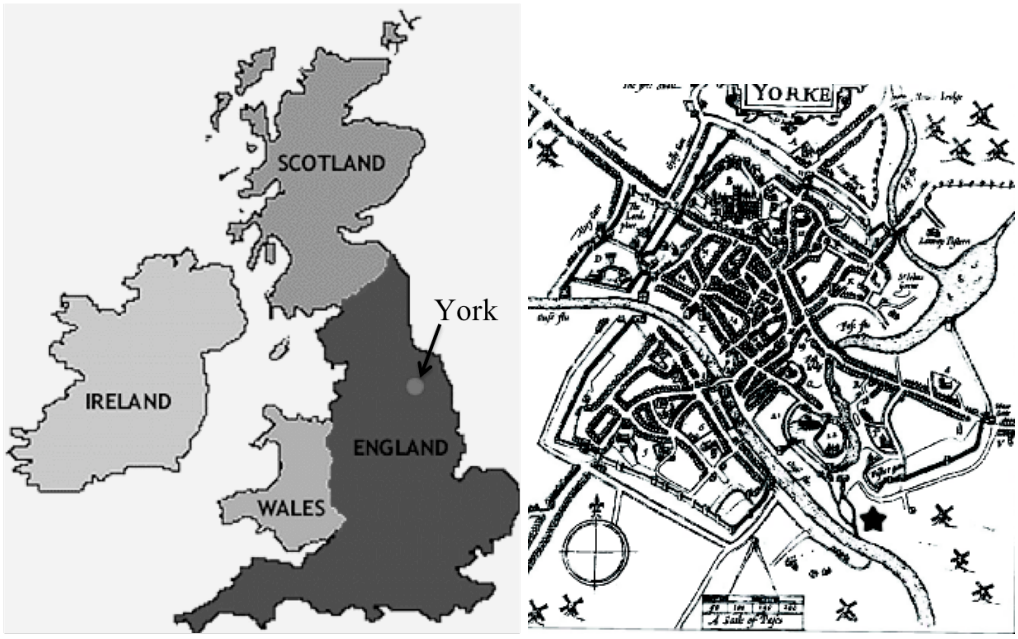


Figure 5-2 - Nitrogen results for juvenile Fishergate House tooth samples. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details). Adult females are of reproductive age.

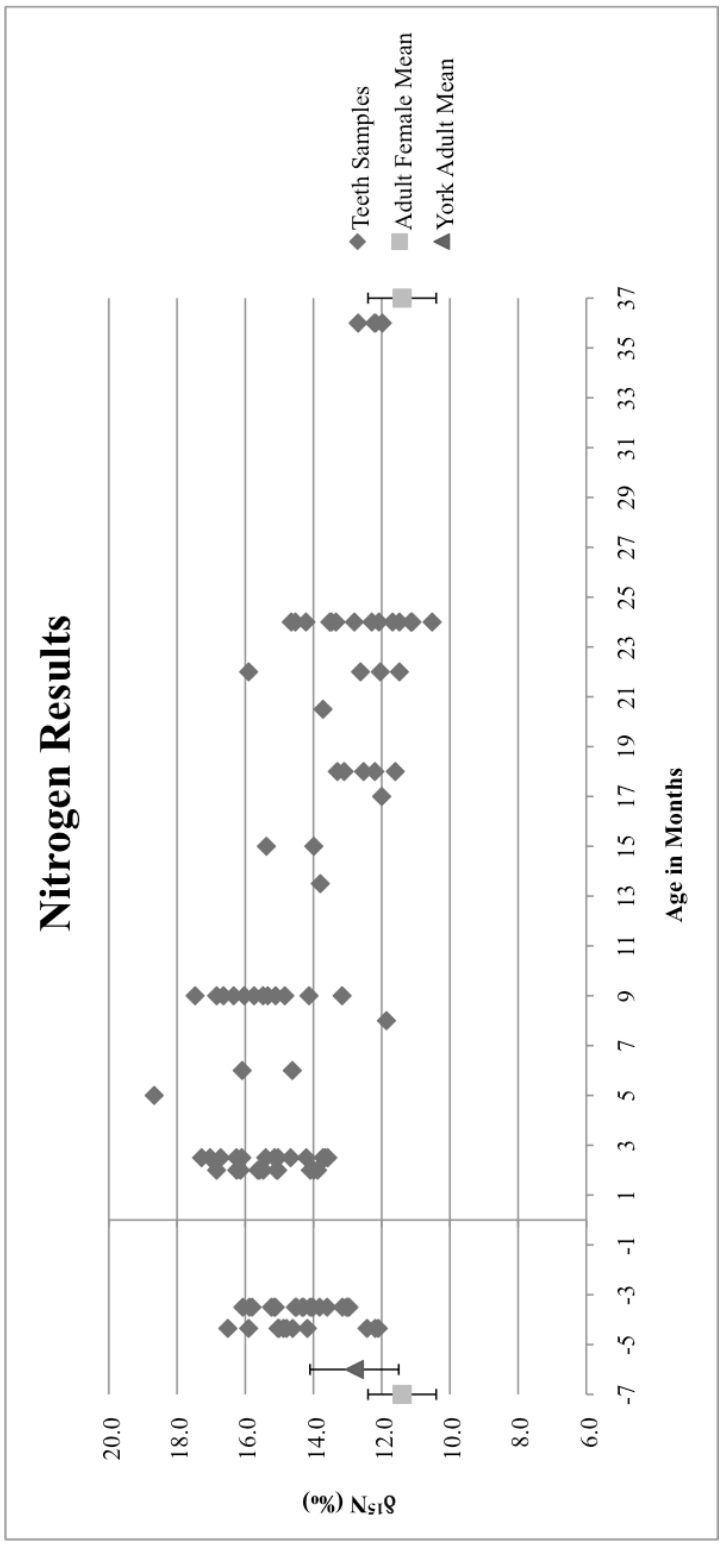


Figure 5-3 - Carbon results for juvenile Fishergate House tooth samples. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details). The continuous line connects the means and shows the trend between the two periods. Adult females are of reproductive age.

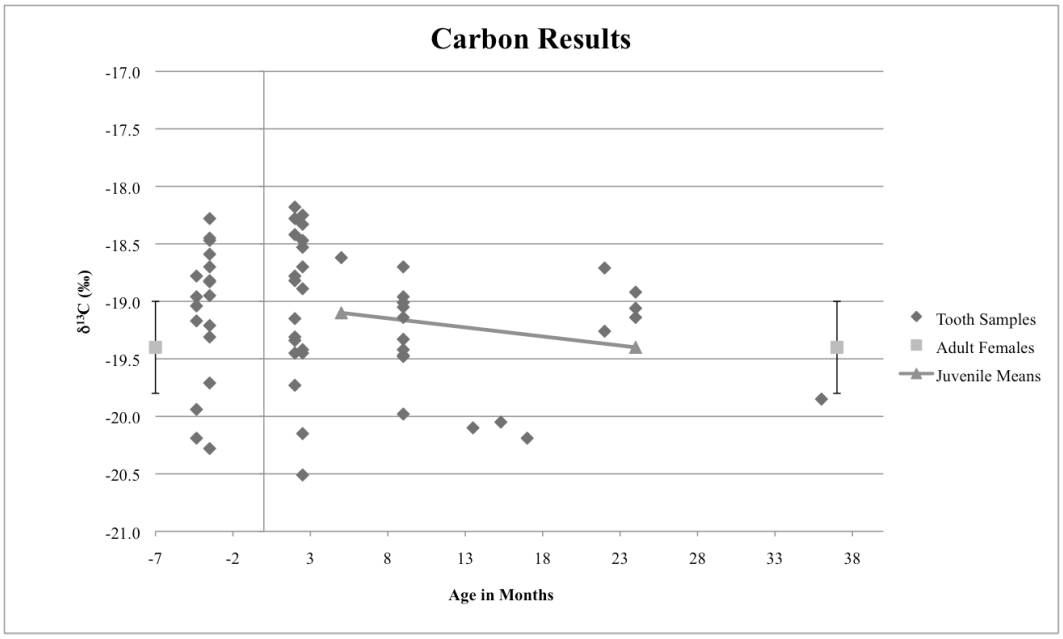


Figure 5-4a - Nitrogen results for individuals using central incisors. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details).

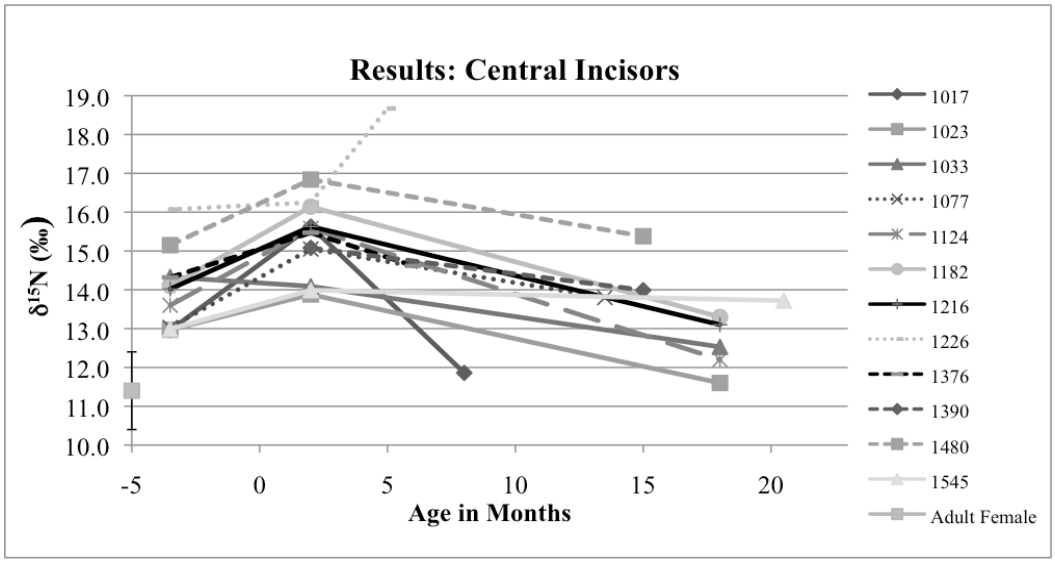


Figure 5-4b - Nitrogen results for individuals using lateral incisors. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details).

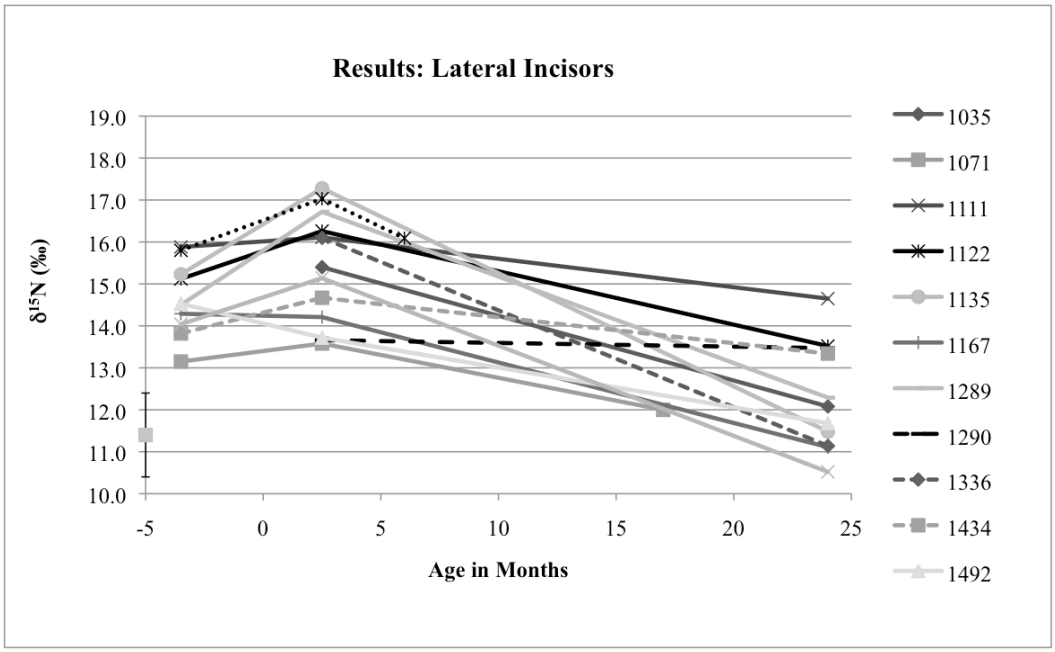


Figure 5-5 - Nitrogen results for individuals using canines. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details).

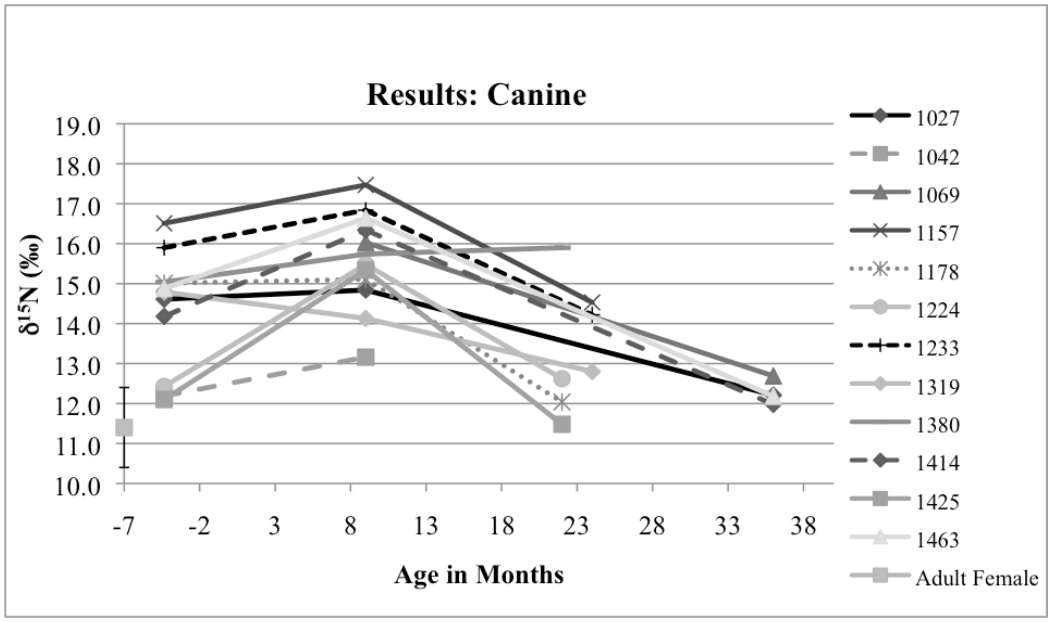


Figure 5-6 - Nitrogen results for individuals using molars. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details).

