Postnatal Dental Mineralization: a Comparative Analysis of Dental Development Among Contemporary Populations of the Southeastern United States

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Postnatal Dental Mineralization: a Comparative Analysis of Dental Development Among Contemporary Populations of the Southeastern United States

by

Meryle Akeara Dotson

A thesis submitted in partial fulfillment of the requirements of the degree of Master of Arts Department of Anthropology College of Arts and Sciences University of South Florida

Major Professor: Erin H. Kimmerle, Ph.D. David A. Himmelgreen, Ph.D. Lorena Madrigal, Ph.D.

Date of Approval: November 4, 2011

Keywords: Transition Analysis, Bayesian Analysis, Forensic Anthropology, Human Variation, Age Estimation

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DEDICATION

I dedicate this thesis to my parents, Murl and Geraldine Dotson, and to my sisters, Regina, Tammy, and Kyla, in recognition of their continued support. I would like this thesis to be an inspiration for my nieces, Taja and Victoria, so that they may always have faith in their abilities to pursue their dreams.
ACKNOWLEDGEMENTS

I would like to express sincere gratitude to my committee, Drs. Erin Kimmerle, David Himmelgreen, and Lorena Madrigal for their guidance and support in my research endeavors. I would like to thank Dr. Barry Lipton for his leadership and support, and his office staff for all their help in making my research possible. Finally, I would also like to thank Dr. Lyle Konigsberg for his assistance in statistical analyses, and Drs. Edward F. Harris and Joy H. McKee, for their generous contributions of comparative samples.
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ABSTRACT

Due to the strong genetic component of dental development, research has shown that mineralization patterns of the human dentition are relatively buffered against environmental influences that normally affect bone growth and development. It is because of this resistance to environmental factors and the continuous growth of the permanent dentition throughout childhood and adolescence that the evaluation of dental development patterns has become the preferred method of age estimation in living and deceased children.

Researchers (Harris and Mckee 1990; Tompkins 1996; Blankenship et al. 2007; Kasper et al. 2009) have suggested that the timing of dental development varies by ancestral descent and geographic populations. However, further evaluations of these perceived differences in the timing of dental development among populations are necessary as classical statistical methods result in age estimations that are biased toward the age structure of the reference population. However, the Bayesian approach is beneficial since it incorporates relevant prior knowledge into the analysis and formalizes the relationship between assumptions and conclusions (Buck et al. 1996). Therefore, the purpose of this research is to incorporate methods in Bayesian analysis to compare the timing of dental development between two contemporary populations of the Southeastern United States, as well as test the accuracy of dental development age parameters devised
by Moorrees *et al.* (1963) on a contemporary Florida Population.

For this study, 51 panoramic radiographs of individuals from a contemporary Florida population ranging in age from 7.7-20.4 years were reviewed. Statistical analyses incorporated a Bayesian approach to compare the timing of dental development for individuals comprising the contemporary Florida sample with the timing of dental development for a contemporary Middle Tennessee population by utilizing the age structure of the Middle Tennessee population as informed prior knowledge, otherwise referred to as an informed prior. Transition distributions for age, given stage of dental development, were also modeled for individuals comprising the contemporary Florida sample. The accurate observation and comparison of probability density distributions for age can serve as a noninvasive method for evaluating the probability of whether or not an unknown individual is a particular age, given the stage of dental development.

Results of this research indicate that there is a consistent underestimation of age for individuals comprising the contemporary Florida population when the age structure of the Middle Tennessee population is utilized as an informed prior. Additionally, the results of this thesis indicate that there is a consistent underestimation of age when utilizing age parameters of Moorrees *et al.* (1963) for the estimation of age for individuals from a contemporary Florida population. By incorporating a Bayesian approach to compare two contemporary populations of the Southeastern United States, a comprehensive analysis of the relationship between age and stage of dental development can be achieved. Therefore, the results of this thesis support Bayesian analysis as an appropriate method of evaluating perceived differences in the timing of dental development between contemporary populations. Furthermore, the results of this
research are beneficial to the field of forensic anthropology as the observation of advanced stages of molar development utilizing panoramic radiographs serves as a noninvasive method in estimating age for unknown juveniles and young adults, and can also assist courts within the United States in determining whether or not an individual is legally considered a minor or an adult.
CHAPTER 1: INTRODUCTION

For several generations, researchers within biological anthropology and forensic anthropology have used particular aspects of human dentition to assist in human identification and provide insight into human evolution. For example, researchers (Moorrees et al. 1963; Demirjian et al. 1973) have considered the calcification patterns of teeth to be reliable in the estimation of age in juveniles and young adults. However, as with many other aspects of human growth and development, researchers (Harris and McKee 1990; Blankenship et al. 2007; Kasper et al. 2009) have observed that the timing of dental development may vary across populations, and that it is imperative to take this possible variation into account when devising practical age estimation standards to be applied in forensic and bioarchaeological contexts.

However, while many recent comparative studies of dental development across populations claim to identify differences in the timing and tempo of dental development among populations from various ancestral groups and geographic regions, many statisticians, anthropologists, and paleodemographers (Hoppa and Vaupel 2002; Boldsen et al. 2002; Konigsberg et al. 2008) assert that the perceived differences in dental development among populations are the result of inappropriate statistical analyses. As a result of inappropriate statistical analyses, researchers (Hoppa and Vaupel 2002; Boldsen et al. 2002; Konigsberg et al. 2008) suggest that previous comparative studies do not
accurately identify population differences in the timing of dental development. Furthermore, according to Madrigal and Barbujani (2007:27), discontinuous groups that are identified from the physical aspects of people “are not reliable predictors of variation.” Therefore, many existing comparative dental development studies that incorporate ancestral descent as a variable may inappropriately attribute observed differences in the timing of dental development to ancestral population variation.

According to several authors (Kittles and Weiss 2003:38; Madrigal and Barbujani 2007:24) differences in human variation are better understood as a result of isolation by distance rather than ancestral descent. For example, Kittles and Weiss (2003:38) state that “genetic distances between populations are roughly proportional to the geographic distance between them.” For this study, dental development data were obtained from two contemporaneous geographic regions in the Southeastern United States. Tooth mineralization data were collected from a contemporary Florida population and a contemporary Middle Tennessee population. Differences in the timing and tempo of dental development between the two populations are hypothesized to be minimal, since both samples are derived from contemporaneous Southern populations of similar geographical contexts.

The purpose of this study is to address five primary research goals. This study aims to achieve the following:

1. Provide an extensive review of the published literature concerning perceived differences in the timing of dental development among various human populations.

2. Compare the timing and tempo of dental development between a contemporary Florida population sample and a contemporary Middle Tennessee population sample utilizing statistical methods in Bayesian analysis.
3. Determine whether or not the perceived differences in timing and tempo of dental development among contemporary populations are the result of statistical biases or inappropriate statistical analyses, rather than a reflection of inter-population variation of human dental calcification.

4. Assess the accuracy of dental age parameters devised by Moorrees et al. (1963) on a contemporary Florida population sample.

5. Assess the need for population specific standards in dental age estimations.
CHAPTER 2: LITERATURE REVIEW

Dental Development Defined

Dental development, or odontogenesis, refers specifically to the formation of organic matrices within the alveolar portions of the mandible and maxilla, and the subsequent calcification that eventually gives rise to the 20 deciduous teeth and the 32 permanent teeth (Smith 1991:144). The process of dental development occurs over a significant amount of time in an individual’s life. The initial stages of dental development begin in utero, during the sixth or seventh week of embryonic life, and it is during this time that initial cusp formation of teeth comprising the deciduous dentition occurs. However, postnatal calcification of the permanent dentition continues until early adulthood, and the process of dental development is generally considered to be complete upon the root apex closure of the third molar. Though highly variable, complete root apex closure of the third molar generally occurs between the ages of 16.75 and 20.00 years (Van der Linden and Duterloo 1976:4; Miles 1978:476; Moss-Salentijn and Hendricks-Klyvert 1990:165; Smith 1991:144).

The mineralization or development of human teeth is considered by many physical anthropologists to be the equivalent to bone ossification in the human skeleton. Age estimation utilizing dental development is possible since various stages of tooth development are identifiable at particular ages throughout childhood (Scheuer and Black,
2000:150, 154). Each tooth begins as a soft tissue tooth bud or tooth germ that is mineralized within the alveolar portion of the mandible or maxilla. While dental development begins in utero, the postnatal mineralization of the permanent dentition continues until approximately 18-20 years of life. Additionally, due to the strong genetic component of dental development, research has shown that mineralization patterns of the human dentition are relatively buffered against environmental influences that normally affect bone growth and development in growing children (Saunders et al. 1993:173; Pelsmaekers et al. 1997:1340; Hoppa and FitzGerald 1999:3; Scheuer and Black 2000:151-153). It is because of this resistance to environmental factors, the continuous growth of the permanent dentition throughout childhood and adolescence, and the ability to yield concise age ranges that the evaluation of dental development patterns has become the preferred and most accurate method of age estimation in living and deceased children (Ubelaker 1978:46; Lewis 2007:38; Halcrow and Tayles 2008:208).

**The Biology, Histology, and Embryology of Human Dental Development**

**Biological Processes of Dental Development**

Similar to the manner in which cartilaginous tissues in the body eventually give rise to various long bones, dental development begins with the development of a soft tissue tooth bud or tooth germ. Once soft tissues that give rise to the mandible and maxilla have assumed their initial shape, localized tooth buds soon form within the jaws of an embryo (Van der Linden and Duterloo 1976:4). During the bud stage of development, the tooth germ is comprised of a ball of epithelial cells. Each tooth bud then progresses through two additional stages of development, collectively referred to as
morphodifferentiation, prior to beginning the stages of dental mineralization. The stages of morphodifferentiation are significant to the process of dental development as each stage contributes to establishing the foundation for the shape of the developing tooth (Moss-Salentijn and Hendricks-Klyvert 1990:167). Immediately following the bud stage of development, the tooth germ then enters the cap stage. During this stage of development, the future shape of the tooth becomes evident. Finally, after completion of the cap stage, the developing tooth germ then enters the bell stage. It is during the bell stage that the specialization of cells occurs (Moss-Salentijn and Hendricks-Klyvert 1990:167).

Once the tooth germ has progressed through all stages of development, mitotic activity within the inner enamel epithelium results in the differentiation of specialized cells that are essential in the further advancement of tooth development (Van der Linden and Duterloo 1976:4). These specialized cells are primarily responsible for the calcification of the hard tissues that comprise teeth, and are known as cementoblasts, odontoblasts, and ameloblasts. Cementoblasts within the tooth bud are responsible for the development of cementum, while odontoblasts and ameloblasts are responsible for the development of dentin and enamel, respectively (Moss-Salentijn and Hendricks-Klyvert 1990:166-167). However, it is important to note that while dentin and cementum are considered connective tissues and are thus influenced by the constant activity of cells throughout life, enamel is recognized as a secretion product of epithelium, or an “epithelial product” (Moss-Salentijn and Hendricks-Klyvert 1990:166, 179-181). As such, enamel is not considered a true tissue by clinical standards, and is therefore unable to repair itself from damages once formed.
Though dental development is relatively buffered against environmental influences in comparison to dental eruption, researchers have observed that nutritional stressors and diseases experienced while \textit{in utero} are likely to affect the tempo of dental mineralization. For example, Smith \textit{et al.} (1978:150-151) state that debilitating diseases, such as rubella, experienced while \textit{in utero} may cause “considerable disruption in dental development during the embryological period of life.” Such an observation is supported by the fetal origins hypothesis originally proposed by Barker in 1994 which asserts that conditions prevailing at or around the time of birth or early infancy are likely to impact health conditions and experiences during adulthood (Ellison 2005).

\textit{Patterning of Dental Development}

Once the mineralization process of dental development has begun, a predictable pattern of tooth formation can be observed. Tooth mineralization in growing children follows a structured pattern that can be divided into distinct and conveniently observable stages that span from the mineralization of the cusps of the central maxillary incisors of the deciduous dentition to the root apex closure of the third molars of the permanent dentition (Lewis 2007:39). The mineralization process of a human tooth always begins with the calcification of the crown or cusps. Soon after the development of the crown, the process of calcification continues with the formation of the root, and then is completed upon closure of the root apex. Figure 2.1 depicts various stages of dental development in the mandible and maxilla of a 7 year old male.
While there is significant variation in the amount of time it takes for each individual tooth to completely develop, it is generally accepted that a deciduous tooth takes approximately 2-3 years to develop while a tooth in the permanent dentition takes approximately 8-12 years to develop. Very few studies have involved the mineralization of teeth comprising the deciduous dentition as most of the development process of the deciduous dentition occurs prenatally. However, the mineralization of the permanent dentition is entirely postnatal, and therefore is relatively easy to observe by researchers (Smith 1991:145). Of the permanent teeth, the third permanent molars are considered to be the most variable and generally take the longest time to complete development (Scheuer and Black 2000:152; Hillson 2005:227).