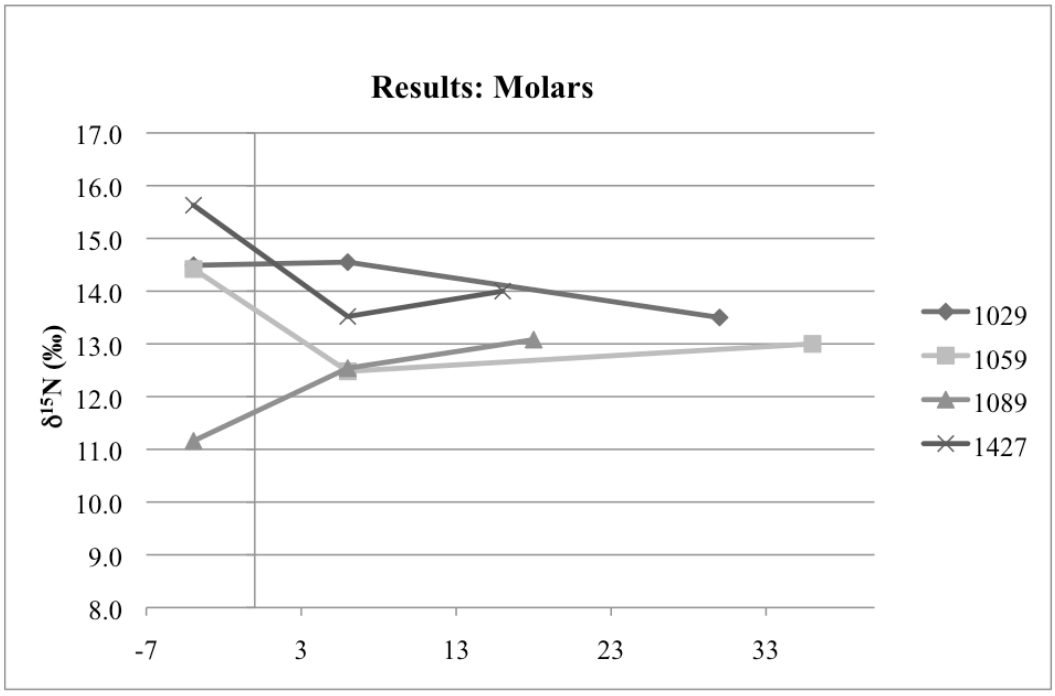


Figure 5-7 – All individual carbon results. These ages are estimates of the midpoint of each age range, which was determined by level of tooth development achieved (see text for details).

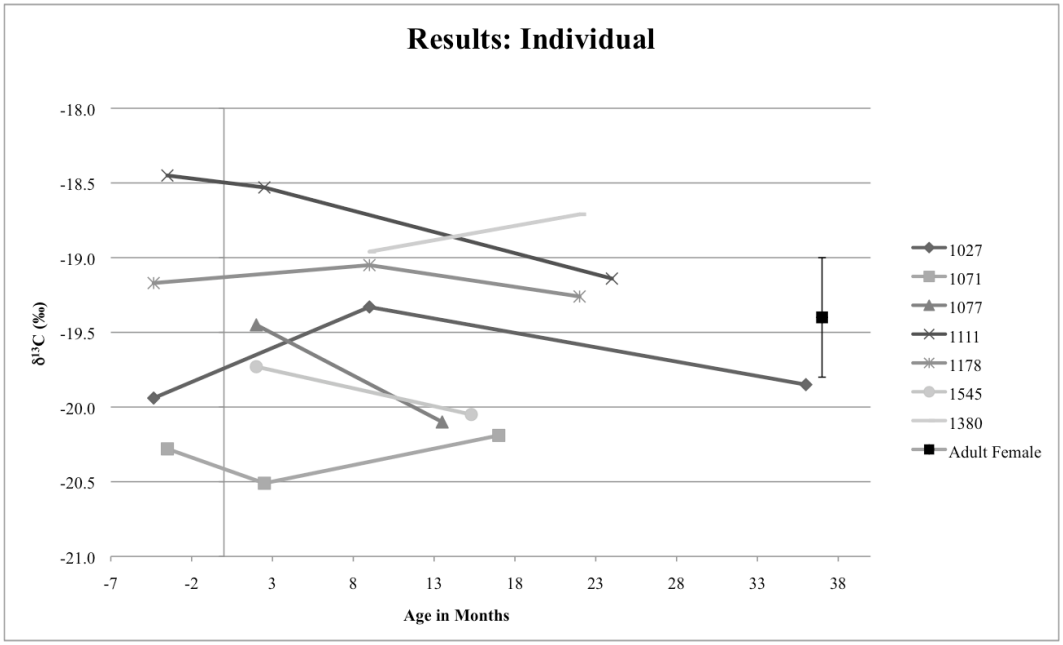


Figure 5-8 - Combined rib and tooth results for nitrogen. These ages are estimates of the midpoint of each age range as estimated for each sample type (see text for details). Adult females are of reproductive age.

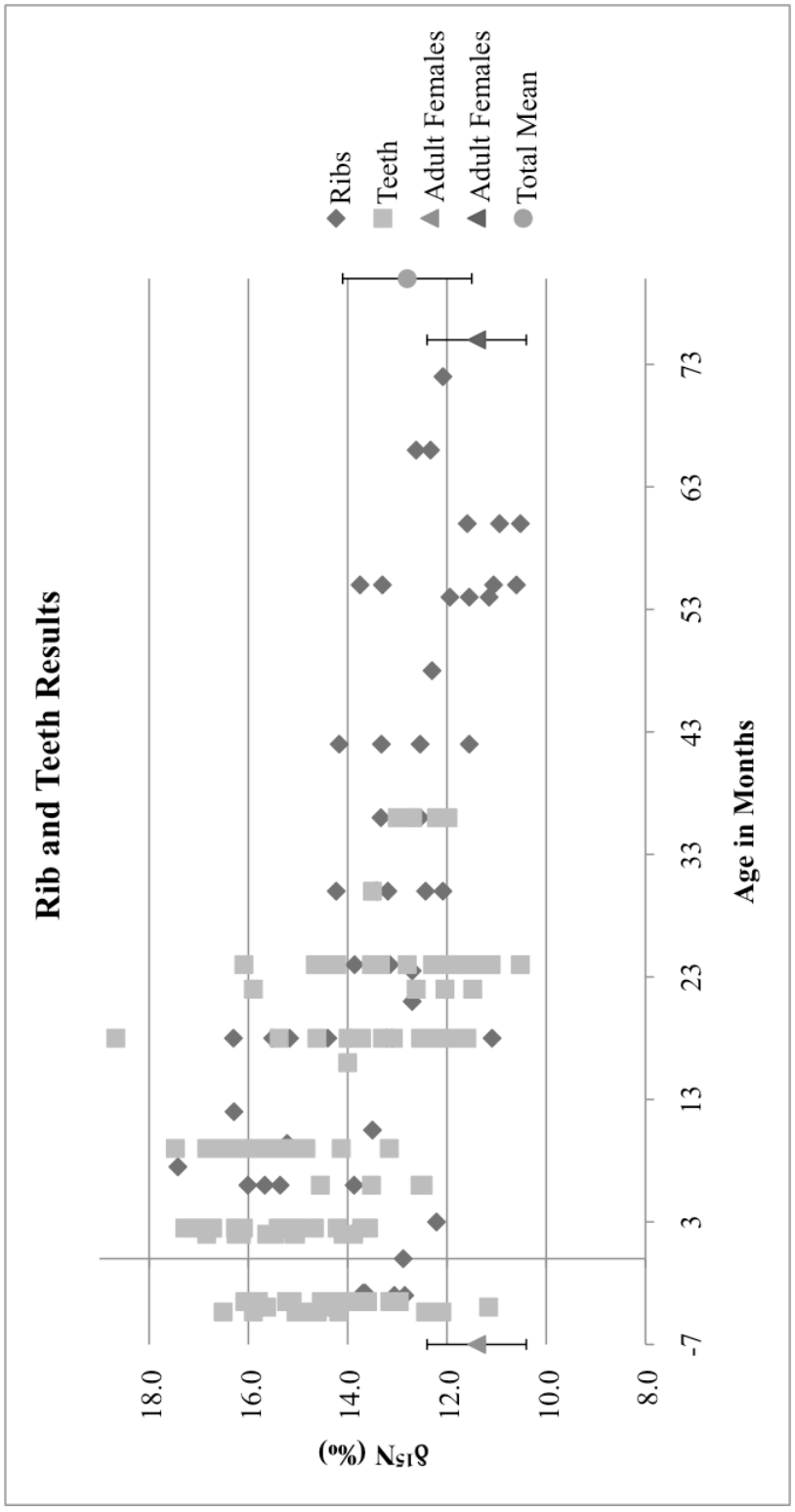


Figure 5-9a - Nitrogen results for central incisors and ribs. These ages are estimates of the midpoint of each age range as estimated for each sample type (see text for details). Rib values are the last value shown for each individual.

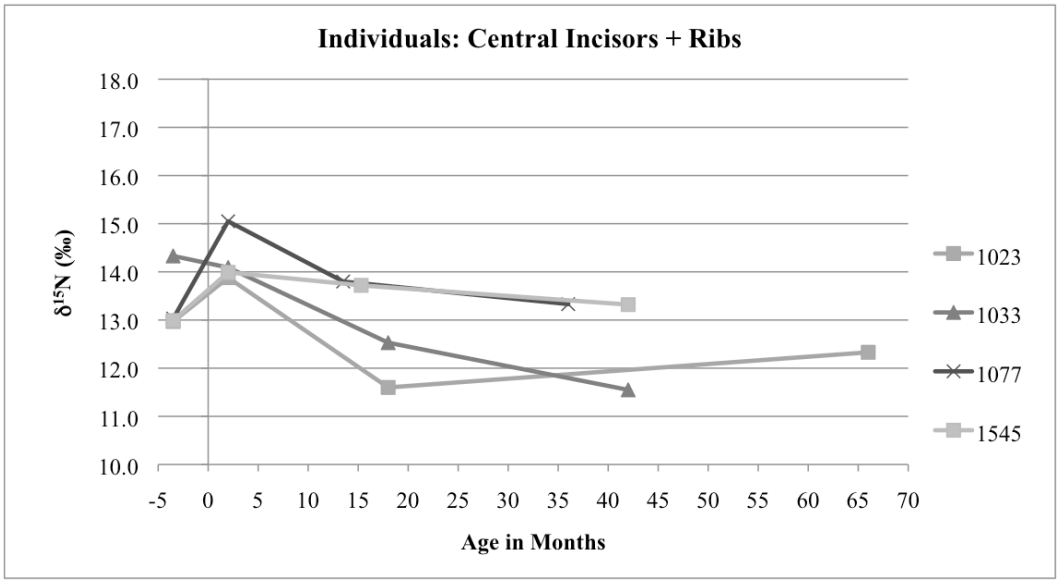


Figure 5-9b - Nitrogen results for lateral incisors and ribs. These ages are estimates of the midpoint of each age range as estimated for each sample type (see text for details). Rib values are the last value shown for each individual.

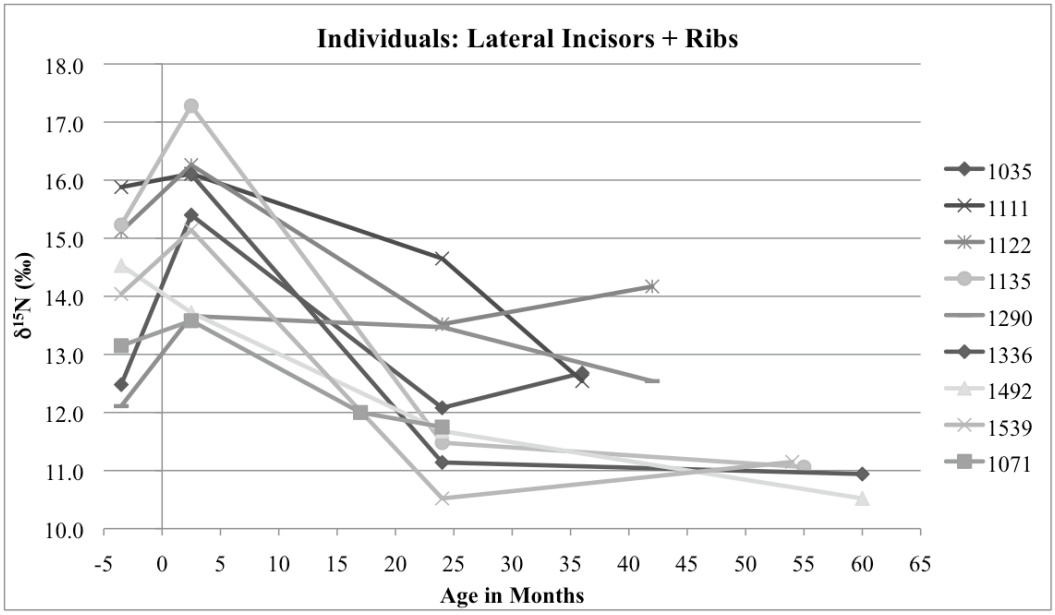


Figure 5-10 - Nitrogen results for canines and ribs. These ages are estimates of the midpoint of each age range as estimated for each sample type (see text for details). Rib values are the last value shown for each individual.

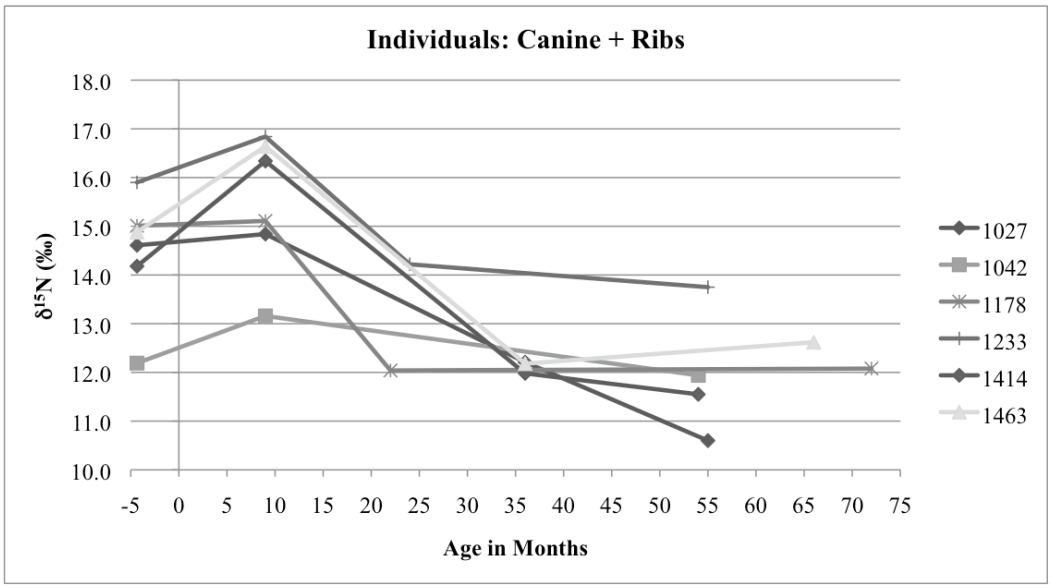


Figure 5-11 - Combined rib and tooth results for carbon. These ages are estimates of the midpoint of each age range as estimated for each sample type (see text for details). Adult females are of reproductive age.

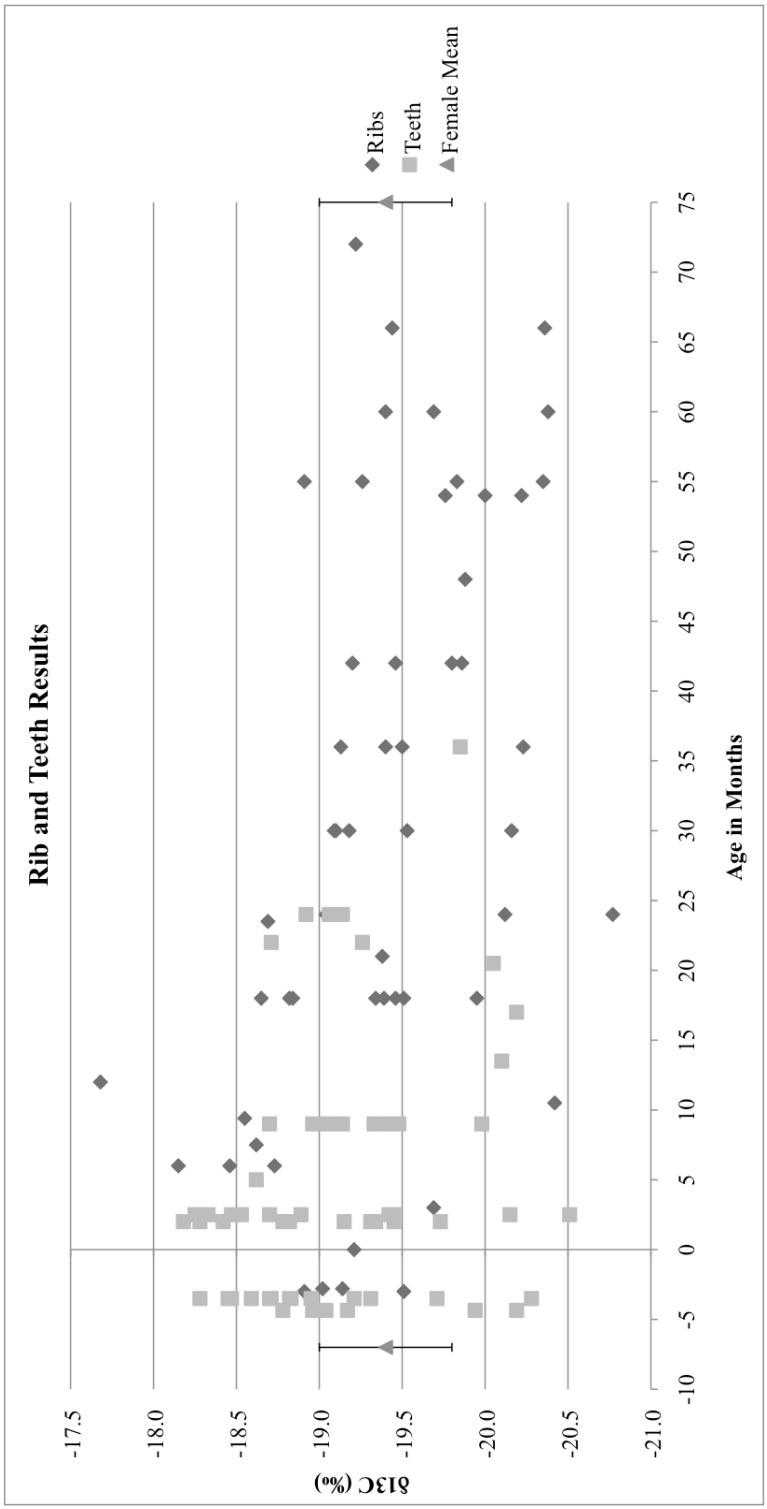
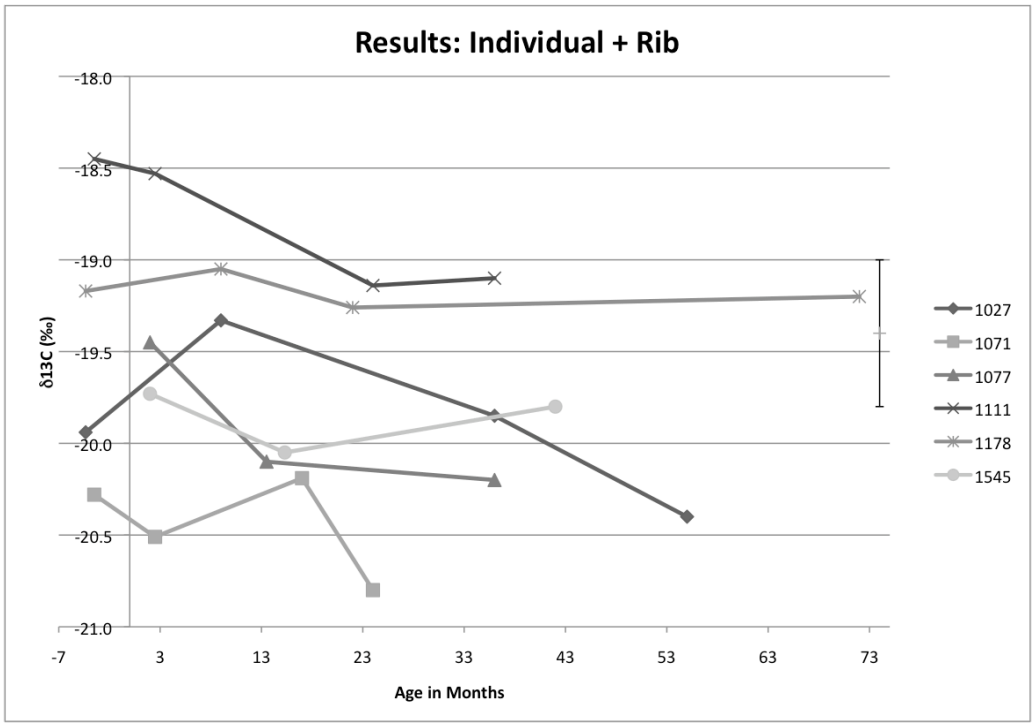


Figure 5-12 - Carbon results for teeth and ribs, by individual. These ages are estimates of the midpoint of each age range as estimated for each sample type (see text for details). Rib values are the last value shown for each individual.



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Chapter 6

Understanding Health at Medieval Fishergate House Using Growth, Diet, and Indicators of Stress

6.1 Introduction

This study uses reconstructed juvenile diet, metric analysis of juvenile long bones and prevalence of stress-related lesions to gain a better understanding of health at medieval Fishergate House, York, UK. Initial research at the site led to the conclusion that the individuals were stressed and likely in poorer health than more prosperous medieval communities (Holst, 2005). The same study argued that weaning was very late in this community, based on the fact that the peak mortality of juveniles at the site is four to six of age. However, bone and dentine stable isotope analysis indicate that weaning occurred at approximately two years of age at Fishergate House (Chapters 4 and 5). The difference between weaning age and peak mortality may be a key point to understanding health at the site, as weaning is generally regarded as the most stressful period of juvenile development other than birth (Lewis, 2007; Stuart-Macadam, 1995; Sellen, 2009; Van Esterik, 1988; Van Esterik, 2008; Winikoff and Laukaran, 1988). By combining growth, diet, and pathology data for the Fishergate House juveniles it is possible to better understand health during the early childhood period (birth to six years) and propose a possible model for stress in the population.

To better understand patterns of growth and health at Fishergate House, remains from the site will be compared to data from the extensively studied contemporary site of Wharram Percy (Mays et al., 2002; 2007). Wharram Percy is a rural site, making it an excellent contrast to the Fishergate House individuals,

who are from the large city of York. By comparing the two samples, it should be possible to consider environmental conditions affecting Fishergate House individuals during early childhood. Although many researchers have hypothesized that medieval urban individuals should have been more physiologically stressed than their rural counterparts due to the pressures of urbanization, most research on this issue has not detected significant urban-rural differences in this era, finding that true differences only emerged during the industrial revolution (Cardoso, 2007; Cardoso and Garcia, 2009; Lewis, 2002; Mays et al., 2008). Given this, Fishergate House and Wharram Percy may actually have had very similar health profiles.

In this study, growth is assessed based on femur and tibia lengths, diet is based on the results of stable isotope analyses previously done by the author (Chapters 4 and 5), and stress is measured using the prevalence of cribra orbitalia, dental enamel hypoplasias, sinusitis, and non-specific infections. By looking at growth, diet, and illness independently and then combining the outcomes of these analyses, it is possible to better understand the lives of the Fishergate House juveniles, and to gain some general insights into the health of poor urban people during the medieval period. *(Chapter 2 Section 2.8 covers pathology background)*

6.2 Background: Wharram Percy

Wharram Percy is a deserted medieval village located in Yorkshire, UK, eight miles from York in the countryside that likely helped to supply the city (Mays et al., 2002; 2007; 2008). The main use of the village was between the 12th

and 14th century, with abandonment occurring early in the 16th century as the land owners wanted to use the village land for other purposes. Wharram Percy is believed to have been a typical medieval village. There is evidence for trade with York as well as small scale lime burning, brewing, and smithying operations (Lewis, 2002; Milne and Richards, 1992). The churchyard cemetery includes 700 skeletons, many of which are children (Mays et al., 2007). The human remains date to the 10th – 16th centuries, making it contemporary to the Fishergate House sample. Given the nature of the village site, they can be assumed to represent lower class rural individuals. Wharram Percy is also interesting because of the large quantity of bioarchaeological research already conducted at the site (Fuller et al. 2003; Lewis, 2002; Mays et al. 2002; 2008; Richards et al. 2002).

Wharram Percy is an ideal comparative site for an examination of health and growth at Fishergate House given its geographic proximity and similar socio-economic status as well as the extensive research conducted to date on the remains. The fact that it is a rural community will allow for a consideration of possible urban-rural health differences between the two sites. All Wharram Percy data used in this study are drawn from previously published research (Lewis, 2002; Fuller et al. 2003; Mays et. al. 2002; 2008; Richards et al. 2002). Two prior comparative studies using the Wharram Percy remains are of interest here. A study by Lewis et al. (2002) looking at dental and skeletal development and several key stress indicators failed to find a difference in health between Wharram Percy and a nearby contemporary lower-class urban sample from York (St. Helen-on-the-Walls). Although no significant differences were seen between these

medieval rural and urban sites, the Industrial Revolution had a real impact on growth and health as seen in the comparison of Wharram Percy to the later urban group from Christ Church, Spitalfields. Growth and stress indictors showed that the sample from the Industrial Revolution had dietary deficiencies and a delay in skeletal growth, despite being of higher social status.

In another attempt to determine whether the shift from rural living conditions to urban working class living conditions during the Industrial Revolution resulted in a shift to poorer health, Mays et al. (2008) looked at differences in dental and skeletal development between Wharram Percy and the 19th century urban sample from St Martin's Birmingham. Mays et al. (2008) found that individuals less than two years old at the rural site exhibited more rapid skeletal development than their urban peers did. The authors attribute this difference to a longer breastfeeding period for the rural children, affording them better nutrition in these early years. Their argument is based in part on previous stable isotope analyses that indicated a relatively long breastfeeding period for the rural community, with weaning completed at approximately two years of age (Mays et al., 2008; Richards et al., 2002). In contrast to Lewis they did not find a difference between older rural and urban juveniles in these groups, despite documentary evidence indicating that the Industrial Revolution had a real impact on growth and health. It is possible that catch up growth obscured the difference that had been seen at earlier ages or that population intercomparability was an issue due to temporal and geographical distance between the two groups.

The closeness of Fishergate House and Wharram Percy will hopefully add a meaningful component to the rural/urban comparison. While most of the findings on rural/urban difference have been conflicting and only definitive for the change to the Industrial Revolution (Cardoso, 2007; Cardoso and Garcia, 2009; Lewis, 2002; Mays et al., 2008), living conditions should have been significantly different between the urban and rural environment during the late medieval period. The industry practiced by the inhabitants of Fishergate House was known to be polluting and harsh (Lewis et al., 1995, Roberts, 2007). Differences between the two groups are expected due to these conditions, although they will likely not be as great as those seen with the transition to the Industrial Revolution. By comparing Fishergate House to such a well studied site it is hoped that a better understanding of the health of the community in comparison to its contemporaries can be formed.