The chronological development of the permanent dentition generally occurs in three phases (Schour and Massler 1941; Smith 1991:145). The first phase of
development involves the mineralization of the first permanent molar (M1) as well as the first permanent incisor, the second permanent incisor, and the canine (I1, I2, and C). These teeth begin to mineralize during the first year of life. The second phase occurs when the posterior teeth, the first and second premolars (P1 and P2) and the second permanent molar (M2), mineralize approximately between the ages of 2.0 and 4.0 years. The calcification of the third permanent molar (M3) is significantly delayed, and represents the third phase of dental development. The third permanent molar generally begins to mineralize approximately 5 to 6 years after the crown formation of the second permanent molar (M2) (Smith 1991:145). Table 2.1 depicts the chronological order for mineralization of teeth comprising the permanent dentition, and contains the approximate chronological ages (in years) for the completion of each phase of tooth development.

<table>
<thead>
<tr>
<th>Table 2.1: Chronology of Formation of the Human Dentition*</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Adapted from Smith (1991:144)</td>
</tr>
<tr>
<td>Tooth Type</td>
</tr>
<tr>
<td>M1</td>
</tr>
<tr>
<td>I1</td>
</tr>
<tr>
<td>I2</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>P1</td>
</tr>
<tr>
<td>P2</td>
</tr>
<tr>
<td>M2</td>
</tr>
<tr>
<td>M3</td>
</tr>
</tbody>
</table>

*Ages are approximate and are represented in years. Sources: Moorrees et al. (1963) and Anderson et al. (1976)
A Chronological Assessment of Dental Emergence

Though known to possess a more considerable amount of variation in timing than the process of dental mineralization, the process of dental eruption also follows a relatively predictable pattern and has been comparable to dental calcification in regard to sequence and patterning (Tompkins 1996:95). Therefore, it is beneficial to become familiarized with the general chronological sequence of tooth emergence in order to discuss the variation of timing in dental development that may be observable among populations.

Once calcified within the alveolar portion of the maxilla or mandible, the developed tooth then begins the process of emergence, or eruption. While dental development primarily refers to the manner in which hard tissues of the tooth calcify within the jaw, the process of dental eruption or emergence refers to “the movement by which a tooth advances from the alveolar crypt to its functional occlusal position in the mouth” (Scheuer and Black 2000:150). In other words, during the process of dental eruption, the mineralized tooth root forces the crown into a functional position in the oral cavity. The process of eruption is complete once the emerging tooth has occluded with the tooth above or below it (Gleiser and Hunt 1955:267).

As with the process of dental development, the process of dental eruption in regard to the permanent dentition can be described as occurring in three primary segments or waves of movement. During the first wave of emergence, the first permanent molars and the permanent central incisors become visible in the oral cavity. The first permanent molar does not possess a deciduous predecessor at its eruption site in the jaw, and therefore, emerges behind the existing deciduous second molar (Gleiser and
Hunt 1955:254). On the other hand, the permanent central incisors replace the existing deciduous central incisors. This first wave of emergence generally occurs between 6.0 and 8.0 years old (Scheuer and Black 2000:152).

Shortly thereafter, during the second wave of emergence, the permanent canines and premolars become visible in the oral cavity. While the permanent canines replace the existing deciduous canines, the erupting premolars take the place of the first and second deciduous molars. This wave of emergence typically occurs between the ages of 10.0 and 12.0 years (Scheuer and Black 2000:152). The final wave of emergence solely involves the eruption of the third permanent molars. The third molar is considered to be the most variable tooth in regard to development and emergence, and is also known to take the longest amount of time for completion. Nonetheless, most researchers generally acknowledge that eruption of the third molar is most likely to occur between the ages of 17 and 20 years (Scheuer and Black 2000:152). Rogers (1988:26) suggests that the delayed emergence of the permanent third molar is due to the likelihood that the third molar is considered to be “largely unneeded” as a result of its diminished function in the oral cavity. Rogers (1988:26) also suggests that due to the decrease in jaw size that has been noted to occur evolutionarily within the human species, the permanent third molar is typically forced into diminished space in the mouth. Therefore, this highly variable tooth may only erupt partially or may remain unerupted in the alveolar portion of the maxilla or mandible (Rogers 1988:26).
Standards for Age Estimation Utilizing Dental Development

Dental development is generally considered to be the most accurate method of aging performed for unknown nonadult individuals. Age estimations obtained utilizing dental mineralization stages are considered to be more accurate than age estimations determined by the eruption or emergence patterns of deciduous and permanent dentitions (Scheuer and Black 2000:153; Lewis 2007:38). Observations of postnatal mineralization patterns in children and adolescents have primarily been made with the analysis of radiographs depicting the various stages of dental development in growing children. In fact, several standards for dental development have been created through the performance of cross-sectional and longitudinal studies evaluating mineralization stages of living children in various modern populations (Scheuer and Black 2000:154). According to Klepinger (2006:44), studies of dental formation in living children of known ages yield the best results for the construction of standards for dental development as variations in mineralization patterns among populations and between sexes are better recognized. The mineralization of teeth is especially reliable for the age estimation of younger individuals, since development is best observed between birth and 14 years of age (Liversidge 1994:39; Lewis 2007:38-39).

Dental Mineralization Standards Devised by Moorrees et al. (1963)

One of the most recognized sets of standards for dental mineralization in the permanent dentitions of children is that of Moorrees et al. (1963). In this set of standards, Moorrees, Fanning, and Hunt (1963) defined stages of development for ten permanent teeth by utilizing intraoral radiographs and by noting the timing of crown
development, root development, and root apex closure for a sample of 246 living children of European ancestry. Data for this set of standards were collected from the Forsyth Dental Infirmary in Boston, Massachusetts.

According to Moorrees *et al.* (1963:1490-1491), physiologic age can be estimated by observing the thirteen developmental stages of the permanent mandibular canines and incisors, the thirteen developmental stages of the permanent maxillary canines and incisors, and the fourteen developmental stages of the permanent mandibular premolars and molars. The thirteen developmental stages for single rooted teeth evaluated by Moorrees *et al.* (1963:1493) include the six stages of crown development, the five stages of root development, and the two stages of apex development. Similarly, the fourteen developmental stages for multi-rooted teeth include the six stages of crown development, the single stage of initial cleft formation, the five stages of root development, and the two stages of apex development.

Tables 2.2 and 2.3 represent standards developed by Moorrees *et al.* (1963:1964-1965) for age estimation utilizing dental development for males and females respectively. The tables contain calculated mean ages for corresponding mineralization stage for each mandibular tooth. These tables are designed for the estimation of age based on the stage of tooth development, and are adapted from those presented by Smith (1991:159, 161). These tables are appropriate when attempting to determine what age should be assigned to an individual based on dental development. In utilizing Tables 2.2 and 2.3, each available tooth is assessed independently, and is assigned a corresponding age based on stage of development. The mean of all available ages is then calculated to estimate the dental age of an individual (Moorrees *et al.* 1963:1497; Smith 1991:159). Due to its
large sample size of 99 permanent teeth and age estimation of formation stages
determined for each individual tooth, the standards devised by Moorrees et al. (1963)
represent the most commonly implemented method of age estimation utilizing dental
development stages for nonadult individuals contained in the archaeological record
(Scheuer and Black 2000:158).

Nonetheless, despite the popularity of dental development standards devised by
Moorrees et al. (1963), the applicability of these standards has been re-evaluated by
researchers (Harris and Buck 2002; Philips and van Wyk Kotze 2009). A limitation
worth noting is that these standards have been developed utilizing a population of
children of European descent. Since it has been observed that, though resistant to most
environmental influences, the timing and sequence of mineralization patterns in the

<table>
<thead>
<tr>
<th>Table 2.2: Predicting Age from Stages of Development for Permanent Teeth - Males*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adapted from Smith (1991:161)</td>
</tr>
<tr>
<td>Tooth</td>
</tr>
<tr>
<td>Stage of Development</td>
</tr>
<tr>
<td>C₁</td>
</tr>
<tr>
<td>Cₚ₀₀</td>
</tr>
<tr>
<td>Cₚ₈₀</td>
</tr>
<tr>
<td>Cr₂/₃</td>
</tr>
<tr>
<td>Cr³/₄</td>
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<td>Cl₄/₅</td>
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<tr>
<td>R₃/₄</td>
</tr>
<tr>
<td>A₁/₂</td>
</tr>
<tr>
<td>A₃</td>
</tr>
</tbody>
</table>

*All teeth are mandibular. Ages are approximate and are represented in years. Source: Moorrees et al. (1963)
dentitions of children are likely to vary among ancestral populations (Loevy 1983:62), it cannot be assumed that the standards developed by Moorrees et al. (1963) will yield appropriate age estimations for all ancestral populations. For example, according to a study performed by Phillips and van Wyk Kotze (2009:23), the standards of Moorrees, Fanning, and Hunt (1963) consistently underestimated the ages of children of three different South African population samples (Tygerberg, Indian, and Zulu). According to Phillips and van Wyk Kotze (2009:23), the standards of Moorrees et al. (1963) are not appropriate for estimating ages for South African juveniles. The authors (Phillips and van Wyk Kotze 2009:23) recommend that careful consideration should be given to the categorization of ancestral descent when constructing a reference group for devising population specific standards.

Moreover, Harris and Buck (2002:17) also address another limitation of standards devised by Moorrees et al. (1963). The authors (Harris and Buck 2002:17) state that the standards of Moorrees et al. (1963) assign age based on the independent assessment of individual teeth, and therefore, do not take into consideration the statistical interrelationship of the tempo of tooth development between teeth. This statistical interrelationship can also be referred to as the total tooth variance, and refers to the dependent relationships of developmental stages among multiple teeth in the oral cavity. The authors (Harris and Buck 2002:17) consider this to be a limitation of the standards devised by Moorrees et al. (1963) since the “structure of tooth interrelationships has not been described in any detail” (Harris and Buck 2002:17), yet is known to vary among individuals and among populations (Tompkins 1996:94).
Dental Mineralization Standards Devised by Demirjian et al. (1973)

Similarly to those developed by Moorrees et al. (1963), Demirjian et al. (1973) also developed standards for age estimation utilizing dental development. According to the classification standards of dental development developed by researchers Demirjian, Goldstein, and Tanner (1973:220), stages of dental mineralization are rated on a scale consisting of eight stages with scores ranging from A-H. The authors constructed standards in which each of the eight stages is categorized utilizing detailed criteria that describe all observable characteristics of dental mineralization, including observations of

<table>
<thead>
<tr>
<th>Stage of Development</th>
<th>I1</th>
<th>I2</th>
<th>C</th>
<th>P1</th>
<th>P2</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
<td>2.0</td>
<td>3.3</td>
<td>0.2</td>
<td>3.6</td>
<td>9.9</td>
</tr>
<tr>
<td>C₉₀</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>2.5</td>
<td>3.9</td>
<td>0.5</td>
<td>4.0</td>
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<td>-</td>
<td>-</td>
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</table>

*All teeth are mandibular. Ages are approximate and are represented in years. Source: Moorrees et al. (1963)
cusp fusion and changes in the shape and size of the pulp chamber, rather than strictly tooth size. Stages A-D represent stages of crown formation in single rooted and multi-rooted teeth, while stages E-H represent stages of root formation and root apex closure for single rooted and multi-rooted teeth. Nonetheless, while Demirjian et al. (1973:217) recommend their standards for dental age estimation as a “valid measuring instrument for universal use,” several studies (Koshy and Tandon 1998; Blankenship et al. 2007) have since re-evaluated the applicability of universal age estimation standards for human populations of various geographic regions and ancestral descent.

**Dental Development Within Biological Anthropology**

For many years, anthropologists have been able to utilize components of the human dentition to provide insight into particular aspects of human evolution (Scheuer and Black 2000:148). Within biological anthropology, researchers have addressed two principal issues concerning human dental development that are likely to have considerable implications for paleoanthropology and forensic anthropology: the strong genetic influence in the timing and tempo of dental development, and the variability in the timing and tempo of dental development among human populations.

*Genetic Influence in the Timing and Tempo of Human Dental Development*

First, it is generally accepted that human dental development is “regulated to a significant extent by the action of genes” (Scott et al. 2000:2, 128). Due to the strong genetic component of tooth mineralization, it has been suggested that the process of tooth mineralization essentially occurs the same in all humans, in that “each tooth always
passes through the same stages in each individual” (Demirjian et al. 1973:213), with some latitude of variation. Unlike dental eruption, the timing of dental development is generally considered to be relatively buffered against the environmental factors that may delay the emergence of teeth. Additionally, due to the strong genetic component of dental development, it has been suggested that dental calcification is likely to be more of an accurate representation of genetic variation among human populations than patterns of dental eruption (Cardoso 2007:223).