6.3 Materials

The primary sample for this study consists of juvenile remains from Fishergate House, York. Bone and tooth samples of 51 juvenile individuals were collected for carbon and nitrogen stable isotope analysis; the results of this analysis are reported elsewhere (see Chapters 4 and 5). The available metric and pathology data (see below) were collected and analyzed for all individuals sampled for stable isotope analysis. However, many of the individuals that were sufficiently preserved for sampling did not have intact long bones and could not contribute to the metric component of this study. The sample was not divided by

sex due to the difficulty of estimating sex from juvenile skeletal remains, but both males and females are likely present.

Wharram Percy was chosen as the primary comparative sample in part because of the research questions outlined above and in part for practical reasons: it is nearby and contemporary to Fishergate House and has abundant metric, dietary, and pathological information available in the literature (Fuller et al., 2003; Lewis, 2002; Mays et al., 2002; 2008; Richards et al., 2002). Mays et al. (2008) was used for femur and tibia length data. Lewis (2002) was used for pathological data. Stable isotope reconstruction of diet is from Fuller et al. (2003), Mays et al. (2002), and Richards et al. (2002). Full details on the individual methodologies and sample sizes for the Wharram Percy studies are available in those publications. Fortunately, these studies used methods comparable to those used in prior work on Fishergate House for long bone length, stable isotope analysis, and many paleopathological indicators.

A modern sample was also used to better understand the pattern of growth at Fishergate House. The data used are from Ruff (2007), which used a longitudinal study of 20 individuals from the Denver Growth Study to generate stature and body mass predictions from femur and tibia length for ages one to 17 years. The study found that their equations could accurately determine the stature of juveniles up to year 17; by year 17 full adult height had been attained in most cases and the adult formulae were necessary to accurately estimate stature. For this study, the mean femur and tibia lengths for 17 year olds were used in lieu of adult femur and tibia length, which were not given in Ruff (2007).

6.4 Methods

Dental age was used as a proxy for chronological age. All Fishergate House samples were aged using Ubelaker (1989). If dental age was not available for an individual, it was excluded from the metric study. Only femora and tibiae were used for the growth portion of this study, as these two long bones are the best indicators of stature and growth disruption (Eveleth and Tanner, 1990; Feldesman, 1992). Long bone measurements and scoring of pathological conditions (sinusitis, dental enamel hypoplasia, non-specific infection, and cribra orbitalia) for Fishergate House were taken from Holst (2005). Age estimates and adult femur lengths for the Wharram Percy site follow those reported by Mays (2007). Juvenile femur and tibia length for Wharram Percy are reported in Mays et al. (2008).

For each site, femur and tibia length were plotted against dental age to create a growth profile. Percent of adult femur length, based on mean adult femur length for the site in question, was also calculated to ensure that differences found were not due to stature differences between the two populations. The metric analysis was done using age categories due to small sample size. Each sample was divided into six age categories of one year each. Unequal variance t-tests were used to determine whether differences between each age category were statistically significant.

The growth patterns obtained were then compared to the breast feeding and weaning habits of each population and the diet of weaned juvenile individuals, as reconstructed from collagen stable isotope values. The

methodology used for the stable isotope analyses can be found in the original studies (Fuller et al., 2003; Mays et al., 2002; Richards et al., 2002; see also Chapters 4 and 5). Further insights into health and growth were gained by comparing the pattern of growth to the age-specific prevalence of cribra orbitalia, sinusitis and non-specific infection and the overall prevalence of dental enamel hypoplasia. To make the Fishergate House paleopathology data comparable to the previously published Wharram Percy results three age categories were used: 0-0.5 years, 0.6-2.5 years, and 2.6-6.5 years (Lewis, 2002). Further information on the collection procedures for pathological data is available in Lewis (2002) and Holst (2005).

6.5 Results and Discussion

6.5.1 Growth

Estimates of adult stature at Fishergate House and Wharram Percy indicate that the populations would have been roughly the same height. The Fishergate House adults have a mean stature of 164.6 cm, with males having an average stature of 170.1cm and females 159.1 cm. Mean adult stature at Wharram Percy is reported to be 163.5 cm, with means for males of 169 cm and females of 158 cm (Mays, 2007). Differences in juvenile bone length seen between these populations should reflect differences in growth trajectory rather than differences in population body size.

The graphs of femur length and tibia length versus dental age show different patterns of growth at Fishergate House and Wharram Percy (Table 6-1,

Figs 6-1 and 6-2). The femur graph shows that Fishergate House lags slightly in growth relative to Wharram Percy in the one year category, although there is a great deal of overlap in the standard deviations. Fishergate House overtakes Wharram Percy by the second year and thereafter shows a substantial difference in femur length through the six year category. The standard deviations do not overlap at the older ages. This indicates faster growth during this period at Fishergate House. A slightly different pattern is seen in the tibia results, which shows mean tibia lengths to be about equal at the two sites during the first year and greater in Fishergate House children in the second through sixth years. Again there is a good deal of overlap in the earlier ages. Thus, although the details of patterning differ, in general Fishergate House children show more rapid growth in both femur and tibia length after the first year.

Percent of adult femur or tibia length attained was plotted against dental age to determine whether the difference could in part reflect a difference in overall stature (Figures 6-3 and 6-4). As expected given the comments above on adult stature at the sites, the results clearly show that the same pattern exists when adult stature is taken into account. Although the Fishergate House and Wharram Percy children start at nearly the same level in the first year, the Fishergate House children grow more quickly through the rest of the young childhood period.

The differences between the percent adult growth obtained for the two groups were analyzed using unequal variance t-tests (Ruxton, 2006). This tested the means at each age category to determine whether the two groups were statistically different from each other (Table 6-3). Although none of the

differences were significant at the p = .05 level, this may reflect the very small sample sizes or highly unequal sample sizes available for Fishergate House. The overall trend remains clear, despite the lack of statistical significance. Further testing of the overall trend could not be conducted, as only the grouped data is available for Wharram Percy. It is interesting to note that there is no sign of a slowing of growth or abnormal growth in the Fishergate House children in the four through six year categories. This is the period of peak mortality for this group, but it does not appear to be reflected in the growth of these individuals.

Due to the unexpected results showing relatively rapid growth at Fishergate House up to age six, the sample was compared to a modern sample (Denver Growth Study) to determine if the growth profile approached the rate seen in modern children (Ruff, 2007) (Fig 6-5 and 6-6). When the femur lengths from the two groups are graphed, they seem to be comparable at most ages. A similar result can be seen in the tibia length graph, which shows that the modern growth pattern would be an excellent proxy for growth at Fishergate House at most ages (Figure 6-6). Plots of percent attained adult femur or tibia length were also created (Fig 6-7 and 6-8). These graphs indicate that the Fishergate House individuals are growing at a rate comparable to the modern sample. Whatever health problems might have been present at Fishergate House, they certainly do not seem to be affecting growth during early childhood. There is also no indication of any kind of slowing of growth that could indicate a correlation with high mortality in four to six year olds.

6.5.2 Diet

Previous isotopic research conducted by the author on Fishergate House has shown that weaning finished around the age of two (Chapters 4 and 5). Age profiles of $\delta^{15}N$ values indicate that the completion of weaning occurred fairly quickly between the ages of 1.5 and two years. The diet of young weaned children, rather than being the same as that of adult females, had slightly higher $\delta^{15}N$ values, with adult females having a mean $\delta^{15}N$ value of 11.4‰ and weaned children having a mean $\delta^{15}N$ value of 12.4‰ (Chapter 4). The mean $\delta^{13}C$ value of adult women and weaned children is the same, at -19.4‰. The slight $\delta^{15}N$ difference suggests a juvenile diet more enriched in high trophic-level proteins. This diet differs from that of adult women in the Fishergate House group, but is comparable to the diet of the general population of medieval York, for which Müldner and Richards (2007a) reported means of -19.1‰ for $\delta^{13}C$ and 12.8‰ for $\delta^{15}N$, a close match to the juvenile values. This suggests that children at Fishergate House were eating a protein-rich diet that probably incorporated marine foods, just as the York population as a whole was. This diet would likely have contained more high trophic-level protein than the diets of many adult females at the site, and there is no evidence that it would have been nutritionally poor.

The mean adult $\delta^{13}C$ values of Wharram Percy (-19.7‰) and Fishergate House adult females (-19.4‰) are very close, but the mean $\delta^{15}N$ values are quite different, suggesting dependence on different protein sources (Fuller et al., 2003; Richards et al., 2002). Wharram Percy adult $\delta^{15}N$ values range from

approximately 10.5‰ to 8.0‰ with an average of 9.5‰, much lower than what is seen in the Fishergate House adults analyzed to date (mean $\delta^{15}N$ of 11.4‰ with a range from 9.8‰ to 13.1‰). For a graphic depiction of this, see Figure 6-9. The isotopic differences suggest different adult diets, with the Wharram Percy lacking in marine foods and generally replying on protein of a much lower trophic level than that consumed at Fishergate House. As at Fishergate House, the isotopes indicate that weaning at Wharram Percy was likely completed around two years of age (Fuller et al., 2003; Mays et al., 2002; Richards et al., 2002). This process would have been quick, beginning around one year of age and finishing by two years. Juveniles at Wharram Percy have lower $\delta^{15}N$ values (mean = 8.5‰) than those of the adults and likely consumed a more plant-based diet (Fuller et al., 2003; Richards et al. 2002). This is a contrast to the high marine protein diet of the Fishergate House juveniles and it is possible that these differences in diet affected growth, creating the differing growth profiles.

Fishergate House and Wharram Percy exhibit a similar weaning pattern, with nursing ending fairly abruptly between one and two years of age, which coincides with the point at which the sites' growth profiles diverge. Weaning is considered the most stressful period of early childhood and it appears to be more negatively affecting the Wharram Percy children. After weaning, the Fishergate House individuals appear to be growing faster through the young juvenile period, which agrees well with the marine-rich diet, as suggested by $\delta^{15}N$, for this period. Increased high-quality protein in the diet would lead to better growth and fewer delays in growth, while low protein diets lead to delayed growth and lower body

weight (Cameron and Demerath, 2002; Bennike et al., 2005; Ozanne, 2009). Better juvenile nutrition is considered the reason for increased stature in modern populations (Eveleth and Tanner, 1990). From this perspective, the similarity between Fishergate House's growth profiles to that of a modern group of well-nourished children appears to further support good juvenile nutrition at Fishergate House. Both of these samples would have had high protein diets and appear to be following the same growth trajectory.

At Fishergate House, better diet in the early years seems to be leading to better (or rather faster) growth. However, it is clear from the similar estimates for adult stature at the two sites that the two groups would reach almost the same adult height. The Fishergate House sample has the greatest mortality in four to six year olds, but this study only looks at growth until age six. It is possible that stress began to negatively affect the Fishergate House children at this time, influencing mortality although it does not appear to have affected growth or diet directly.

6.5.3 Stress

Cribra orbitalia, dental enamel hypoplasia (DEH), sinusitis, and non-specific infection were used to compare stress in Fishergate House and Wharram Percy and try to reconstruct differences in overall health. Table 6-2 gives the number of cases of each of these lesions, while a pictorial version can be seen in Figure 6-10. The prevalence of each condition in each age category for both Fishergate House and Wharram Percy is graphed in Figures 6-11 to 6-14. Age category 1 (birth to six months) shows almost no sign of any pathological lesions

in either sample. This is not unexpected as these are extremely young individuals who may not have had time to develop skeletal signs of these conditions. These individuals were also all likely being breastfed, which would reduce the risk for infection, as well as establishing a good nutritional base for growth. The fragile and often fragmentary nature of these bones also made assessment of this age category difficult. Age category 1 will not be discussed in depth for each lesion type, but is included to show that all samples have the same health indicators during this period.

The first lesion to be considered is cribra orbitalia (see Fig 6-15 for an image of a typical lesion at Fishergate House). Although Holst (2005) did not record whether cribra orbitalia lesions were healed or unhealed in individual children, she does state that no signs of healing are seen until late childhood. Thus, it will be assumed here that all recorded cases are active. When looking at the total prevalence of cribra orbitalia in each population, it appears that the two samples are equally affected by the condition (Fig 6-10 and 6-11). However, the patterns seen in age categories 2 and 3 are diametrically opposed in Fishergate House and Wharram Percy. The second age category (six months to 2.5 years) spans the weaning period for both groups. The prevalence of cribra orbitalia is quite high in both groups in this age category, but it is higher in the Fishergate House sample. For Fishergate House, prevalence decreases in category 3 (2.5 – six years) and for Wharram Percy it increases, with the net effect that fewer individuals at Fishergate House than at Wharram Percy show signs of cribra orbitalia. This suggests that the main factor affecting cribra orbitalia at Fishergate

House may have been weaning. The weaned diet at Fishergate House was apparently richer in high trophic level protein than that of Wharram Percy, and this may explain the reverse in cribra orbitalia frequencies in age category 3. Once again, four to six year olds at Fishergate House do not appear to have been more stressed than younger children. Rather than reflecting poor diet, cribra orbitalia in this age category could indicate other stressors. For example, poor water quality could lead to diarrhea, which could lead to the prevalence of cribra orbitalia despite a protein rich diet.

The prevalence of dental enamel hypoplasia (DEH) is moderate in both groups for the early childhood period, with a greater overall prevalence at Wharram Percy (Fig 6-10 and 6-12). Figure 6-16 shows the only tooth sampled for the dietary study of Fishergate House with a DEH present. The locations of DEH lesions along the tooth are not recorded in the Fishergate House report, so a detailed analysis by age at formation cannot be conducted. The difference in the prevalence of DEH between the sites is so minor as to imply they were equally affected. It does not appear that stress was at a level to cause stunting or delays during the period of dental formation. This does not necessarily indicate that only minor stress affected these populations, but rather that the stress was not enough to affect dental development.

The prevalence of sinusitis at Fishergate House and Wharram Percy shows the most striking differences (Fig 6-10 and 6-13). Figure 6-17 shows an image of sinusitis in the floor of a sinus. The juveniles at Fishergate House have five times the prevalence of sinusitis as is recorded at Wharram Percy. Sinusitis is quite

common during age category 2 at Fishergate House, and is found in extremely high numbers by age category 3. Comparison during category 2 is complicated by the fact that Lewis (2002) states that she did not score sinusitis in children younger than 2.6 years because of difficulties in diagnosing anomalies in the forming sinuses, though she does include raw data for age category 2 in her table. Even without a direct comparison being made for category 2 the levels are unexpectedly high as the children get older, the Fishergate House juveniles appear to be more affected by sinusitis. When the cases in age category 3 at Fishergate House are broken down further, it is interesting to note that all were in individuals four to six years old. This could be a useful indicator for understanding the high mortality of four to six year olds at Fishergate House. One of the major differences between Fishergate House and Wharram Percy is that the former is urban and the later is rural. This opens the possibility for different environmental stress, reflected in the large difference in sinusitis rates. While the Wharram Percy individuals may have been able to stay around the home with their mothers, the Fishergate House individuals likely ventured out either on their own or accompanied their mothers on their work outside the home. The more dangerous work environment may have contributed to the high mortality in the later age category at Fishergate House. The larger more crowded urban environment would increase the number of people to catch different illnesses from and could be an issue at Fishergate House. Environmental conditions that contribute to infection may have been a major health concern at Fishergate House rather than malnutrition from dietary insufficiency. Poor air quality was a known issue in

urban centers even during the medieval period. This would have been particularly true for children accompanying their mothers to workplaces where coal was burned (Hanawalt, 1977; Jewel, 2007; Roberts, 2010). The closeness of people in an urban environment would also contribute to the spread of illness. Fishergate House is also situated in the flood plain of the River Ouse. The proximity to the river likely led to high rates of colds and allergies, which are conditions known to lead to sinusitis.

Non-specific infection is an indication of stress and immune response issues in a population. Some caution must be used when interpreting these results, as the methods of calculating this category are the most subjective. When looking at the overall comparison of non-specific infection, it is quite clear that Fishergate House is more affected (Fig 6-10). Interestingly, the greatest prevalence for non-specific infection is in the second age category at Fishergate House (Fig 6-14). Non-specific infection can have a number of causes. One possibility is that poor or deficient breastfeeding and weaning foods could be affecting this stress indicator. The prevalence decreases at Fishergate going into age category 3, though it is still higher than what is seen at Wharram Percy. Non-specific stress indicators are thought to reflect conditions having a lasting effect on health and growth, so the high prevalence of non-specific infection during the weaning period might contribute to mortality after this point at Fishergate House. It seems that Fishergate House children are possibly suffering from something suppressing their immune systems. This kind of illness would be a major health issue. The

issues do not appear to be based on diet or affecting growth. Again, environmental stress is a candidate for the conditions seen here.

6.6 Conclusion

From this initial analysis of health at Fishergate House, it appears that sinusitis and non-specific infection could be contributing to mortality at the site, particularly during the four to six year period. A variety of illnesses could cause these conditions. The other stress indicators are at a comparable level to Wharram Percy. What activity or environmental stress that might have led to this susceptibility is not easily determined by this study, though poor air quality and environmental conditions stemming from the urban environment are likely. Poor air quality is associated with textile weaving and with fuels, such as wood and coal, burned for light and heat to support the work (Roberts, 2010). York was a textile and manufacturing center with women participating in the workforce, likely accompanied by their children (Hanawalt, 1977; Jewel, 2007). This could easily be contributing to the high levels of sinusitis found at Fishergate House. The harsh conditions of the urban environmentally likely also contributed to the high levels of non-specific stress at Fishergate House. The high protein diet of the children and their likely good nutritional profile support the conclusion that it is poor environmental conditions that most affected health at the site. Very young children were likely more protected from these factors by staying closer to the home. The high mortality rate of individuals between four to six years may have been due to the increased risk associated with life experiencing more of the urban

environment. Throughout the early childhood period, the Fishergate House children show no evidence for growth delay. The protein rich diet suggested by the stable isotope values probably led to this growth curve, which matches that of modern children (Bennike et al., 2005; Cameron and Demerath, 2002; Ozanne, 2009). Fishergate House children seem to be growing faster than those at Wharram Percy during early childhood, though the difference is not statistically significant. Wharram Percy juveniles must experience later catch up growth, as the two populations had similar adult statures, though Fishergate House adults were slightly taller. It is also possible that Fishergate House juveniles suffered stunting at a later point in their growth. The weaning times were similar for the two groups, but the weaned diet at Fishergate House contained more high trophic level proteins (likely marine fish) than Wharram Percy. The $\delta^{13}C$ values were very similar for both groups. The same pattern was seen with the adults, with the Fishergate House adult female $\delta^{15}N$ values being higher that the Wharram Percy diet for all adults. Neither of these populations appears to be eating a nutritionally poor or inadequate diet. When all the indicators are considered together, it appears that the Fishergate House children might have been suffering from more infectious disease than their neighbors. In this case, the urban environment does not appear to be affecting growth, but does seem to be contributing to poor immune reaction and a high level of infection in the population. By combining different methods and comparing Fishergate House to Wharram Percy, it was possible to get a nuanced look at health during early childhood. This method does not examine two populations in complete opposition, one in poor health one in

good health, rather this methodology allows a picture of differential health to be created. By looking at the different health problems that affect different populations, researchers can discover what aspects of life might be different for contemporary children living in different places and environments.

Table 6-1: Growth Data. All measurements are in mm.

Fishergate House Femur

Age Category	N	Mean	Standard Deviation	% Adult Length
1	6	111.6	24.2	25.5
2	3	165.1	8.8	37.7
3	1	200.1	0	45.6
4	4	217.8	11.3	49.7
5	4	228.0	7.6	52.0
6	1	242.0	0.0	55.2

Fishergate House Tibia

Age Category	N	Mean	Standard Deviation	% Adult Length
1	3	111.0	9.0	32.0
2	4	146.8	25.4	42.3
3	1	152.5	0.0	43.9
4	4	173.5	6.8	50.0
5	2	179.5	0.7	51.7
6	2	183.0	2.8	52.7

Wharram Percy Femur (Mays et al., 2008)

Age Category	N	Mean	Standard Deviation	% Adult Length
1	10	125.5	10.9	29.0
2	10	151.9	10.3	35.3
3	11	173.1	12.8	40.3
4	11	186.0	12.1	43.3
5	6	195.5	9.9	45.5
6	21	214.6	12.8	49.9

Wharram Percy Tibia (Mays et al., 2008)

Age Category	N	Mean	Standard Deviation	% Adult Length
1	11	103.1	6.8	30.1
2	7	121.6	11.9	35.4
3	12	136.3	9.6	39.7
4	10	149.9	11.1	43.6
5	4	154.0	10.9	44.8
6	14	174.1	10.2	50.7

Denver Femur (Ruff, 2007)

Age Category	N	Mean	Standard Deviation	% Adult Length
1	20	132.4	5.0	28.0
2	20	166.7	7.1	36.0
3	20	192.8	8.6	41.0
4	20	216.0	10.8	46.0
5	20	237.1	11.9	50.8
6	20	258.4	15.2	55.0

Denver Tibia (Ruff, 2007)

Age Category	N	Mean	Std	% Adult Length
1	20	105.7	4.9	27.0
2	20	134.8	6.5	35.0
3	20	157.7	8.5	40.0
4	20	176.7	10.1	45.0
5	20	194.3	11.8	49.0
6	20	211.7	13.3	54.0

Table 6-2: Summary of pathological conditions.

Fishergate House Pathology Summary

Cribra Orbitalia

Age Category	N with Orbits	N with Cribra	% Total Individuals with Orbits	% Category
1	3	0	0	0
2	14	9	32	64
3	11	6	21	54.5
Total	28	15	54	

Dental Enamel Hypoplasia (DEH)

Age Category	N with Teeth	N with DEH	% Total Individuals with Teeth	% Category
1	5	0	0	0
2	21	1	2	5
3	17	5	10	29
Total	43	6	14	

Sinusitis

Age Category	N with Max	N with Sinusitis	% Total Individuals with Maxilla	% Category
1	3	0	0	0
2	12	4	14	33
3	14	8	28	57
Total	29	12	41	

Non-specific Infection (NSI)

Age Category	N with Tibia	N with NSI	% Total Individuals with Tibia	% Category
1	0	0	0	0
2	7	2	12.5	28.5
3	9	1	6	11
Total	16	3	19	

Wharram Percy Pathology Summary (Lewis, 2002)

Cribra Orbitalia

Age Category	N with Orbits	N with Cribra	% Total Individuals with Orbits	% Category
1	34	2	1	6
2	55	34	22	62
3	67	47	30	70
Total	156	83	53	

Dental Enamel Hypoplasia (DEH)

Age Category	N with Teeth	N with DEH	% Total Individuals with Teeth	% Category
1	0	0	0	0
2	28	3	4	11
3	53	13	16	24.5
Total	81	16	20	

Sinusitis

Age Category	N with Maxilla	N with Sinusitis	% Total Individuals with Maxilla	% Category
1				
2	8	1	2	12.5
3	46	3	5.5	6.5
Total	54	4	7.5	

Non-specific Infection (NSI)

Age Category	N with Tibia	N with NSI	% Total Individuals with Tibia	% Category
1	24	2	2	8
2	39	5	4	13
3	53	3	3	6
Total	116	10	9	

Age category 1 = 0 - 0.5 years, Age category 2 = 0.6 – 2.5 years, Age category 3 = 2.6 – 6.5 years

Table 6-3: Summary of t-Tests.

Unequal Variance t-Test Results: % Femur Length				
Age Category 1				
Mean (FH): 25.46 n = 6 std = 24.185		Mean (WP): 28.76 N = 10 std: 10.9		
t -0.316	*df* 5.7	*sig (2-tail)* 0.767	*mean difference* -3.3	*std error diff* 10.458
Age Category 2				
Mean (FH): 37.68 n = 3 std = 8.776		Mean (WP): 35.34 n = 10 std: 10.3		
t .388	*df* 3.3	*sig (2-tail)* 0.806	*mean difference* 2.34	*std error diff* 6.023
Age Category 3				
Mean (FH): 45.63 n = 1 std = 0		Mean (WP): 40.27 n = 11 std: 12.8		
Sample Size Too Small				
Age Category 4				
Mean (FH): 49.7 n = 4 std = 11.325		Mean (WP): 43.28 n = 11 std: 12.1		
t 0.953	*df* 5.2	*sig (2-tail)* 0.366	*mean difference* 6.42	*std error diff* 6.736
Age Category 5				
Mean (FH): 52.04 n = 4 std = 7.612		Mean (WP): 45.49 n = 6 std = 9.9		

t 1.18	*df* 7.2	*sig (2-tail)* 0.264	*mean difference* 6.55	*std error diff* 5.552
Age Category 6				
Mean (FH): 55.24 n = 1 std = 0		Mean (WP): 49.93 n =21 std = 12.8		
Sample Size Too Small				
Unequal Variance t-Test Results: % Tibia Length				
Age Category 1				
Mean (FH): 31.95 n = 3 std = 8.958		Mean (WP): 30.1 n =11 std = 6.8		
t 0.333	*df* 2.2	*sig (2-tail)* 0.800	*mean difference* 1.85	*std error diff* 5.56
Age Category 2				
Mean (FH): 42.27 n = 4 std = 25.403		Mean (WP): 35.4 n =7 std = 11.9		
t 0.51	*df* 3.3	*sig (2-tail)* 0.746	*mean difference* 6.87	*std error diff* 13.474
Age Category 3				
Mean (FH): 43.91 n = 1 std = 0		Mean (WP): 39.67 n =12 std = 9.6		
Sample Size Too Small				
Age Category 4				
Mean (FH): 49.95 n = 4 std = 6.758		Mean (WP): 43.63 n =10 std = 11.1		
t 1.297	*df* 8.8	*sig (2-tail)* 0.209	*mean difference* 6.32	*std error diff* 4.872

Age Category 5				
Mean (FH): 51.68 n = 2 std = 0.707		Mean (WP): 44.83 n = 4 std = 10.9		
t 1.252	*df* 2.6	*sig (2-tail)* 0.303	*mean difference* 6.85	*std error diff* 5.473
Age Category 6				
Mean (FH): 52.69 n = 2 std = 2.828		Mean (WP): 50.68 n = 14 std = 10.2		
t 0.595	*df* 6	*sig (2-tail)* 0.587	*mean difference* 2.01	*std error diff* 3.381

Figure 6-1: Femur length comparison between Fishergate House (FGH) and Wharram Percy (WP).

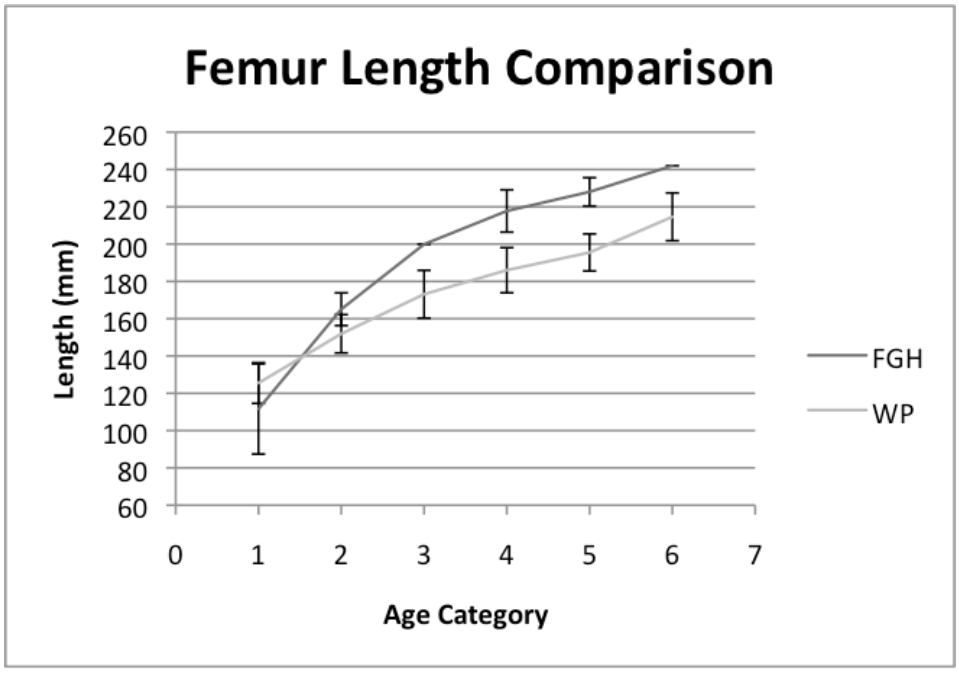


Figure 6-2: Tibia length comparison between Fishergate House (FGH) and Wharram Percy (WP).