Variation in Dental Development Among Human Populations

Many published dental development studies test the applicability of existing dental mineralization standards for age estimation, and compare the timing and tempo of dental development among populations of varying geographic regions and ancestral descent. While early research suggests that the patterning of dental development “will not vary very much in different populations” (Demirjian et al 1973:217), recent studies (Harris and McKee 1990:859; Tompkins 1996:76; Olze et al. 2004:74; Kasper et al. 2009:656) have suggested that ancestral descent may likely influence the timing and patterning of dental development among various populations, and that more research is necessary to further investigate to what extent genetic variation occurs.

Though anthropologists and the author of this thesis recognize that the social concepts of “race” and “racial categories” as they relate to skin color do not have a basis in human biology, many researchers seek to improve the accuracy of dental development standards in the estimation of age for living individuals of unknown age in contemporary populations or for unidentified skeletons within a forensic context. According to existing
literature (Harris and McKee 1990; Kasper et al. 2009), this improvement in the accuracy of age estimation standards can be achieved by evaluating whether or not differences in the timing of dental development among various human populations exist. However, while previous researchers have emphasized ancestral descent as a significant contributor for observed differences in the timing of dental development among human populations, it cannot be ignored that genetic admixture among perceived “racial” or ancestral groups complicates interpretations of genetic variation among populations (Madrigal and Barbujani 2007:20). Table 2.4 contains information for recently published comparative studies of dental development among various populations. Each study varies in the ancestral population observed, the age ranges of participants, and the dental arcade from which teeth are selected for analysis.

Nonetheless, despite the varying population samples evaluated, similar trends in human dental development are reported in many comparative studies. For example, similar findings concerning sexual dimorphism in the timing of molar development, as well as advanced timing of dental development in populations of Hispanic, Native American, and African descents are presented among the published studies. Table 2.5 contains a summary of the conclusions presented for each published dental development study, and further discussions of findings are presented below.

**Variation of dental development between sexes.** Many researchers (Gleiser and Hunt 1955:260; Moorrees et al. 1963:1494; Harris and McKee 1990:859) have observed that the process of dental development is sexually dimorphic, and that in many cases, females consistently achieve dental development stages earlier than their male
<table>
<thead>
<tr>
<th>Source</th>
<th>Population</th>
<th>Teeth Analyzed</th>
<th>Sample Size</th>
<th>Age Range (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fanning and Moorrees (1969)</td>
<td>Australian</td>
<td>Third molars</td>
<td>210</td>
<td>Not Specified</td>
</tr>
<tr>
<td>Moorrees et al. (1969)</td>
<td>American, European Descent</td>
<td>Permanent mandibular teeth</td>
<td>246</td>
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<td></td>
<td></td>
<td>Permanent maxillary incisors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demirjian et al. (1973)</td>
<td>French-Canadian</td>
<td>Permanent mandibular teeth</td>
<td>2928</td>
<td>2-20</td>
</tr>
<tr>
<td>Loevy (1983)</td>
<td>American, African Descent</td>
<td>Permanent Dentition</td>
<td>1085</td>
<td>2-15</td>
</tr>
<tr>
<td>Harris and McKee (1990)</td>
<td>American, European Descent</td>
<td>Permanent mandibular and maxillary teeth</td>
<td>665</td>
<td>3.5-13</td>
</tr>
<tr>
<td>Tompkins (1996)</td>
<td>American, African Descent</td>
<td>Permanent mandibular and maxillary teeth</td>
<td>335</td>
<td>3.5-13</td>
</tr>
<tr>
<td></td>
<td>South African</td>
<td>Permanent mandibular teeth</td>
<td>687</td>
<td>3-18</td>
</tr>
<tr>
<td>Prehistoric Native American</td>
<td>Permanent mandibular teeth</td>
<td>520</td>
<td>Not Specified</td>
<td></td>
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<td>French-Canadian</td>
<td>Permanent mandibular teeth</td>
<td>329</td>
<td>6-15</td>
<td></td>
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<tr>
<td>Willems et al. (2001)</td>
<td>Belgian, European Descent</td>
<td>Permanent mandibular teeth</td>
<td>2116</td>
<td>1.8-18</td>
</tr>
<tr>
<td>Bolaños et al. (2003)</td>
<td>Spanish</td>
<td>Permanent mandibular premolars and molars</td>
<td>786</td>
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<tr>
<td>Gunst et al. (2003)</td>
<td>Belgian, European Descent</td>
<td>Third molars</td>
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<td>15.7-23.3</td>
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<td>Blankenship et al. (2007)</td>
<td>American, African Descent</td>
<td>Third molars</td>
<td>637</td>
<td>14-24</td>
</tr>
<tr>
<td>Kasper et al. (2009)</td>
<td>American, Hispanic Descent</td>
<td>Third molars</td>
<td>950</td>
<td>12-22</td>
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Table 2.5: Conclusions for Published Dental Development Studies

<table>
<thead>
<tr>
<th>Source</th>
<th>Population</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kasper et al. (2008)</td>
<td>American, Hispanic Descent</td>
<td>Third molar development advanced in Hispanic populations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Males advanced in third molar development</td>
</tr>
<tr>
<td>Harris and McKee (1990)</td>
<td>American, European Descent</td>
<td>Females are advanced in dental development</td>
</tr>
<tr>
<td></td>
<td>American, African Descent</td>
<td>Advanced development in population of African descent.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Females are advanced in dental development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Males more advanced in third molar development.</td>
</tr>
<tr>
<td>Willems et al. (2001)</td>
<td>Belgian, European Descent</td>
<td>Evaluated overestimation of dental age utilizing Demirjian et al.’s (1973) method</td>
</tr>
<tr>
<td>Gunst et al. (2003)</td>
<td>Belgian, European Descent</td>
<td>Males advanced in third molar development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Earlier third molar development in maxilla than mandible</td>
</tr>
<tr>
<td>Bolaños et al. (2003)</td>
<td>Spanish</td>
<td>No sexual dimorphism evident in third molar development.</td>
</tr>
<tr>
<td>Demirjian et al. (1973)</td>
<td>French-Canadian</td>
<td>Suggests universal dental mineralization standards for age estimation</td>
</tr>
<tr>
<td>Moorrees et al. (1969)</td>
<td>American, European Descent</td>
<td>Sex differences pronounced in root development.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>None presented</td>
</tr>
<tr>
<td>Tompkins (1996)</td>
<td>South African</td>
<td>African population advanced in molar development over French-Canadian population</td>
</tr>
<tr>
<td></td>
<td>Prehistoric Native American</td>
<td>Native American population advanced in most stages of molar development over French-Canadian population</td>
</tr>
<tr>
<td></td>
<td>French-Canadian</td>
<td>French-Canadian females advanced in canine development over African females</td>
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</table>
counterparts in populations of European and African descent. However, this may not hold true for all teeth in the oral cavity, as recent studies (Gunst et al. 2003:54; Blankenship et al. 2007:428; Harris 2007:101; Kasper et al. 2009:651, 654) suggest that the permanent third molar begins and completes all stages of development at earlier ages in males than in females. For example, Kasper et al. (2009), Blankenship et al. (2007), and Gunst et al. (2003) found that males of Hispanic or African descent are considerably advanced in the timing of third molar development in comparison to females.

**Contemporary American populations of African descent.**

*Harris and McKee (1990).* In a study performed to “provide sex-specific standards for blacks and a regionally and economically comparable series for whites,” Harris and McKee (1990:860, 868) observed that individuals comprising a contemporary Middle Tennessee population of African descent attained advanced stages of dental development in teeth earlier than individuals comprising a contemporary Middle Tennessee population of European descent. According to the authors (Harris and McKee 1990:868), when utilizing standards of dental development devised by Moorrees *et al.* (1963), males of African descent are significantly advanced in comparison to males of European descent in the attainment of dental stages in 26% of comparisons. Similarly, females of African descent are significantly advanced in the achievement of dental development stages in 42% of cases (Harris and McKee 1999:868).

Harris and McKee (1990:868) also note that development is achieved earlier for later developing teeth in individuals of African descent than in individuals of European descent. In other words, for cases in which the developing tooth is among the last to
develop in a series, such as the maxillary canine and the third molar, advanced
development is statistically significantly earlier for children of African descent in
comparison to children of European descent. Also, advanced dental development in the
contemporary Middle Tennessee population of African descent is “proportionately
greater” in the initial stages of dental development, such as cusp mineralization and
crown formation, than in later stages of dental development, such as root formation and
closure of the root apex (Harris and McKee 1990:868). The authors (Harris and McKee
1990:868) state that in the earlier stages of tooth development, males of African descent
attain a formation stage “4% ahead” of males of European descent, and females of
African descent attain a formation stage “6% ahead” of females of European descent.

*Blankenship et al. (2007).* In a study intended to utilize dental development
standards devised by Demirjian *et al.* (1973) to assess the timing of third molar
development for American populations of African descent, Blankenship *et al.* (2007:428-
429) observed that individuals comprising a contemporary Middle Tennessee and
Arkansas population of African descent achieved the advanced stages of third molar
development at an earlier time than individuals of European descent. According to the
authors (Blankenship *et al.* 2007:430), though the timing of development of the third
molar is considered to be highly variable, individuals of African descent comprising the
research sample obtained stages of crown and root development “on average much
earlier” than individuals of European descent.

Additionally, both males of African and European descent were observed to be
completing root formation considerably earlier than females. The authors (Blankenship
Blankenship et al. (2007:430) report that males achieved this stage of third molar development about “three-quarters of a year earlier than females on average.” Finally, the authors also evaluated the likelihood of an individual being at least 18.0 years of age based on the stages of third molar development. Blankenship et al. (2007:430) report that a male of African descent who has attained the final stage of third molar development, or the closure of the root apex, has a 93.0% probability of being 18.0 years old, while a female of African descent who has attained the final stage of third molar development has an 84.0% probability of being 18.0 years old. Though the determination of social adulthood is ultimately defined by cultural or legal attributes (Kasper et al. 2009:652), this information can assist courts within The United States in determining the likelihood of whether or not an individual of African descent is legally considered a minor or an adult.

**Populations of African, French-Canadian, and Native American descent.**

Studies by Tompkins (1996:93) have also suggested that there is a significant amount of variation in dental development among ancestral groups. In a study comparing the age of attainment for advanced dental calcification stages among a “white French-Canadian” population, a “black Southern African” population, and a “prehistoric Native American” population (Tompkins 1996:80), significant relative variation in the timing of dental calcification was observed. According to Tompkins (1996:82-84), the timing of dental development in the African population was significantly advanced over the timing of dental development in the French-Canadian population. This variation in dental development was particularly observable in the first permanent molar and second permanent molar as advanced calcification stages of these teeth were attained earlier in
individuals of the African population. Similarly, Tompkins (1996:83) also notes that individuals within the Native American population reached advanced calcification stages of the first permanent molar and second permanent molar earlier than individuals comprising the French-Canadian population. However, while apparent differences in the tempo of dental mineralization were observable between the French-Canadian population and the African population, as well as between the French-Canadian population and the Native American population, it is worth noting that no significant differences in the timing of dental development for the first permanent molar and second permanent molar were observed between the Native American population and the African population (Tompkins 1996:83).

Furthermore, Tompkins (1996:83) observed that the most variable tooth to develop, the permanent third molar, exhibited the most variation in the timing of development among all three populations observed. In regard to the timing of development for the permanent third molar, Tompkins notes that development was significantly advanced among individuals of the African population in comparison to individuals of the French-Canadian population. Additionally, individuals of the African population also exhibited advanced stages of dental development of the permanent third molar earlier than individuals of the Native American population. However, discussions of comparisons of the timing of third molar development between the Native American population and the French-Canadian population were limited. Nonetheless, it is possible to infer based on the data presented by Tompkins (1996) that mineralization of the third molar also occurred earlier in members of the Native American population than in members of the French-Canadian population.
Contemporary Texas population of Hispanic descent. In a study intended to evaluate the accuracy of age estimation utilizing the third molar for a Texas Hispanic population, Kasper et al. (2009:652-653) note that individuals comprising a Texas Hispanic population achieved advanced stages of third molar development earlier than individuals comprising a contemporary population of European descent. According to the authors, when incorporating the dental age estimation standards of Demirjian et al. (1973), males and females of Hispanic descent consistently achieved latter stages of dental development, such as complete root length development and complete root apex closure, for third molars “8-18 months” earlier than males and females of European descent (Kasper et al. 2009:653). The authors also suggest that Texas Hispanic males achieve all observable mineralization stages of the third molar earlier than Texas Hispanic females (Kasper et al. 2009:656).