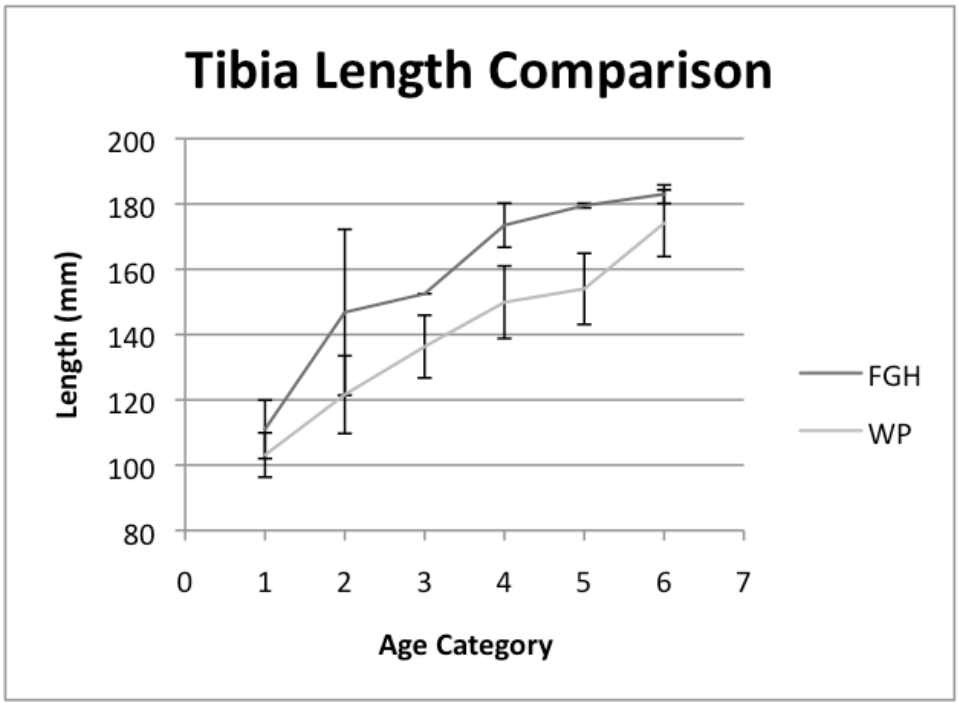


Figure 6-3: % of Adult stature obtained using femur length and height. Comparison between Fishergate House (FGH) and Wharram Percy (WP).

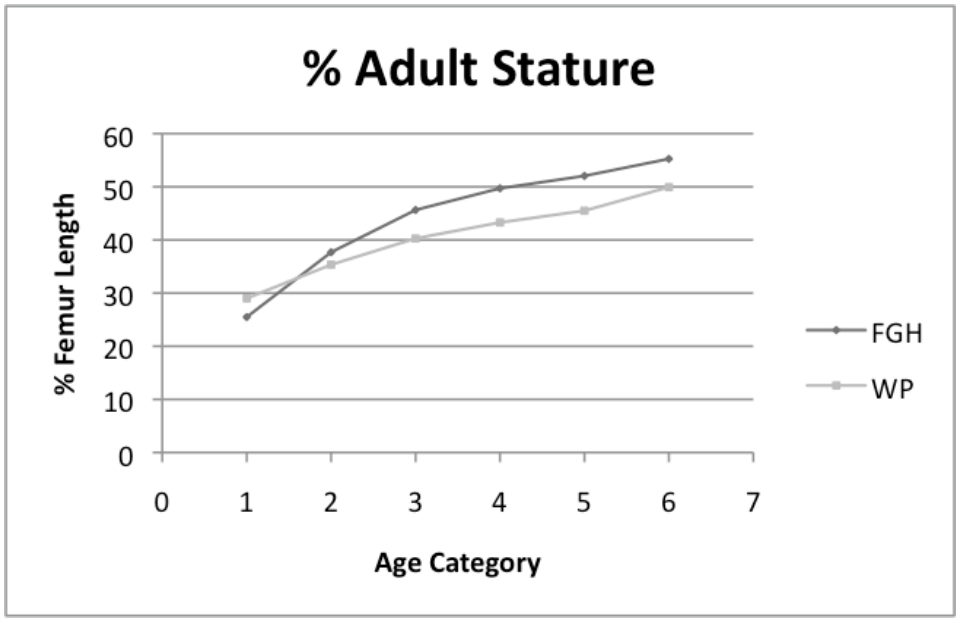


Figure 6-4: % of Adult stature obtained using tibia length and height. Comparison between Fishergate House (FGH) and Wharram Percy (WP).

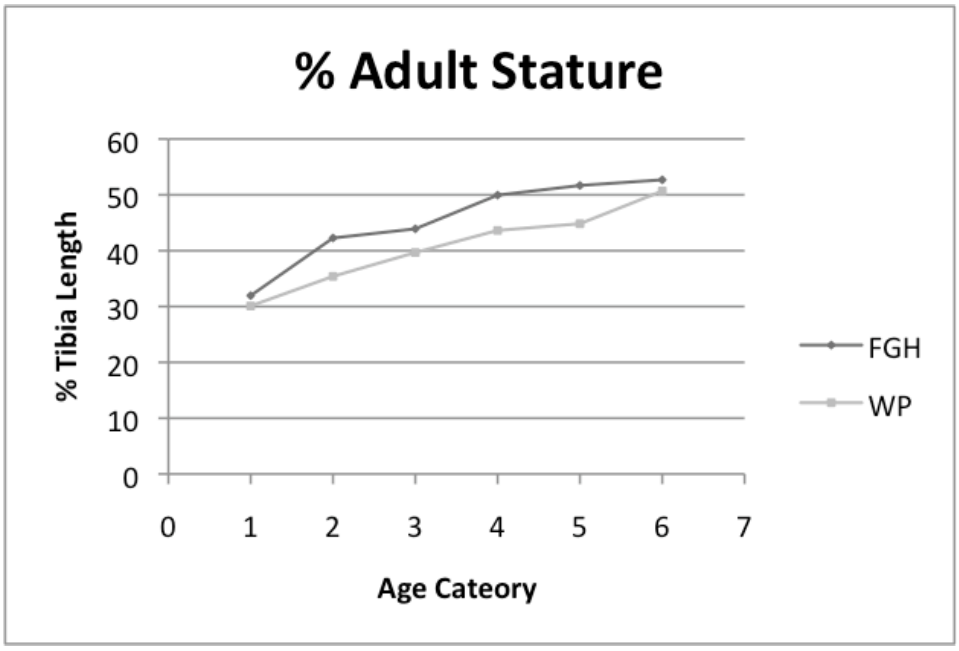


Figure 6-5: Femur length comparison between Fishergate House (FGH) and Denver sample (DV).

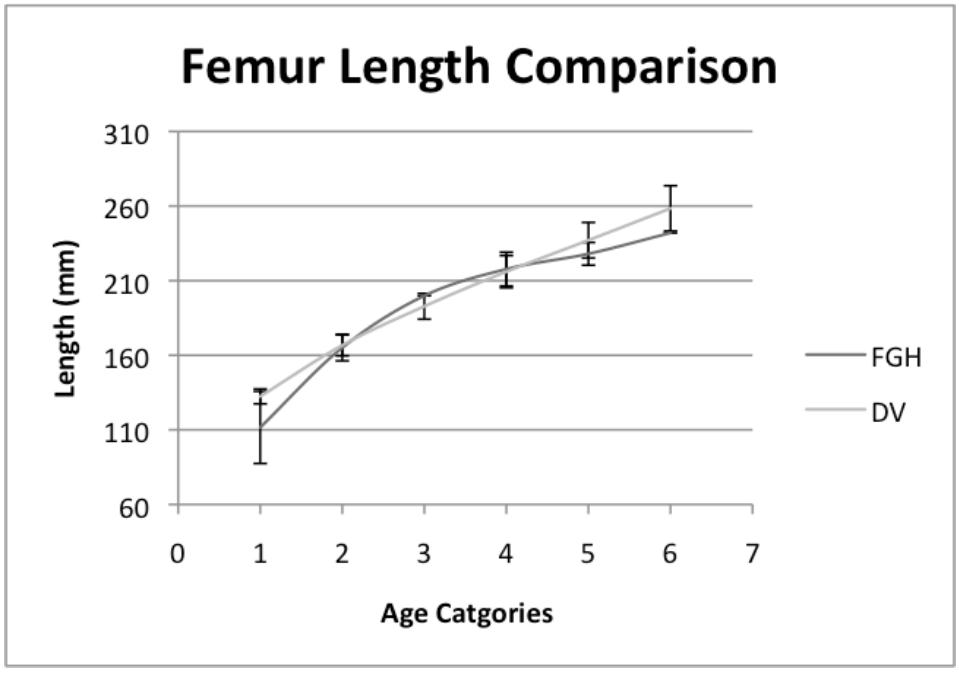


Figure 6-6: Tibia length comparison between Fishergate House (FGH) and Denver sample (DV).

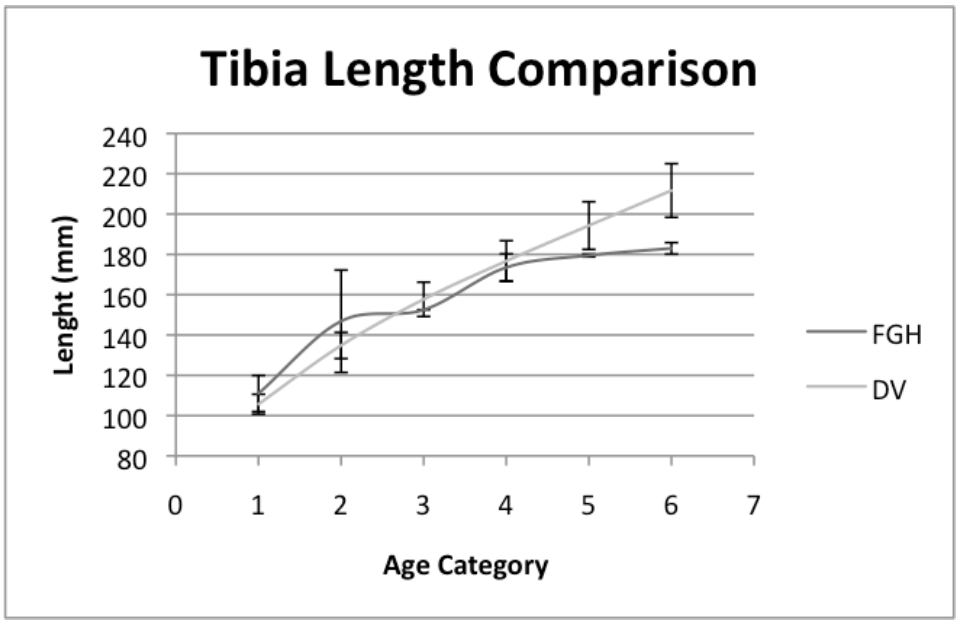


Figure 6-7: % of Adult stature obtained using femur length and height. Comparison between Fishergate House (FGH) and Denver sample (DV).

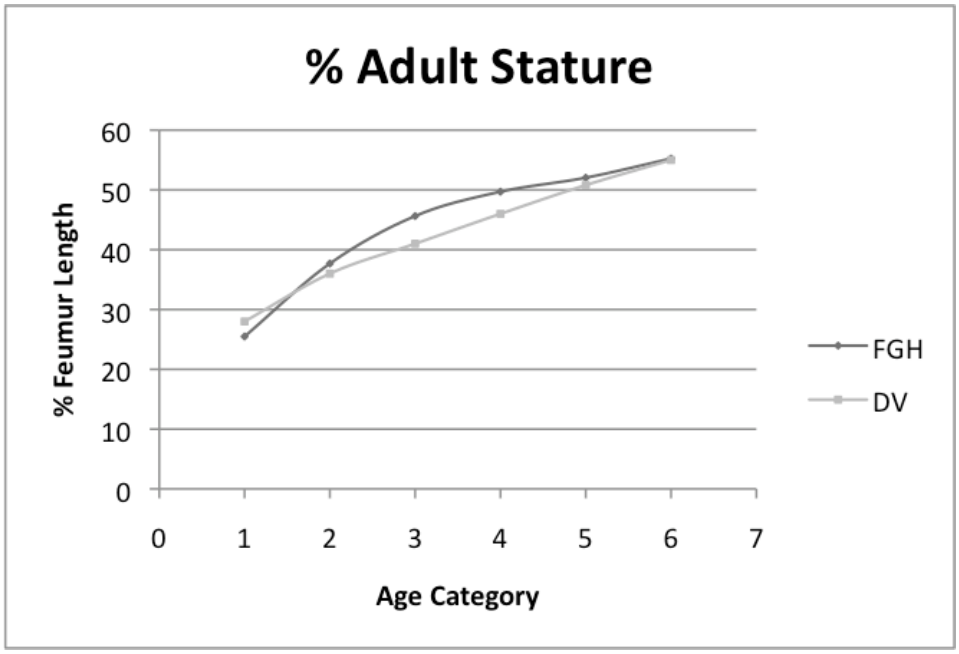


Figure 6-8: % of Adult stature obtained using tibia length and height. Comparison between Fishergate House (FGH) and Denver sample (DV).