Due to the perceived variation in timing of dental development across populations, many researchers (Harris and McKee 1990; Blankenship et al. 2007; Kasper et al. 2009) call for the development of population specific standards that can be utilized to appropriately estimate age for individuals within various populations.

Explaining Dental Development Variability

Histological contributions to dental development variability. Since many researchers suggest that dental development has the potential to vary among populations, it is important to investigate possible hypotheses for how this variation may occur. While the process of dental development essentially follows the same histological pattern in all
humans, researchers have taken into consideration particular periods during dental
development in which variation in timing has the potential to occur. For instance, the
development of the human dentition is highly dependent on interactions between
principle components of the developing tooth germ (Moss-Salentijn and Hendricks-
Klyvert 1990:173). In order for further advancement of dental development to occur,
there must be communication between the epithelial and mesenchymal components of the
tooth germ during the stages of morphodifferentiation. These two tissues of the
developing tooth bud continuously interact with one another and progression through the
stages of tooth germ development proceeds once the mesenchyme secretes a product
across a boundary, known as the basil lamina. This mesenchymal secretion then signals
the epithelium to increase mitotic division and begin forming the shape of the tooth
(Moss-Salentijn and Hendricks-Klyvert 1990:173). Though it is not fully understood to
what extent and in what capacity this stage of dental development may contribute to the
variation in tempo of dental development across human populations, it is known that this
signaling process is an important part of initial tooth development as mineralization
cannot occur until epithelial receptors are triggered by these mesenchymal secretions.
Figure 2.2 depicts a developing tooth germ of a human embryo.
Evolutionary contributions to dental development variability. Though several researchers acknowledge an apparent difference in the timing of dental development among populations, very few studies propose explanations or hypotheses as to why this variation in the tempo of dental calcification among human populations may occur. Tompkins (1996) is among one of the few researchers to provide potential hypotheses to explain the possible variation in the timing of dental development that is observed among ancestral groups. According to Tompkins (1996:95-97), there are two hypotheses that pose potential explanations for the differences in timing of dental development between populations of European and African descent. Tompkins (1996:97) asserts that the
following hypotheses are “potentially falsifiable,” and recommends that these hypotheses be tested by researchers in future comparative studies.

*Hypothesis #1: jaw size.* The first hypothesis Tompkins (1996:95) proposes relates the rate and timing of dental development to jaw size among individuals of African descent. This hypothesis states that “an interplay between tooth and jaw size determines the relative and absolute timing of dental calcification and eruption, and the frequency of third molar agenesis” (Tompkins 1996:95). In other words, Tompkins (1996:95) suggests that populations that have been found to have larger relative jaw sizes experience earlier attainment of dental calcification stages for later developing teeth, specifically permanent third molars, than populations with smaller relative jaw sizes. According to Stringer et al. (1990:121), individuals of African descent typically exhibit larger relative jaw sizes than individuals of European descent. In support of this observation by Stringer and colleagues (1990:121), Tompkins (1996:95) hypothesizes that since individuals from populations of African descent have larger jaws, there is more adequate space to facilitate developing and erupting teeth. As a result, Tompkins (1996:95) suggests that populations of African descent are likely to experience dental calcification stages earlier than populations of European descent.

*Hypothesis #2: correlation with skeletal development.* Tompkins (1996:96) also suggests that, by evaluating the genetic skeletal and dental growth potential that members of each population possess, researchers are able to gain insight into why the rate of dental development may vary between populations of European descent and populations of
African descent. The second hypothesis Tompkins (1996:96) proposes compares advanced dental development to evidence of advanced skeletal development that has previously been observed in populations of African descent (Masse and Hunt 1963). According to previous research (Masse and Hunt 1963:15), the rate and timing of initial skeletal development is advanced in populations of African descent in comparison to populations of European descent. However, due to its high level of plasticity and its vulnerability to environmental stressors, such as poor nutrition and disease, the skeletal development of growing children in populations of African descent may not necessarily follow a consistent rate of growth and development throughout the growth period. Therefore, Tompkins (1996:96) suggests that children of African descent may not consistently exhibit an advanced pattern of skeletal growth and development in comparison to the skeletal development of growing children of European descent.

Nonetheless, Tompkins (1996:96) states that the advanced relative molar development observed in populations of African descent “is a genetic correlate of the potential for advanced skeletal development.” This hypothesis follows the theory presented by Tanner (1990) that children of African descent have reached a maturational stage at birth that children of European descent may reach at a later time. Therefore, children of African descent possess an advanced genetic potential for dental and skeletal development in comparison to children of European descent (Tompkins 1996:96). Since dental development is relatively buffered against environmental factors that may otherwise influence skeletal growth and development, Tompkins (1996:96) suggests that dental development is more likely to accurately represent the physical expression of genetic potential than growth and development of skeletal elements. As a result of this
physical expression of advanced genetic potential, dental mineralization stages are likely to be attained earlier in children of African descent than in children of European descent (Tompkins 1996:97).

**Limitations in the Comparison of Dental Development Among Populations**

While many published authors claim to observe differences in the timing and tempo of dental development among populations, there are many limitations to existing comparative studies of dental development that negatively impact the validity of published results. For example, results included in published literature on the estimation of age in juveniles utilizing the mineralization patterns of teeth vary according to the geographic location of the sampled population, the sample size, and the researcher’s methodology of recording (Scheuer and Black 2000:152). For instance, the categorization and assignment of dental development attainment stages vary considerably among researchers and among published studies as some researchers (Moorrees et al. 1963:1492-1493) identify 13 or 14 observable stages of dental development, while other researchers (Köhler et al. 1994 in Gunst et al. 2003:53) may define 10 or 8 (Demirjian et al. 1973:220) observable stages. In addition to the incorporation of arbitrarily defined dental development stages, several researchers (Millard and Gowland 2002:199; Konigsberg et al. 2008:541-542) suggest that errors in statistical analyses also contribute to inaccurate results for which many authors claim are representative of inter-population variation in dental mineralization. As a result, Hoppa and FitzGerald (1999:6) suggest that much of the population variation in the timing of dental development that has been observed by researchers is not an accurate representation of intra- or inter-population
variability, but rather a result of “methodological inconsistencies” that have been implemented during the data collection and analysis stages of each study.

**Intra-population variability.** While physical anthropologists have suggested that metric and non-metric characteristics of human teeth can exemplify human variation and can be utilized to differentiate between geographic populations, little research has been conducted to address the manner in which intra-population variation in dental development may be evident between geographic regions of a single population (Hanihara and Ishida 2005). However, according to Kittles and Weiss (2003:37), geographic distance within a single population may account for more genetic variation than assessments of genetic variation attributed to “categories.” Kittles and Weiss (2003:37) assert that genetic variation can occur within a single geographic population for the historic reasons of “drift, selection, and demographic history.” Furthermore, Jorde and Wooding (2004; In Madrigal and Barbujani 2004:24) state that correlations between genetic data and traditional classifications of “race” are imperfect due to the fact that “variation is distributed in a continuous and overlapping manner among populations”. Therefore, it is reasonable to hypothesize that much of the perceived variation in dental development among human populations that is discussed in published literature is actually representative of within population variation, rather than of genetic variation among ancestral populations.

**Defining populations.** A significant limitation in existing studies of dental development among populations is that researchers frequently construct arbitrary
classifications of ancestral groups. Most early comparative studies of human dental mineralization stages sought to compare the timing of dental development among pre-defined “racial” categories rather than ancestral groups or populations (see Garn et al. 1965; Loevy 1983; Harris and McKee 1990; Kasper et al. 2009). Authors often declare certain physical attributes or surnames as appropriate indicators of a pre-defined “racial” group. Researchers then attribute these components to the construction of racial categories for research samples. For instance, Harris and McKee (1990:860) categorized “race” for individuals included in two contemporary Middle Tennessee samples by evaluating “cultural criteria and physical appearance.” Individuals comprising the sample were subjectively classified as either American white or American black (Harris and McKee 1990:860).

Similarly, Kasper et al. (2009:652) determined Hispanic ancestry of individuals comprising a contemporary Texas Hispanic sample by assessing the surname of unmarried individuals, as well as by assessing the parents’ names of married individuals. However, “racial” categories are problematic in anthropological research studies as they lack biological significance, and are of little significance to biological anthropologists. Therefore, it is recommended that ancestral descent, rather than “racial” categories, be taken into consideration when planning and performing comparative dental development studies.

Construction of reference populations. A reference population, as defined by Konigsberg and Frankenberg (1992:237) refers to a sample that “provides reference
information on age development” for the sample of unknown individuals, or the target sample, for which age estimations will be applied.

Logan and Kronfeld (1933) are credited with contributing to the earliest efforts to create chronological standards for juvenile dental development. Logan and Kronfeld (1933:418-421) assembled a schedule for the mineralization of deciduous and permanent dentitions from birth to 15.0 years of age. Smith (1991:147) notes that this chronological schedule of dental development is of historic significance since it “forms the basis” of future dental development standards. Nonetheless, Smith (1991:147) criticized the accuracy and applicability of early dental development charts devised by Logan and Kronfeld, since the researchers (1933:394) constructed their results from a small sample size of only 20 individuals who suffered from debilitating diseases and possessed pathological cleft palates. These factors may have influenced the timing of tooth development. However, Hillson (2005:225) suggests that the standards devised by Logan and Kronfeld (1933), though devised primarily from children possessing various pathologies, may be more applicable for estimating the dental age of the remains of children comprising archaeological death assemblages than standards devised from the radiographs of healthy children, as children recovered from an archaeological context are likely to have died from debilitating diseases.

While Logan and Kronfeld (1933) are credited with contributing chronological standards of dental development, Schour and Massler (1941) provided the first notable publication of dental mineralization as an accurate age assessment method in juveniles. The charts devised by Schour and Massler (1941:1154) depict the various stages of dental development for juveniles, and were considered the standard for several years (Smith
1991:146). However, though generally accepted among dentists and scholars of anthropology, Smith (1991:147) criticized these charts as it was noted that Schour and Massler (1941) failed to provide sources of information from which the charts were devised. Later, Ubelaker (1978:46) adapted charts devised by Schour and Massler (1941) to include larger standard deviations as well as data from a sample of American Indian individuals (In Klepinger 2006:45-46).

**Selection of teeth for analysis.** Many dental age estimation standards and comparative studies of dental development among populations differ in the selection of teeth incorporated within each analysis.

*Mandibular teeth vs. maxillary teeth.* In the case of popular standards, such as those devised by Moorrees et al. (1963), most measurements have been determined by mandibular teeth, and are therefore not practical for forensic cases in which only maxillary teeth are available. Furthermore, several researchers advise against the use of maxillary incisor standards determined by Moorrees et al. (1963), as these standards only include values after the age of 4 years old (Scheuer and Black 2000:158-159; Klepinger 2006:45). Nonetheless, Smith (1991:161) reworked the charts devised by Moorrees et al. (1963) so that each tooth can be assessed independently, thus making the charts more applicable to individual teeth found in the forensic context (see Tables 2.2 and 2.3).

*Dental arcades and symmetry.* Many comparative studies of dental development differ in the selection of which half of the dental arcade is utilized for analysis, and many
researchers continue to provide conflicting evidence for whether or not symmetry in the timing of dental mineralization is present between right and left halves of the dental arcade. For example, according to Bolaños et al. (2003:218), the presence of symmetry in human dental development is “well known,” as several researchers (Demisch and Wartmann 1956:465; Blankenship et al. 2007:429) note that a high degree of symmetry is present in the development of third molars between the right and left halves of the dental arcade. Therefore, it can be understood why authors such as Harris and McKee (1990:860) choose to score teeth from “either the left or right side” for the purpose of their analyses.

On the other hand, after performing a cross-tabulation, Kasper et al. (2009:655) observed that antimere third molars exhibited the same stage of development in less than 33.0% of their research sample. According to the authors (Kasper et al. 2009:655), these results suggest that symmetry in the development of third molars between corresponding halves of the dental arcade cannot always be assumed, and that each half should be “evaluated independently.”

**Ordinal scoring and inter-observer variation.** Due to its inherent subjectivity, the popular method of observing and scoring dental mineralization stages is often considered a limitation in many dental development studies. According to Cardoso (2007:434), “subjective assessments of fractional stages of dental development” have the innate potential to influence accurate comparisons of the timing and tempo of dental development among ancestral and geographic populations. Nonetheless, several researchers (Dhanjal et al. 2006:S75; Kasper et al. 2009:653) suggest that inter-observer
variation does not account for a significant amount of variation observed in the timing of
dental development among populations, and that standards utilizing clearly defined and
fewer stages of dental development provide better reproducibility. Additionally, Baccino
et al. (1999:936) suggest that the accuracy and reliability of an observer’s assessment of
skeletal and dental indicators of age are likely to increase as the observer’s experience in
evaluating skeletal and dental indicators of age increases, and that further studies of
dental age estimations should focus on repeatability tests.

However, Kimmerle et al. (2008:597) state that observer experience is only “part
of the picture,” and that the apparent morphological variation of dental and skeletal
elements frequently utilized to estimate age accounts for much of the variation among
observers in assigning ordinal stages. Though research performed by Kimmerle et al.
(2008:597) emphasizes the “range of morphology” for skeletal indicators of age as
having significant influence in inter-observer variation, a similar parallel can be inferred
in the scoring of dental development stages as dental development stages are often
assigned based on drawings that do not necessarily account for the continuous nature of
dental development, or the possibility of transitional stages between pre-defined stages
(Smith 1991:145).

**Statistical biases in dental age estimation.** Many studies attempt to compare the
timing and tempo of dental development among populations by utilizing inappropriate
statistical tests that may misleadingly portray strong statistically significant results. In
other words, according to Konigsberg and Holman (1999:265), it is imperative that the
entire age distribution of a comparative sample be implemented in hypotheses tests,
rather than distributional information surrounding the mean and median. By using the entire age distribution of reference and target populations, researchers are more likely to gain more accurate inferences in regard to dental age estimation. On the other hand, by relying on results facilitated by distributional information, such as results obtained from the comparison of mean and median ages, researchers gain a “false sense of statistical power about statements based on that age” (Konigsberg and Holman 1999:265).

For example, Kasper et al. (2009:653, their Table 3) rely on students’ t-tests to compare the mean ages for third molar development of a Texas Hispanic population with the mean ages for third molar development of a North American population of European descent. From these comparisons of mean age of attainment, the authors conclude that individuals of Hispanic descent are generally experiencing advanced third molar development in comparison to individuals of European descent (Kasper et al. 2009:656). Likewise, Harris and McKee (1990:860) implemented similar analyses in comparing the timing of dental development between a contemporary Middle Tennessee population of European descent and a contemporary Middle Tennessee population of African descent by performing one-way analyses of variance (ANOVA) to compare mean ages of attainment for dental development stages based on tooth, sex, and ancestral descent. Based on their comparisons, the authors (Harris and McKee 1990:868) concluded that individuals of African descent are generally experiencing advanced dental development over individuals of European descent. However, the results of such studies in which mean ages of attainment comprise the basis for comparison between populations may be inaccurate as entire age distributions of reference and target populations are not taken into consideration.
Similarly, in order to accurately estimate ages of individuals in target populations, it is necessary to take into consideration the categorical structure of age, and the relationship between ages and ordinal stages of dental development. For example, due to the variation in age of attainment for dental development stages among individuals, it is not feasible to infer an exact chronological age from the observation of dental mineralization stages since the attainment of any given mineralization stage is not perfectly correlated with age (Konigsberg and Holman 1999:268; Millard and Gowland 2002:199). Furthermore, while the age at which children may attain a particular stage of dental development varies, the duration of time for which a child may remain in that stage of dental development will also vary considerably from child to child. Therefore, the ubiquitous implementation of ordinal scoring methods when observing stages of dental mineralization also poses problems for statistical analyses by generating age distributions rather than exact, chronological ages (Konigsberg and Holman 1999:268).

An additional bias in existing dental age estimation studies is the implementation of regression analyses in relating ages of attainment with particular stages of dental mineralization. According to Aykroyd et al. (1997:260), a regression analysis is “a means of establishing a relationship, expressed as a mathematical equation \( y = ax + bx + e \) between variables which are thought to be related.” In studies of dental age estimation, it may seem plausible to perform a simple linear regression analysis in order to assess the relationship between two variables, \( x \) and \( y \). In such analyses, a reference population is utilized to construct a regression equation in which the variable \( x \) represents the age indicator, or stage of dental development, and the variable \( y \) represents the age. However, according to Bocquet-Appel and Masset (1982), utilizing regression analyses
to estimate age by plotting ages of attainment against ordinal stages of dental mineralization is problematic as the age distribution derived for the target population is partly dependent on the age distribution of the reference sample used as a standard. In other words, the execution of a regression analysis to estimate age for individuals in a target population relies on the “fundamental assumption” that the age distribution of the target sample is the same as the age distribution of the reference population (Millard and Gowland 2002:200). As a result, age estimations for the target sample will be biased in the direction of the composition of the known-age reference sample used as a standard (Boldsen et al. 2002:77). This problem of “age mimicry” results in inaccurate age estimations for unknown individuals in the target sample as the ages of younger individuals in the target sample are overestimated, and the ages of older individuals in the target sample is underestimated (Aykroyd et al. 1997:261; Boldsen et al. 2002:77).

For example, results from dental age estimation studies such as those performed by Koshy and Tandon (1998), in which a simple linear regression was utilized to estimate age for a population of South Indian children, may be misleading as there is an inherent bias in the authors’ statistical methods. For their study, Koshy and Tandon (1998:75-76) scored the dental development stages of 7 mandibular teeth from 184 South Indian children utilizing dental development standards devised by Demirjian et al. (1973). The authors then performed a regression analysis with chronological age as the independent variable, and the stage of dental development as the dependent variable. Upon performing a simple linear regression analysis, Koshy and Tandon (1998:78) observed that utilizing dental age estimation standards devised by Demirjian et al. (1973) for a population of South Indian children resulted in the overestimation of age for both males
and females. While the authors (Koshy and Tandon 1998:84) suggest that the results of their study emphasize the inaccuracy of standards devised by Demirjian et al. (1973) and the need for population specific dental age estimation standards, the inherent biases in the authors’ methodology should not be ignored. The authors’ (Koshy and Tandon 1998:94) results are an example of age mimicry, in which the age estimations of the South Indian individuals in the target population are biased in the direction of the known ages of individuals comprising the Demirjian et al. (1973) reference sample. To accurately compare the timing and patterning of dental mineralization across contemporary populations, researchers must take population age structure into consideration and remove inherent biases in statistical modeling that result in age mimicry.

An additional example of age mimicry inherent in comparative dental development studies is that of Kasper et al. (2009). Results from a comparative study of third molar development in a contemporary Texas Hispanic population performed by Kasper et al. (2009) suggest that third molar development is significantly more advanced in a Texas Hispanic population than in a contemporary population of European descent (Kasper et al. 2009:656). However, the authors (Kasper et al. 2009:652) neglect to consider an appropriate age structure of the target population, and instead focus the “target age range by limiting the subject maximum to 22 years” and “concentrate a higher percentage of subjects in the 16-19 year age groups”. This choice in sampling is likely to have significant implications on results of the comparative study, and may not appropriately represent accurate timing of dental development for the target population.
Bayesian Analysis for dental age estimation

Due to the statistical biases inherent in existing dental development studies, several researchers (Konigsberg and Frankenberg 1992; Buck et al. 1996; Aykroyd et al. 1999; Hoppa and Vaupel 2002; Millard and Gowland 2002; Konigsberg et al. 2008) suggest that appropriate age estimation for archaeological and skeletal material requires the utilization of Bayesian analysis. According to Buck et al. (1996:xvii), the Bayesian approach to analyzing data permits the “incorporation of relevant prior knowledge or beliefs,” and therefore facilitates a more comprehensive interpretation of the data. In other words, Bayesian analysis is unique in that, within a single analysis, researchers are able to combine their “present understanding of a problem” with the “data [that] bear (sic) on that problem” (Buck et al. 1996:2). Though frequently implemented in other fields of forensic science and in disciplines outside of anthropology, only recently has the interpretational impact of the Bayesian approach to statistical analysis been taken into consideration in studies within bioarchaeology and forensic anthropology (Konigsberg et al. 2006:319).

In support of the incorporation of Bayesian analysis in studies of physical anthropology, Hoppa and Vaupel (2002:2) strongly encourage a shift in theoretical framework among researchers, termed the “Rostock Manifesto.” The “Rostock Manifesto” calls for new directions in osteological and dental research in which researchers are encouraged to devise more accurate standards of age estimation utilizing Bayes’ theorem, and by taking into consideration “more vigorously validated age indicator stages that relate skeletal morphology to known chronological age” (Hoppa and Vaupel 2002:2). Due to the genetic influence, mineral component, and relative durability
of human dentitions, the principles of the Rostock Manifesto also appropriately apply to
the evaluation of tooth mineralization stages.

Hoppa and Vaupel (2002:2-3) outline four major recommendations for accurate
paleodemographic research that comprise the “Rostock Manifesto”. The four major
recommendations are discussed below:

1. Authors must strive to develop more reliable and vigorously validated skeletal and
dental age indicators that correlate well with known chronological age.

2. Researchers within the disciplines of anthropology, paleodemography, and statistics
must strive to develop statistical models to estimate Pr(c|a), or the probability of
observing a suite of skeletal or dental characteristics, c, given known age, a.

3. Osteologists should realize that Pr(a|c) is of particular interest to paleodemographic
research, since Pr(a|c) represents the probability that an individual died at age a, given
the evidence regarding c, the characteristics of the skeletal remains. The probability,
Pr(a|c) is not the same as the probability of Pr(c|a), as the latter is known from
reference samples. Instead, Pr(a|c) must be calculated utilizing Bayes’ theorem from
Pr(c|a). Information concerning f(a), the probability distribution of ages-at-death in
the target population of interest, must also be obtained.

4. Therefore, f(a) must be estimated prior to the estimation of Pr(a|c). In order to
estimate f(a), a model is necessary to determine the manner in which the likelihood of
death varies with age. Additionally, a method is necessary to relate empirical
observations of skeletal characteristics in the target population to the probability of
observing the skeletal characteristics in this population. The empirical observations
will generally consist of the counts of numbers of skeletons that are classified into
each of the stages or categories, c.

Furthermore, Konigsberg et al. (2008:542) emphasize that many studies within
biological anthropology have focused on the need for population specific standards;
however, few of those studies perform statistical analyses that take the underlying age
structure of the target population into consideration. Intuitively, one can understand that
the more prior knowledge that is had about a research sample, the more accurate are the
results of subsequent analyses. Therefore, Konigsberg et al. (2008:542) recommend the
Bayesian approach to facilitate the inclusion of this prior knowledge, or population age
structure, as this information will likely have a positive interpretational bearing on the analysis of collected dental development data.

According to Buck et al. (1996:20), Bayes’ theorem formalizes the relationship among three primary components: the prior probability, the likelihood, and the posterior probability. The prior probability, which is mathematically expressed as $Pr(\text{parameters})$, represents the prior information about the values of the parameters before new data is analyzed. The likelihood, which is mathematically expressed as $l(\text{parameters}|\text{data})$, introduces the new data into the analysis. Finally, the posterior probability, which is mathematically expressed as $Pr(\text{parameters}|\text{data})$, represents a combination of the data and the prior information. The posterior probability “represents the results of Bayesian analysis” (Buck et al. 1996:20). Therefore, Buck et al. (1996:21) succinctly state Bayes’ theorem as follows: “the posterior probability is proportional to the likelihood times the prior probability” (Buck et al. 1996:21). This statement can be mathematically written as

$$Pr(\text{parameters}|\text{data}) \propto l(\text{parameters}|\text{data}) \times Pr(\text{parameters}).$$

In cases of dental age estimation, researchers utilizing a Bayesian approach will consider a population’s age structure as a prior, and will construct a mathematical model that will calculate the posterior probability of an individual being a certain age, given the observable stage of dental development. For instance, Millard and Gowland (2002:200) implement a Bayesian approach in the analysis of dental development for an archaeological sample of Anglo-Saxon and Roman skeletons excavated from 10 cemeteries located in Oxfordshire and Hampshire, England. For their analysis, the
authors implement Bayes’ theorem by posing the mathematical model \( Pr(A|I) \propto l(I|A) \times Pr(A) \), where A = age, and I = age indicator, or dental development stage. The authors applied a similar Bayesian approach to the analyses of tooth wear data of the same Anglo-Saxon population. By incorporating Bayesian approaches into their analyses of dental development and toothwear data, Millard and Gowland (2002:206) were able to provide more accurate confidence ranges for age estimations.

**Transition analysis for dental age estimation.** Researchers in bioarchaeology and paleodemography have often sought to implement a method of age estimation that is appropriate for the estimation of age for individuals comprising small sample sizes, and that takes into consideration the age structure of the known-age population. Boldsen et al. (2002:74) note that senescent changes in skeletal structures, such as the pubic symphysis and cranial sutures, are particularly useful in the estimation of age of adult skeletons. However, it is well known that while the sequence of transitions for stages of osteological development is fixed, the timing of senescent or degenerative changes in the skeleton essentially varies among individuals. Therefore, Boldsen and colleagues (2002:74) propose “transitional analysis” as an applicable method of estimation that allows researchers to make inferences about the timing of transitions from one stage of osteological development to the next. Unlike traditional methods of age estimation, results of transitional analyses produce the probability that death occurred at each possible age, rather than the single age at which death was most likely to have occurred (Boldsen et al. 2002:93). Therefore, supporters of transition analysis argue that graphical representations of probability density distributions produced by transition analyses
provide a more accurate estimation of an individual skeleton’s age at death rather than a single point age estimate.