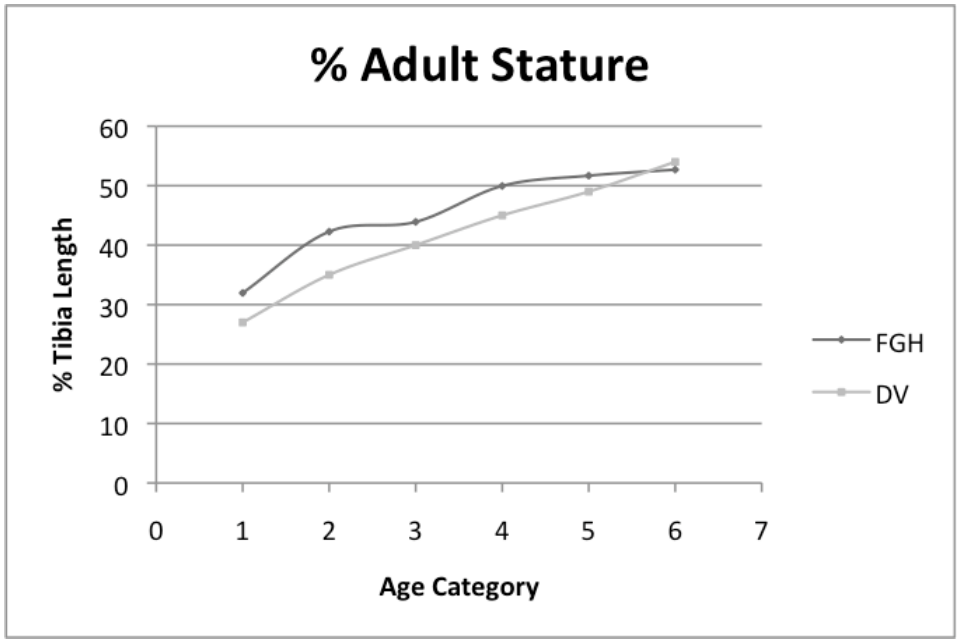


Figure 6-9: Stable Isotope Results. Fishergate House adults results (black squares) and weaned children (black circles) are from this study. Adult females are of reproductive age. Wharram Percy data from Fuller et al. (2003) and Richards et al. (2002). York animal data from Müldner and Richards (2007a;2007b).

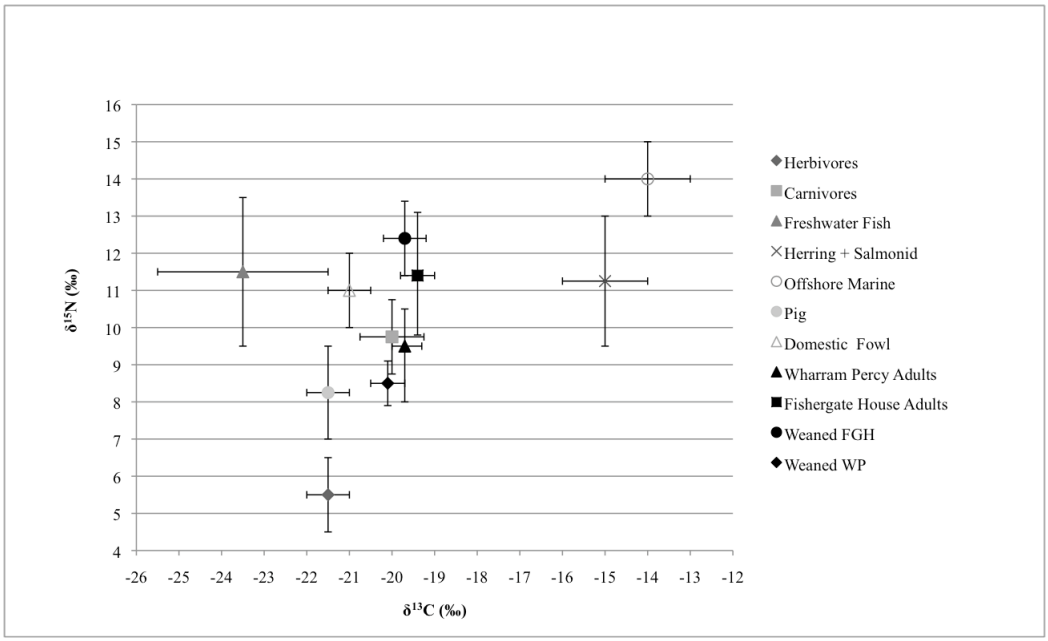


Figure 6-10: Prevalence of disease at Fishergate House (FGH) and Wharram Percy (WP).

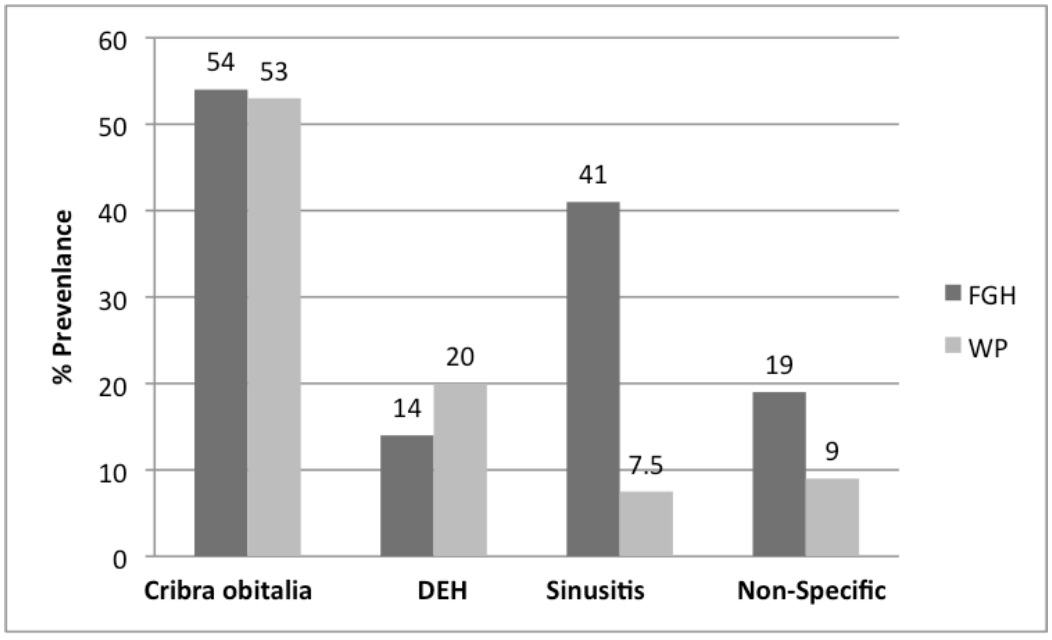


Figure 6-11: Prevalence of cribra orbitalia at Fishergate House and Wharram Percy. Results are separated into age category (1: 0-0.5 years, 2: 0.6-2.5 years, and 3: 2.6-6.5 years)

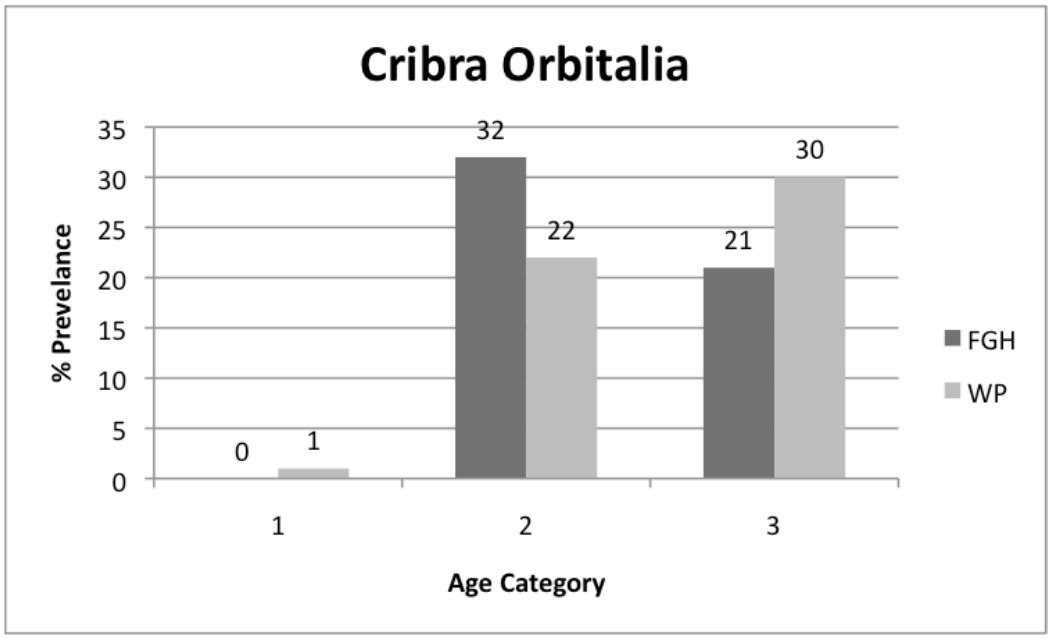


Figure 6-12: Prevalence of dental enamel hypoplasia (DEH) at Fishergate House (FGH) and Wharram Percy (WP). Results are separated into age category (1: 0-0.5 years, 2: 0.6-2.5 years, and 3: 2.6-6.5 years)

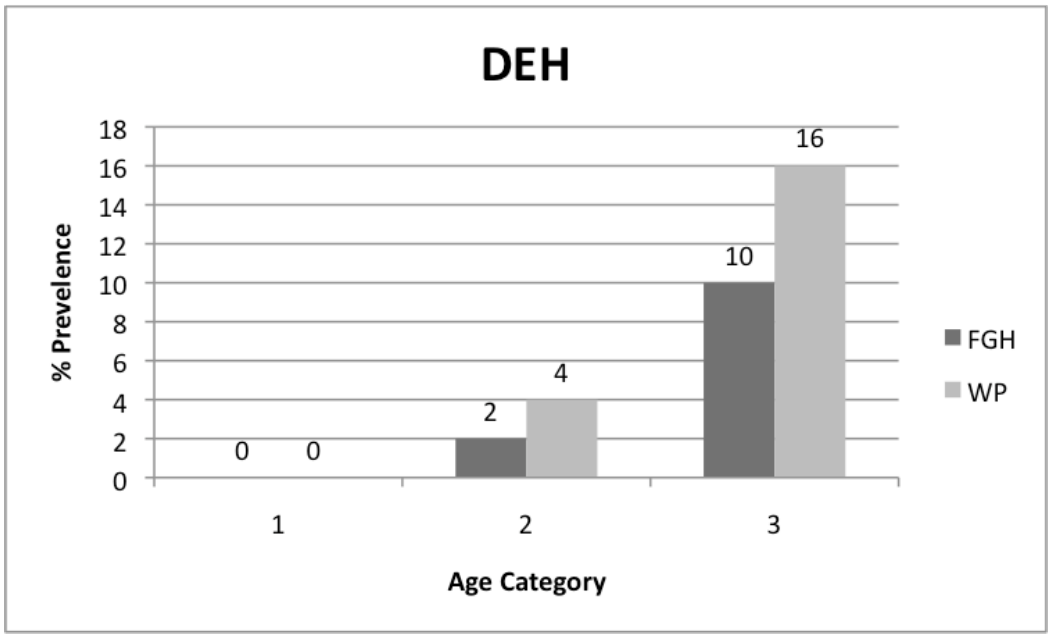


Figure 6-13: Prevalence of sinusitis at Fishergate House (FGH) and Wharram Percy (WP). Results are separated into age category (1: 0-0.5 years, 2: 0.6-2.5 years, and 3: 2.6-6.5 years)

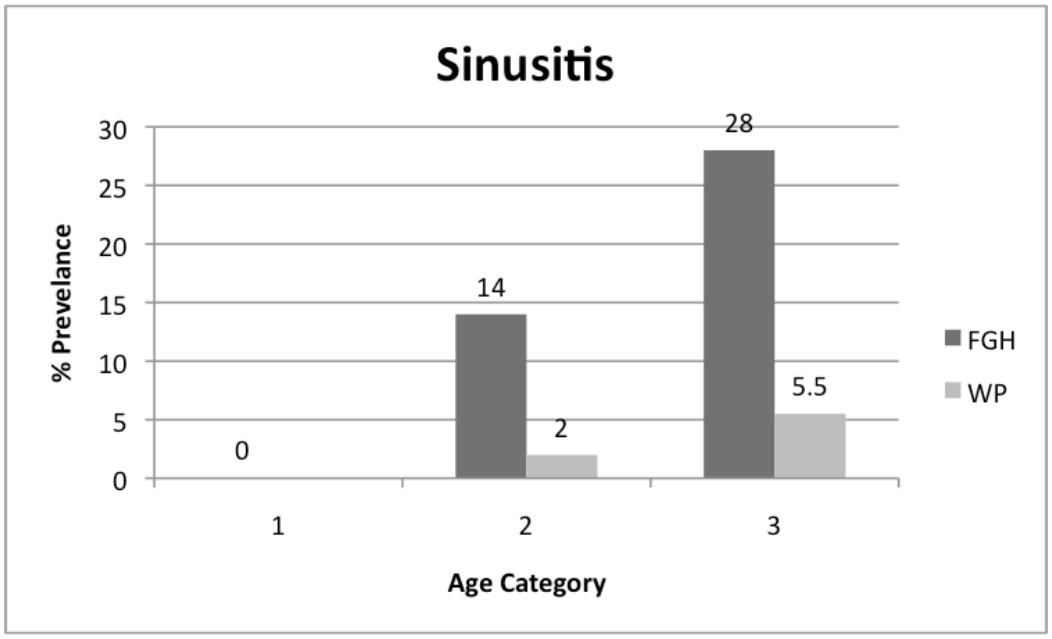


Figure 6-14: Prevalence of non-specific infection at Fishergate House (FGH) and Wharram Percy (WP). Results are separated into age category (1: 0-0.5 years, 2: 0.6-2.5 years, and 3: 2.6-6.5 years)