Though Boldsen et al. (2002:74) emphasize the applicability of transition analysis on stages of senescence in adult skeletons, the authors assert that the method can be used with any skeletal trait that can be “arranged into an invariant series of stages,” and can be applied “equally well to the skeletons of young people.” Therefore, the statistical method of transition analysis can be beneficial to the estimation of age of young adults utilizing stages of dental mineralization.
CHAPTER 3: MATERIALS AND METHODS

Research Goals

The primary research goals of this study are as follows:

1. To compare the timing and tempo of dental development between a contemporary Florida population sample and a contemporary Middle Tennessee population sample utilizing statistical methods in Bayesian analysis.

2. To determine whether or not the perceived differences in timing and tempo of dental development among contemporary populations are the result of statistical biases or inappropriate statistical analyses, rather than a reflection of inter-population variation of human dental calcification.

3. To assess the accuracy of age parameters devised by Moorrees et al. (1963) on a contemporary Florida population sample.

4. To assess the need for population specific standards in dental age estimations.

A Bayesian approach is utilized to compare the timing and tempo of dental development between two contemporaneous geographic populations of the Southeastern United States: a Florida population sample and a Middle Tennessee population sample. Additionally, a Bayesian approach is also utilized to assess the accuracy of dental development age parameters devised by Moorrees et al. (1963) for a Florida sample. By incorporating a Bayesian approach, inherent statistical biases in methods of classical statistical analyses will be removed, resulting in a more accurate representation of dental development variability. The results of this study will be useful in assessing the need for population specific standards in dental age estimations.
Research Setting and Description of Data

Data collection for this study was performed during the summer of 2009 at the dental office of Dr. Barry Lipton in Largo, Florida. Dr. Lipton serves as the Chief Forensic Odontologist for District Six in Pinellas County, Florida, and provided access to the dental records of research participants. Dr. Lipton also supervised the collection of data for this research project. An approval to conduct this research was not needed from the Institutional Review Board (IRB) since identifiable information linking the identities of the participants to the data collected was not obtained.

Longitudinal and cross-sectional data were collected from the dental records of 90 juveniles and young adults. Cases were randomly selected. Cases for which dental development data were missing from two or more teeth were eliminated from the sample, resulting in a sample size of 81 individuals. This sample includes 34 males and 47 females, ranging in age from 7.7 years to 20.4 years. Radiographs observed for this study were shot between 1998 and 2009, and dental development data were obtained for each individual utilizing panoramic and periapical radiographs. All teeth were scored by Dotson.

Additional comparative data previously collected by researchers were also obtained for a comparative analysis. Drs. Edward F. Harris and Joy H. McKee observed the dental records of 684 individuals at The University of Tennessee College of Dentistry in Memphis, Tennessee. Drs. Harris and McKee obtained cross-sectional data from 144 females of African ancestry, 143 males of African ancestry, 233 females of European ancestry, and 164 males of European ancestry. According to the authors, the classification of “race” for research participants was based on “cultural criteria and
physical appearance” (Harris and McKee 1990:860), and research participants were not given the opportunity to provide self-identifications of “race”, ethnicity, or ancestral descent. The age range of individuals of African ancestry within this sample is 3.8 years to 18.7 years, while the age range of individuals of European ancestry within this sample is 5.5 to 22.6 years. These data were analyzed for the 1990 publication of Tooth Mineralization Standards for Blacks and Whites from the Middle Southern United States in The Journal of Forensic Sciences (Harris and McKee 1990).

Table 3.1 provides a summary of the sample and subsample populations included in this thesis, while Figures 3.1 and 3.2 depict the complete age distributions of the contemporary Florida sample and the complete contemporary Tennessee sample, respectively. Figure 3.3 depicts the age distribution of the Tennessee subsample of European descent, while Figure 3.4 depicts the age distribution of the Tennessee subsample of African descent. Table 3.2 provides descriptive data for each population.

<table>
<thead>
<tr>
<th>Ancestry</th>
<th>Region</th>
<th>Age Range (years)</th>
<th>Females (n)</th>
<th>Males (n)</th>
<th>Total</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>African Descent</td>
<td>Middle Tennessee</td>
<td>3.8-21.2</td>
<td>144</td>
<td>143</td>
<td>287</td>
<td>Harris and McKee (1990)</td>
</tr>
<tr>
<td>European Descent</td>
<td>Middle Tennessee</td>
<td>5.2-24.7</td>
<td>233</td>
<td>164</td>
<td>397</td>
<td>Harris and McKee (1990)</td>
</tr>
<tr>
<td>Unknown</td>
<td>Florida</td>
<td>7.7-20.4</td>
<td>48</td>
<td>34</td>
<td>81</td>
<td>Dotson (2009)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Population</th>
<th>n</th>
<th>Mean Age</th>
<th>Median</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Florida Males</td>
<td>34</td>
<td>15.69</td>
<td>16.03</td>
<td>3.2</td>
</tr>
<tr>
<td>Florida Females</td>
<td>47</td>
<td>16.13</td>
<td>16.28</td>
<td>2.64</td>
</tr>
<tr>
<td>Males</td>
<td>307</td>
<td>12.05</td>
<td>11.24</td>
<td>3.99</td>
</tr>
<tr>
<td>Females</td>
<td>377</td>
<td>12.28</td>
<td>12.08</td>
<td>3.92</td>
</tr>
</tbody>
</table>
Figure 3.1: Age Distribution of Contemporary Florida Population

Figure 3.2: Age Distribution of Contemporary Middle Tennessee Population
Figure 3.3: Age Distribution of Contemporary Middle Tennessee Population of European Descent

Figure 3.4: Age Distribution of Contemporary Middle Tennessee Population of African Descent
Methods of Data Collection

Moorrees et al. (1963) as Contemporary Age Parameters

According to Harris and Buck (2002:15), dental age parameters devised by Moorrees et al. (1963) continue to be widely used despite the ancestral limitations of individuals comprising the sample, and the possibility of secular changes resulting in the acceleration of human dental calcification for modern people. Though Moorrees, Fanning, and Hunt began collecting data in the 1930s, Harris and Buck (2002:15) acknowledge that “the long absence of comparable data from other groups” has contributed to the continued acceptance for the utilization of age parameters devised by Moorrees et al. (1963) as contemporary standards. Therefore, due to the lack of availability for more recent, widely accepted age parameters for dental age estimation, this thesis accepts age parameters devised by Moorrees et al. (1963) as the most recent dental age parameters that are available and representative of a contemporary population.

Sample Population 1: Contemporary Florida Sample

Teeth for the contemporary Florida sample were documented utilizing the universal dental numbering system. Dental development stages of permanent maxillary and mandibular teeth on both sides of the oral cavity were observed and assigned mineralization stages according to the classification standards devised by Moorrees et al. (1963). Maxillary molars and premolars were not recorded due to the difficulty in utilizing radiographs to observe stages in root development. Maxillary incisors, maxillary canines, mandibular incisors, mandibular canines, and mandibular premolars were assigned scores ranging from 1-13, while maxillary third molars and mandibular
molars were assigned scores ranging from 1-14. The additional development stage attributed to multi-rooted teeth accounts for one stage of initial cleft development that is otherwise not observable in single rooted teeth. Each root of multi-rooted teeth was assigned a score since it cannot be assumed that development is symmetrical among multiple roots of the same tooth. Table 3.3 represents the thirteen observable mineralization stages of single rooted teeth, such as incisors, canines, and mandibular premolars, as devised by Moorrees et al. (1963). Similarly, Table 3.4 represents the fourteen observable mineralization stages of multi-rooted teeth, such as molars, as devised by Moorrees et al. (1963). Each tooth was assigned a score according to the most advanced observable stage.

Research participants were selected at random from available panoramic periapical radiographs of individuals between 5.0 and 25.0 years old. Ancestral data were not available for individuals comprising the contemporary Florida population; however, this is not considered a limitation since analyses for this thesis seek to compare differences in the timing of dental development between two geographically similar populations and do not consider ancestral descent as a variable. Additionally, it is unknown whether individuals included in the contemporary Florida sample may have possessed pathological conditions or diseases that may have had the potential to adversely affect the timing and tempo of dental development.
Table 3.3: Stages of Tooth Formation for Single Rooted Teeth  
*Adapted from Moorrees, Fanning, and Hunt (1963)*

<table>
<thead>
<tr>
<th>Event</th>
<th>Mineralization Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial cusp formation (Cₙ)</td>
<td>1</td>
</tr>
<tr>
<td>Coalescence of cusps (Cₒₒ)</td>
<td>2</td>
</tr>
<tr>
<td>Cusp outline complete (Cₒₙ)</td>
<td>3</td>
</tr>
<tr>
<td>Crown ½ complete (Cr₋ₙₖ)</td>
<td>4</td>
</tr>
<tr>
<td>Crown ¾ complete (Cr₋ₙ₈)</td>
<td>5</td>
</tr>
<tr>
<td>Crown complete (Cr₋ₙ₉)</td>
<td>6</td>
</tr>
<tr>
<td>Initial root formation (Rₙ)</td>
<td>7</td>
</tr>
<tr>
<td>Root length ¼ (RI₋ₙ₄)</td>
<td>8</td>
</tr>
<tr>
<td>Root length ½ (RI₋ₙ₅)</td>
<td>9</td>
</tr>
<tr>
<td>Root length ¾ (RI₋ₙ₇)</td>
<td>10</td>
</tr>
<tr>
<td>Root length complete (Rₙ)</td>
<td>11</td>
</tr>
<tr>
<td>Apex ½ closed (A₋ₙ₅)</td>
<td>12</td>
</tr>
<tr>
<td>Apical closure complete (A₋ₙ₇)</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 3.4: Stages of Tooth Formation for Multi-Rooted Teeth  
*Adapted from Moorrees, Fanning, and Hunt (1963)*

<table>
<thead>
<tr>
<th>Event</th>
<th>Mineralization Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial cusp formation (Cₙ)</td>
<td>1</td>
</tr>
<tr>
<td>Coalescence of cusps (Cₒₒ)</td>
<td>2</td>
</tr>
<tr>
<td>Cusp outline complete (Cₒₙ)</td>
<td>3</td>
</tr>
<tr>
<td>Crown ½ complete (Cr₋ₙₖ)</td>
<td>4</td>
</tr>
<tr>
<td>Crown ¾ complete (Cr₋ₙ₈)</td>
<td>5</td>
</tr>
<tr>
<td>Crown complete (Cr₋ₙ₉)</td>
<td>6</td>
</tr>
<tr>
<td>Initial root formation (Rₙ)</td>
<td>7</td>
</tr>
<tr>
<td>Initial cleft formation (Cl₋ₙ₇)</td>
<td>8</td>
</tr>
<tr>
<td>Root length ¼ (RI₋ₙ₄)</td>
<td>9</td>
</tr>
<tr>
<td>Root length ½ (RI₋ₙ₅)</td>
<td>10</td>
</tr>
<tr>
<td>Root length ¾ (RI₋ₙ₇)</td>
<td>11</td>
</tr>
<tr>
<td>Root length complete (Rₙ)</td>
<td>12</td>
</tr>
<tr>
<td>Apex ½ closed (A₋ₙ₅)</td>
<td>13</td>
</tr>
<tr>
<td>Apical closure complete (A₋ₙ₇)</td>
<td>14</td>
</tr>
</tbody>
</table>
Table 3.5 presents descriptive statistics of permanent molars collected for males comprising the contemporary Florida population, while Table 3.6 presents descriptive statistics of permanent molars collected for females comprising the contemporary Florida population.

Sample Population 2: Contemporary Middle Tennessee Sample of African and European Descent

Similarly, Harris and McKee (1990:860) also observed the periapical radiographs, or standardized orthopantomographs, of “phenotypically normal children” to obtain cross-sectional dental development data. Mineralization stages according to standards devised by Moorrees et al. (1963) were assigned to maxillary and mandibular teeth. Symmetry in dental development was assumed; therefore, data were collected from teeth “on either the left side” of the dental arcade for all 16 tooth types, and teeth were scored according to the “closest morphologic full stage” (Harris and McKee 1990:860).

| Table 3.5: Descriptives of Permanent Molars of Florida Sample (Males) |
|---|---|---|---|---|
| Tooth | n | age range | mean (age in years) | median (age in years) | s.d. |
| M1 | 32 | 7.7-20.3 | 15.61 | 16.00 | 3.22 |
| M2 | 32 | 7.7-20.3 | 15.63 | 15.75 | 3.29 |
| M3 | 22 | 9.4-20.3 | 15.85 | 15.97 | 2.49 |

| Table 3.6: Descriptives of Permanent Molars of Florida Sample (Females) |
|---|---|---|---|---|
| Tooth | n | age range | mean (age in years) | median (age in years) | s.d. |
| M1 | 46 | 10.5-20.4 | 16.05 | 16.25 | 2.61 |
| M2 | 45 | 10.5-20.4 | 15.98 | 16.20 | 2.55 |
| M3 | 19 | 11.2-19.9 | 16.06 | 16.20 | 2.37 |
Drs. Harris and McKee collected ancestral descent for individuals included in each sample; however the authors (Harris and McKee 1990:860) inappropriately categorized this variable as “race”. Drs. Harris and McKee assigned “racial” categories to research participants according to “cultural criteria and physical appearance” (Harris and McKee 1990:860). Additionally, Drs. Harris and McKee reviewed medical records to ensure that individuals who may have possessed diseases or pathological conditions that may adversely affect the rate of dental development were not included in the sample. Table 3.7 presents descriptive statistics for all males comprising the contemporary Middle Tennessee sample, while Table 3.8 presents descriptive statistics for all females comprising the contemporary Middle Tennessee sample.

**Protocol Description**

Appendix A represents the protocol that was implemented for this research study. The attached protocol is included in its original form, and not all variables included in the protocol were pertinent to the data analysis presented in this thesis. The protocol was designed to obtain an ordinal score for tooth development for each permanent tooth.

<table>
<thead>
<tr>
<th>Table 3.7: Descriptives of Permanent Molars of Tennessee Sample (Males)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth</td>
</tr>
<tr>
<td>M1</td>
</tr>
<tr>
<td>M2</td>
</tr>
<tr>
<td>M3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3.8: Descriptives of Permanent Molars of Tennessee Sample (Females)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth</td>
</tr>
<tr>
<td>M1</td>
</tr>
<tr>
<td>M2</td>
</tr>
<tr>
<td>M3</td>
</tr>
</tbody>
</table>
utilizing scoring standards for dental development devised by Moorrees et al. (1963). Appendix B represents the data collection form that was utilized to facilitate data collection.

### Methods of Statistical Analysis

#### Treatment of Population Subsamples

According to Madrigal and Barbujani (2007:27), discontinuous groups that are identified from the physical aspects of people “are not reliable predictors of variation.” Therefore, though there is ancestral data available for individuals comprising the contemporary Middle Tennessee population, the subsamples identified by ancestral descent were combined for the analyses presented in this thesis to appropriately represent a contemporary Middle Tennessee population.

#### Statistical Analyses – The Incorporation of Bayes’ Theorem

Statistical analyses were performed using PASW Statistics, Version 18.0 (PASW Statistics 2009) and “R”, Version 2.13.0 (Ihaka and Gentleman 1996:300). Statistical analyses for this thesis utilize Bayesian statistical analyses and transitional analyses. Though the original contemporary Florida sample contained 81 cases, only 59 of these cases were able to be included in the analyses as the remaining 22 cases exhibited complete root apex closure on the third permanent molar (M3), or had complete root apex closure on the second permanent molar (M2) and lacked a calcification stage for the third permanent molar (M3). These 22 cases were unable to be included in the comparative
analysis and the transition analysis distributions as observations of complete root apex closure, or the final stage of dental development, on the last tooth to develop for which a calcification stage is assigned (for example, the second or third permanent molars) does not permit for an accurate age range estimation. Descriptive statistics of the research sample are presented in Table 3.9. Histograms depicting the age distributions of males and females comprising the 59 Florida cases selected for analysis are presented in Figure 3.5.

Unlike classical approaches to statistical inference, Bayes’ theorem, which can be expressed as:

$$\Pr(a|c_j) = \frac{\Pr(c_j \, | \, a) f(a)}{\int \Pr(c_j \, | \, x) f(x)dx}$$

incorporates prior information into the analysis of new data, and therefore, “formalizes the interaction between prior beliefs and new data” (Cowgill 1993:554). In Bayesian analysis, $f(a)$ represents the prior known age distribution, and must be determined prior to the estimation of $\Pr(a|c_j)$, which represents the probability that an individual is at age $a$ given that he or she has characteristics of $c_j$ where $c_j$ is the set of dental traits observed in the $j$-th individual in the sample (Boldsen et al. 2002:76-77). A goal of this research is to use the known age distribution of the contemporary Middle Tennessee Sample to estimate age for individuals comprising the contemporary Florida sample.

**Table 3.9: Descriptive Statistics for 59 Contemporary Florida Cases**

<table>
<thead>
<tr>
<th>Sex</th>
<th>$n$</th>
<th>Age Range</th>
<th>Mean Age</th>
<th>Median</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>23</td>
<td>7.7-19.5</td>
<td>14.90</td>
<td>14.80</td>
<td>3.08</td>
</tr>
<tr>
<td>Females</td>
<td>36</td>
<td>10.5-20.4</td>
<td>15.70</td>
<td>16.00</td>
<td>2.60</td>
</tr>
</tbody>
</table>

58
Figure 3.5: Age Distribution of Males and Females for 59 Florida Cases.

The contemporary Middle Tennessee population sample was chosen as an informed prior for calculating age estimations of the contemporary Florida population sample since both samples are derived from contemporary Southern populations of similar geographical contexts. In other words, for this analysis, \( f(a) \) represents the entire age distribution of the Middle Tennessee Sample, while \( \Pr(a|c_j) \) represents the probability that an individual is at age \( a \) given that he or she has characteristics of \( c_j \), where \( c_j \) is the
dental development score observed in the $j$-th individual in the contemporary Florida sample. All distributions of data analyzed in this thesis are log-normal.

**Comparing Contemporary Southern Populations**

A Bayesian approach was utilized to compare the timing and tempo of dental development between the contemporaneous Florida and Middle Tennessee populations. According to Hoppa and Vaupel (2002:3), the incorporation of an informed prior “maximizes the fit between the observed frequencies” of developmental characteristics and the “underlying probabilities of these characteristics.” In other words, by incorporating an appropriate prior age distribution, or $f(a)$, more accurate age estimations of a target population can be obtained. Statistical analyses of this thesis utilize the dental development stages and known attainment ages of the contemporary Middle Tennessee population sample (Harris and McKee 1990) as an informed prior for age estimation.

According to Boldsen *et al.* (2002:75), due to the inherent variation in skeletal development, many physical anthropologists are hesitant to assign exact age estimations to unknown individuals. Therefore, researchers attempt to address the inherent uncertainty of estimating age of individuals utilizing developmental characteristics of the teeth and skeleton by incorporating fixed age intervals. However, this is problematic as it should not be assumed that all individual age estimates have the same degree of error. Boldsen *et al.* (2002:75) state that “no one would claim that all skeletons that appear roughly the same age can be assigned with equal confidence to a single age interval.” The authors (Boldsen *et al.* 2002:76) instead suggest that confidence intervals be estimated for each individual incorporating an informed prior and based on the
probability density function $\text{Pr}(a|c_j)$. Therefore, Bayesian analyses in this thesis reconcile
the uncertainty of fixed age estimations by incorporating the age distribution of the
Middle Tennessee population. For this thesis, 50.0% confidence intervals for each of the
59 Florida cases were estimated utilizing the age distribution of the Middle Tennessee
population as an informed prior. Graphical results of this analysis are depicted as interval
estimates and are further discussed in the Results section of Chapter 4.

Konigsberg et al. (2008:545) define “coverage” as the percentage of individuals
expected to fall within a predicted highest posterior density region (HPDR). To compare
the timing of dental development between the contemporary Middle Tennessee
population and the contemporary Florida population, a coverage of 50.0% for 59
contemporary Florida cases with the Middle Tennessee sample as the informative prior
was calculated and plotted against the predicted mean attainment ages of Moorrees et al.
(1963). A coverage of 50.0% was chosen as this optimizes the ability to identify
deviations from the expected level of coverage (Konigsberg et al. 2008:545). Graphical
results of this analysis are depicted as scatter plots and are further discussed in the
Results section of Chapter 4.

**Transition Analysis for a Contemporary Florida Population**

According to Konigsberg et al. (2008:542), a transition analysis is a “parametric
method for modeling the passage of individuals from a given developmental stage to the
next higher stage in an ordered sequence,” and is beneficial in allowing researchers to
make inferences about age by incorporating the timing of transitions from one stage of
osteological or dental development to the next. A transition analysis was performed with
the assistance of Dr. Lyle Konigsberg utilizing “R” Version 2.14.0 on the first permanent molars (M1), the second permanent molars (M2), and the third permanent molars (M3) for males and females of a contemporary Florida population to assess the timing of transitions among advanced stages of dental calcification. There are 14 ordered stages for the development of molars utilizing standards for calcification stages devised by Moorrees et al. (1963:1492). For this study, transition distributions were modeled for the advanced stages of 11-14 for the first permanent molar (M1), stages 11-14 for the second permanent molar (M2), and stages 1-10 for the third permanent molar (M3) as the mean ages of 15.69 years for males and 16.13 years for females comprising the contemporary Florida sample are associated with later stages of dental development for M1 and M2, but earlier stages of calcification for M3 (see Table 2.1; Smith 1991:144).

Transition distributions were modeled utilizing stages of development for each of the three permanent molars for each of the 59 cases of the contemporary Florida population. Likelihood estimation plots in the Results section of Chapter 4 represent the results of the transition analyses. The likelihood estimation plots present the probability that at any given age, the tooth would be in the stage of dental development that was observed. The likelihood curves for each distribution were modeled utilizing the parameters extracted from age distribution graphs designed by Moorrees et al. (1963:1495-1496). Sex was taken into consideration when performing the transition analyses since the parameters extrapolated from the charts devised by Moorrees et al. (1963:1495-1496) are sex-specific.

Furthermore, Konigsberg and Frankenberg (1992:239) define a uniform prior age distribution as an “uninformed prior.” A uniform prior assumes that all possible ages are
equally likely, and is used when information for the age structure of the target population is unavailable. A uniform prior was assumed so that the results depicted in the likelihood estimation plots could be inverted to give the probability that an individual in the contemporary Florida sample would be a particular age given the observed stage of dental development.

**Combined Likelihood Estimations**

Combined likelihood estimations were performed for each case for which sufficient calcification stages of the first permanent molar (M1), second permanent molar (M2), and third permanent molar (M3) were available. Conditional independence, or the notion that each tooth develops independently of any other tooth in the oral cavity, was assumed for each tooth so that the likelihoods that an individual is a particular age given the stage of dental development that was observed could be multiplied. Additionally, while it is common practice to assume conditional independence and disregard the variance that occurs between teeth, analyses for this thesis sought to recover the between tooth variance by obtaining the maximum likelihood estimation age for each tooth and then calculating the variance among the tooth ages. This estimation is denoted as the “within tooth variance” or “total tooth variance”, and reflects the assumption that dental development is not independent, but instead is correlated among multiple teeth in the oral cavity. In other words, the “within tooth variance” takes into consideration the relationship in the timing of mineralization between M1 and M2, and between M2 and M3. For example, the “within tooth variance” reflects the notion that a particular tooth in the oral cavity (for example, M3) would not progress to the next calcification stage unless
a tooth that proceeds it in development (for example, M2) attains a certain advanced stage of calcification. It is important to note that “within tooth variance” is highly dependent on observable stages of calcification that are appropriate for known age. Therefore, 4 cases for which delayed root apex closure was observed on either the first permanent molar (M1) or the second permanent molar (M2) were not included in analyses for total tooth variance. Graphical results of the combined likelihood estimations are represented as density distributions in the results section of Chapter 4.

Accuracy of Age Parameters Devised by Moorrees et al. (1963)

To test the accuracy of age parameters devised by Moorrees et al. (1963), known ages of individuals comprising the contemporary Florida population sample were plotted against the mean attainment age estimations on a natural log scale predicted by Moorrees et al. (1963) for a contemporary population of European descent. Additionally, coverage of 50.0% was calculated and plotted against the predicted mean attainment ages of Moorrees et al. (1963). Konigsberg et al. (2008:545) define coverage as the percentage of individuals expected to fall within the limits of the predicted distribution range. In this analysis, coverage refers to the percentage of individuals that fall within the expected age predictions established by Moorrees et al. (1963) that have been determined by particular stages of dental development. In other words, approximately 50.0% of individuals in the contemporary Florida population sample exhibiting a particular stage of dental development should have ages within the predicted age estimations of Moorrees, Fanning, and Hunt (1963). These resulting plots are presented and further discussed in the Results section of Chapter 4.
CHAPTER 4: RESULTS

Comparing Contemporary Southern Populations

The “R” Statistical Software Package (Ihaka and Gentlemen 1996:300) was used to generate results for this thesis. Results of the analyses are presented as predicted ages of individuals comprising the Florida population and maximum likelihood estimations for age given stages of dental development. Scatter plots depict the predicted ages of individuals, while maximum likelihood density distributions depict maximum likelihood estimations for age given stages of dental development.