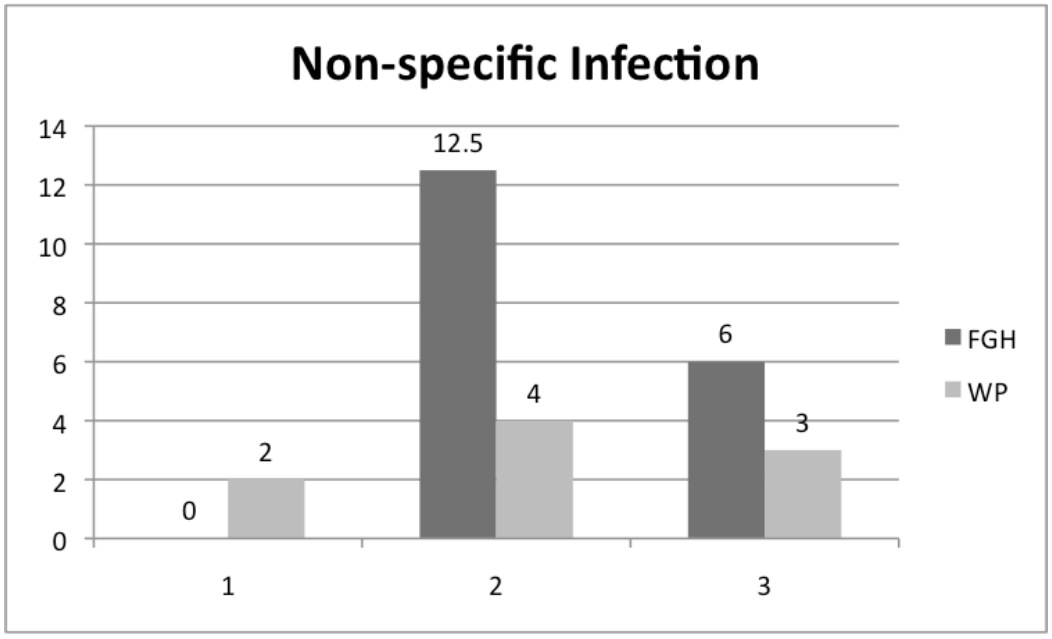


Figure 6-15: Image of cribra orbitalia in a Fishergate House juvenile (Holst, 2005). Lesions can be seen as the pitting in the orbital surface.

Figure 6-16: Image of DEH in a Fishergate House juvenile. DEH is seen approximately 3/4 of the way down the crown.

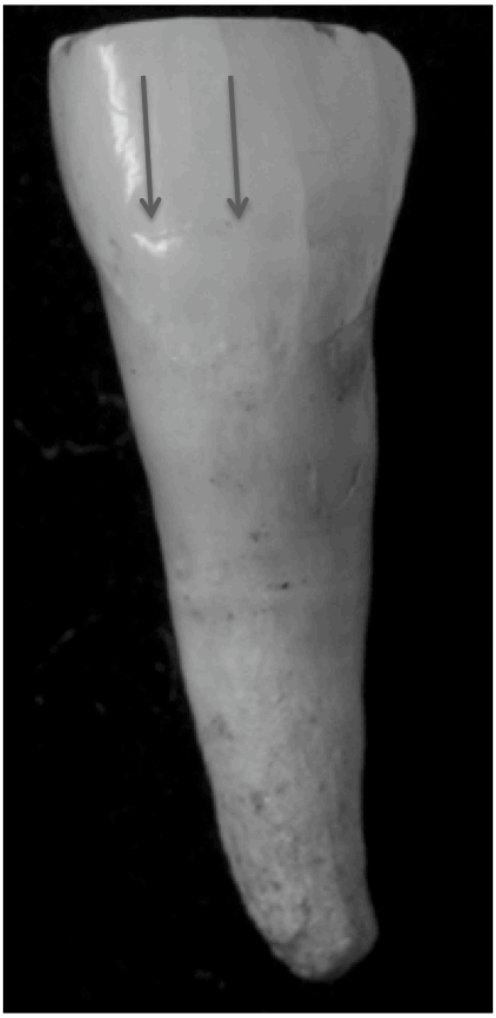
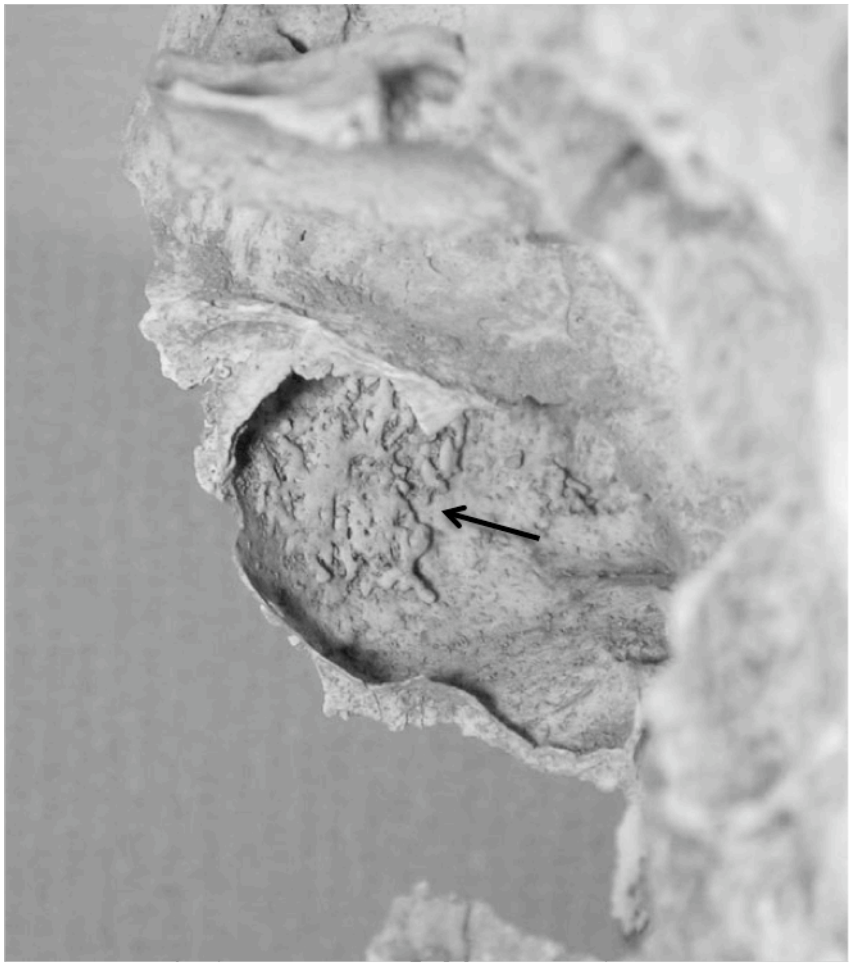


Figure 6-17: Image of sinusitis in a Fishergate house juvenile (Holst, 2005). Lesions can be seen as spicules of bone and pitting in the floor of the sinus.



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Chapter 7
Conclusions

7.1 Introduction

This dissertation presents a new dentine microsampling method developed for use on both modern and archaeological populations for stable isotope analysis as well as the dietary reconstructions for the modern Canadian and medieval British samples used. While the creation and testing of this methodology was a major focus of the research, this dissertation is also the first to examine juvenile diet at medieval Fishergate House, York. Both of these firsts have produced important results and have a range of interesting implications for future biological anthropological research on human diet.

7.2 Major Research Findings

Chapter 3 is the first research based chapter, where the new microsampling method for stable isotope analysis is presented. A modern Canadian sample, collected in Edmonton, was used in the creation of this method. This research showed that microsamples of tooth dentine as small as 0.3 mg could be used to reconstruct diet. No dietary or weaning behavior was recorded for these individuals, but some interesting aspects of diet were reconstructed using the method. First, the prenatal stable isotope values show a lot of variation indicating that mothers likely had varied diets, which is expected in a culture where omnivory, veganism, and vegetarianism are all regular dietary choices. Also expected was the indication that some infants were breastfed, while others were bottle fed. Clear evidence of both these diets were found in the sample. The early

childhood or weaned diets were surprising. Despite the previous range of diets in the population, the weaned diet seems largely uniform. The $\delta^{15}N$ values in particular are extremely close together. This suggests all these children consumed protein of roughly the same average trophic level. Most individuals showed moderate $\delta^{13}C$ values typical of the Americas; only a couple showed signs of increased C_4 dependence that possibly indicates a more maize/sugar rich diet or an origin outside of Americas. It is not clear why there would be a similar diet being eaten by the children sampled here. It is possible this indicates a specific early childhood diet, rather than the diverse diets seen in the adult population.

Chapter 4 presents the stable isotope analysis of the juvenile ribs collected from Fishergate House, York. Because Fishergate House has a large number of juvenile individuals, it was possible to see the dietary pattern at the site. It appears that all individuals were breastfed and had a pattern of quick weaning beginning at about 1.5 years of age and finishing around two years of age. This weaning period fits with the historic literature from the period (Fildes, 1986; Shahar, 1990). It does not help explain why there is a higher mortality rate in four to six year olds who should no longer have been dealing with weaning stress as was speculated previously (Holst, 2005). As with the Canadian sample, the weaned diet is interesting. Rather than being a close match for the adult females from Fishergate House, the diet matches that of the population of York as a whole as reconstructed in other stable isotope studies. The children were clearly not excluded from getting marine proteins, which are often considered a high status food for the medieval period. The results show that in some instances the children

would have been getting higher trophic-level proteins, such as marine resources or pig, than the adult females.

Chapter 5 reconstructed juvenile diet at Fishergate House using dentine microsampling. The new microsampling technique could be used on the archaeological remains with a minimum of changes. This allowed the reconstruction of population dietary patterns and individual dietary changes. The population data confirmed the picture found using the rib samples. However, by microsampling the number of values for each age category was greatly increased. Again, the stable isotope values representing the weaned diet were closer to the signature of the total population diet than to that of the female only diet. By combining the rib and teeth data for each individual, it was possible to show the maintenance of the post weaning diet at a level indicating more marine protein than the adult female diet. One of the most interesting findings is that a number of individuals did not fit the general pattern of breastfeeding and weaning seen for the other children. This implies that they were given special treatment due to personal preferences, maternal preferences, or possible health reasons. An example of this is that some of the special individuals were weaned after two years of age, which could indicate that a longer breastfeeding period was a way in which mothers tried to deal with sickly infants.

Chapter 6 dealt with growth, diet, and health at Fishergate House. The growth data showed that despite being made up of the working class poor, growth was not faltering at Fishergate House during the early childhood period. The dietary evidence for Fishergate House showed that the weaned children ate a diet

similar to that of the general population, meaning it was rich in marine protein. Both the growth and dietary data seem to indicate proper nutrition through the early childhood period. The look at stress-related skeletal lesions in the children whose diets were reconstructed showed that for most lesions prevalence was similar to the comparative medieval sample of Wharram Percy. This is true except for the rates of sinusitis, which were much higher at Fishergate House. Poor air quality associated with the urban environment could have been contributing to the prevalence of this condition. Weaving, a common trade in York is associated with poor air quality. Overall, the children examined do not show many signs of severe nutritional deficiency or illness. The urban conditions do not appear to have had an adverse effect on the Fishergate House children when compared to their rural counterparts.

7.3 Future Research

The new method of stable isotope microsampling described here has been proven to work accurately in modern and past populations. The possibilities for further research using the method are vast. A modern study combining surveys of maternal diet during pregnancy, breastfeeding practices, and weaning practices would help establish how pregnancy diet relates to fetal stable isotope values, as well as giving more information on the stable isotope patterning expected for different breastfeeding and weaning practices. This would need to be a large project collecting shed baby teeth and dietary data from a large number of mothers and infants. Collecting hair and/or fingernail samples from the mothers

and babies to compare to the dentine stable isotope values would further strengthen this study. Ideally, this would be a longitudinal study where the mother is interviewed before the child is born. In other possible modern applications, the microsampling method could be paired with more advanced histological techniques to look at even more specific diets. For example, it could be possible to reconstruct the diet from near linear enamel hypoplasias and compare them with the non-disturbed tooth dentine to determine if an isotopic difference could be found. The method could be used on permanent teeth to expand the dietary age ranges that can be reconstructed. A particularly long range of diets could be collected if deciduous and permanent teeth are collected from a child with mixed dentition. By using the method on permanent teeth, it would be possible to look at the early diet of adults as well.

There are also applications for populations where fetal and very early childhood remains are not found. The method could be used to increase sample size and increase the likelihood of statistical significance when comparing groups. The larger sample sizes could allow for comparisons between fetal and adult female signals, which may lead to a better understanding of the relationship between fetal, pregnancy, and female stable isotope signals.

Fishergate House also has a lot of potential for further study. An isotopic study of the diet of older juveniles and adults would add to the overall dietary picture at Fishergate House. As this work has yet to be done, it would be interesting in its own right, however this group of the urban poor would also offer

the opportunity of gaining a better understanding of medieval diet in Britain through comparison with further contemporary sites.

7.4 Last Words

It is possible to sample human teeth in keeping with their growth pattern. By sampling deciduous teeth, it is possible get reliable signals from dentine collagen samples as small as 0.3 mg that can provide information on fetal life, breastfeeding diet, and weaning diet. It is hoped that other researchers will agree with the merits of the method created as part of this work and incorporate it into their own research plans. This method is simple to use and inexpensive to add to the techniques of an already functioning stable isotope facility.

By application of the microsampling method to the Fishergate House sample, it was possible to reconstruct young juvenile dietary patterns on the population as well as the individual level. This allowed important anthropological questions about weaning age and childhood diets to be answered. By looking at the diet of each individual, it is possible to detect otherwise unnoticeable deviations from the normal breastfeeding and weaning patterns found in a population. Studies such as the one applied here allow for the reconstruction of both weaning norms and deviations from these norms in the archaeological record.

7.5 Literature Cited

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