Figure 4.1 is a plot of the known ages of individuals comprising the 59 contemporary Florida cases against the estimated ages. Log-normal dental development data from the contemporary Middle Tennessee population sample served as an informative prior for these estimations. The x-axis represents the known age of the research participants comprising the contemporary Florida population, while the y-axis represents the estimated or predicted age of the individuals comprising the contemporary Florida sample. Each vertical line on the graph represents a confidence interval of 50.0% for each of the 59 contemporary Florida cases. In other words, each vertical line represents the reliability that the known age of the individual is included within the parameters of the predicted age estimations. The dashed line represents the line of best fit. As can be observed in Figure 4.1, the relationship between the estimated ages and the
known ages for individuals is weak. After incorporating the dental development stages and known ages of the contemporary Middle Tennessee population as an informed prior, only 20 of the 59 contemporary Florida cases fall within the expected age limits predicted by Moorrees et al. (1963). This is observed as only 20 of the 59 Florida cases intersect the line of best fit. Results of a cumulative binomial test are significantly different from 0.5 ($p=0.0092$).

**Accuracy of Age Parameters Devised by Moorrees et al. (1963)**

Figure 4.2 is a scatter plot of the known ages of the 59 contemporary Florida cases plotted against the age estimations predicted by age parameters devised by Moorrees et al. (1963). The $x$-axis of the scatter plot represents the actual ages of the 59 contemporary Florida cases, while the $y$-axis of the scatter plot represents the mean
attainment age predictions of Moorrees, Fanning, and Hunt (1963). Each point on the plot represents a case from the contemporary Florida population sample, while the diagonal dashed line represents the best fit. It is apparent in Figure 4.2 that there is a systematic underestimation of age when the known ages of individuals of the contemporary Florida population sample are compared to the expected ages determined by Moorrees et al. (1963), as 50 of the 59 Florida cases fall below the line of best fit. For example, an individual with a known age of 11.0 years from the contemporary Florida sample was estimated to be at approximately 7.5 years when age parameters devised by Moorrees et al. (1963) were utilized. Similarly, an individual with a known age of 14.0 years from the contemporary Florida sample was estimated to be at age 10.0 years, according to the age parameters of Moorrees et al. (1963).

**Figure 4.2: Plot of Age Estimations for 59 Florida Cases**
Furthermore, Figure 4.3 is a plot of 50.0% interval estimations for the 59 contemporary Florida cases against age parameters devised by Moorrees et al. (1963). Similarly to Figure 4.1, the $x$-axis represents the known ages of individuals comprising the contemporary Florida population, while the $y$-axis represents the age estimations based on the age parameters of Moorrees et al. (1963). The vertical lines represent 50.0% interval estimations for each of the 59 contemporary Florida cases. In other words, each vertical line represents the range in which the known age for each individual is expected to lie. The diagonal dashed line represents the line of best fit. It can be observed in Figure 4.3 that the relationship between known ages of individuals comprising the contemporary Florida sample and estimated ages of individuals based on the age parameters of Moorrees et al. (1963) is weak, since only 19 of the 59 maximum

![Figure 4.3: Plot of 50.0% Interval Estimations for 59 Florida Cases](image-url)
likelihood intervals include the actual age of the individual. This is evident by the 19 cases that intersect the line of best fit. Results of a cumulative binomial test are significantly different from 0.5 ($p=0.0043$).

On the other hand, Figure 4.4 is also a 50.0% interval estimate plot for the 59 cases comprising the contemporary Florida sample; however, the 50.0% maximum likelihood estimations represented in Figure 4.4 do not include the between-tooth component of variance. Instead, each tooth development stage was estimated for age independently without taking into consideration possible relationships with other teeth in the timing of calcification. As discussed, the between-tooth component of variance accounts for the relationship in development among multiple teeth in the oral cavity.

![Figure 4.4: Plot of 50.0% Interval Estimations for 59 Florida Cases (without between-tooth variance)](image)

Figure 4.4: Plot of 50.0% Interval Estimations for 59 Florida Cases (without between-tooth variance)
Since the between-tooth component of variance was not considered for these maximum likelihood estimations, only 15 of the 59 contemporary Florida cases fall within the predicted age estimations of Moorrees et al. (1963). This is observed as only 15 of the 59 Florida cases intersect the line of best fit. Results of a cumulative binomial test are significantly different from 0.5 ($p=0.0001$).

**Transition Analysis for a Contemporary Florida Population**

*Likelihood Estimations for a Contemporary Florida Population*

Table 4.1 summarizes four cases for which analyses results were chosen for discussion in this thesis. These cases consist of case number 1-09, case number 11-09, case number 5-09, and case number 43-09. Case numbers 1-09 and 43-09 are males with known ages of 13.8 years and 19.5 years, respectively. Case numbers 11-09 and 5-09 are females with known ages of 15.2 years and 11.2 years, respectively. While the discussion of these cases does not directly concern the comparison of timing of dental development between the contemporary Middle Tennessee and Florida populations, the discussion of these four cases was included in this thesis to illustrate examples of how transition analyses are applied to estimate the maximum likelihood that an individual is a particular age, given the observed stages of dental development for permanent molars.

Figure 4.5 is a likelihood estimation plot for case 1-09. Case 1-09 is a male with a known age of 13.8 years. The $x$-axis represents possible ages, while the vertical dashed line denotes the individual’s known age. Each vertical row in Figure 4.5 represents a permanent molar for which a probability density for age was estimated. For example, the top row contains the probability density distribution for age for the first permanent molar.
(M1), the middle row contains the probability density distribution for age for the second permanent molar (M2), and the third row contains the probability density distribution for age for the third permanent molar (M3). Each shaded probability density curve represents the likelihood that the individual is a particular age, given the stage of dental development for each molar. The calcification stage for each molar is denoted in the right column.

For case 1-09, the first permanent molar (M1) was observed to have complete root apex closure (A.c), or be in stage 14, of dental development. The probability density curve is open to the right, indicating that the first permanent molar (M1) is exhibiting the final stage of dental development. In other words, it is highly probable that case 1-09 is at least 11.0 years old, since he is exhibiting complete root apex closure of the first permanent molar (M1). On the other hand, the second permanent molar (M2) of case 1-09 was observed to have a root length of \( \frac{1}{2} \) (A.5), or be in stage 10 of dental development, while the third permanent molar (M3) of case 1-09 was observed to have completed crown development (Cr.c), or be in stage 6 of calcification. The shaded distribution curve of the second permanent molar (M2) represents the probability that case 1-09 is between the ages of 10.0 and 20.0 years old, given the observed stage of M2 development. Similarly, the shaded distribution curve of the third permanent molar (M3) represents the probability that case 1-09 is between the ages of approximately 9.0 and 18.0 years, given the observed stage of M3 development.

### Table 4.1: Summary of Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Sex</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-09</td>
<td>Male</td>
<td>13.8</td>
</tr>
<tr>
<td>11-09</td>
<td>Female</td>
<td>15.2</td>
</tr>
<tr>
<td>5-09</td>
<td>Female</td>
<td>11.2</td>
</tr>
<tr>
<td>43-09</td>
<td>Male</td>
<td>19.5</td>
</tr>
</tbody>
</table>
The age distributions for the second and third permanent molars (M2 and M3) for case 1-09 were derived from the difference between the cumulative log normal distributions for transitions from Moorrees et al. (1963). It can be observed in Figure 4.5 that the highest probability for age lies at approximately 13.0 years based on the observed calcification stage for the second permanent molar (M2), while the highest probability for age lies at approximately 12.0 years based on the observed calcification stage for the third permanent molar (M3). The maximum likelihood estimations for age depicted in Figure 4.5 for each of the permanent molars are reasonably accurate for case 1-09, as can be observed by the inclusion of the vertical dashed line representative of the known age of 13.8 years in each of the probability density curves.

Figure 4.5: Likelihood Estimation Plot for Case 1-09 (Male; 13.8 years)
However, of the 59 contemporary Florida cases for which age distributions were calculated, 4 cases exhibited a strong degree of between-tooth variance. In other words, 4 individuals within the sample exhibited dental development stages for permanent molars that yielded disparate age estimations. Figure 4.6 is also a likelihood estimation plot for a case from the contemporary Florida population, and is an example of a case for which disparate age estimations were presented as a result of between-tooth variance.

Case 11-09 is a female with a known age of 15.2 years. The vertical dashed line depicted in Figure 4.6 denotes the known age of 15.2 years. The first permanent molar (M1) and the third permanent molar (M3) appear to suggest different maximum likelihood estimations as the development stage of ½ closed root apex (A.5), or stage 13, for M1 suggests that the individual is likely to be between 5.0 and 10.0 years of age, while the development stage of ¼ root length (R.25), or stage 9, for M3 suggests that the individual is likely to be between 10.0 and 20.0 years of age.

![Figure 4.6: Likelihood Estimation Plot for Case 11-09 (Female; 15.2 years)](image)

Figure 4.6: Likelihood Estimation Plot for Case 11-09 (Female; 15.2 years)
The disparate age estimations depicted for case 11-09 in Figure 4.6 reflect the delay in root closure for the first permanent molar (M1) experienced by this individual. The second permanent molar (M2) for case 11-09 does not contribute to the maximum likelihood estimation as its root apex is closed, and is therefore in stage 14, or the final stage of dental calcification.

Figure 4.7 depicts the maximum likelihood estimation for case 5-09. Case 5-09 is a female with a known age of 11.2 years. An accurate maximum likelihood age estimation for this individual could not be confidently determined based on the development stages of the three permanent molars. In Figure 4.7, it can be observed that the development of the third permanent molar (M3) appears to correlate with the known age of 11.2 years.

**Figure 4.7: Likelihood Estimation Plot for Case 5-09 (Female; 11.2 years)**
age of the individual while the development stages of the first and second permanent molars (M1 and M2) appear to be delayed. If the age of the individual was not known, it could be assumed that the development stages of the first and second permanent molars (M1 and M2) provide the most accurate maximum likelihood estimation, while the development stage of the third permanent molar (M3) may be accelerated. However, since the vertical dashed line represents the known age of 11.2 years, it can be assumed that the development stage of the third permanent molar (M3) is accurate, while the development of the first and second permanent molars (M1 and M2) is delayed.

Figure 4.8 represents the maximum likelihood estimation for case 43-09. Case 43-09 is a male with a known age of 19.5 years. It is apparent that the second permanent molar (M2) was observed to have ½ closure of the root apex (A.5), while the third permanent molar (M3) was observed to exhibit initial cleft development (Cl.i). Development data for the first permanent molar (M1) was not available. The maximum likelihood estimation for case 43-09 presents a similar estimation to that of case 5-09. Though the development stages of the first and second permanent molars (M1 and M2) suggest that the individual is most likely to be between the ages of 11.0 and 16.0 years, it can be observed that this age estimation would not be accurate as the known age of the individual is 19.5 years. Though it cannot be determined for certain, it would not be unreasonable to suggest that the presence of an observed calcification stage for the first permanent molar (M1) would increase the accuracy of the maximum likelihood age estimation for case 43-09.
Figure 4.8: Likelihood Estimation Plot for Case 43-09 (Male; 19.5 years)

Combined Likelihood Estimations for a Contemporary Florida Population

Figure 4.9 is a combined likelihood estimation distribution for case 1-09. Two distribution lines are depicted in Figure 4.9. The dotted line represents the product of the likelihoods, while the dashed line represents the estimation determined from total tooth variance. The vertical line represents the known age of 13.8 years. Distributions depicted in Figure 4.9 are log normal distributions. In other words, points represented on the dotted line are log normal fitted to the combined likelihood. Since the product of likelihoods was derived from cumulative log normal distributions, then the resulting likelihood is also distributed across age as a log normal distribution. The dashed line, which represents within tooth variance, is the resulting estimation of the “within”
Figure 4.9: Combined Likelihood Estimation Plots for Case 1-09 (Male; 13.8 years)

component of dental development derived from the combined likelihood estimations, and the “between” component of dental development derived from the second permanent molar (M2) and the third permanent molar (M3). The first permanent molar (M1) does not contribute to the within tooth variance estimation for case 1-09 since it was observed to be in the final stage of calcification, and therefore does not yield a maximum likelihood estimation.

Figure 4.10 is a combined likelihood estimation distribution for case 11-09. As with Figure 4.9, two distribution lines are depicted in Figure 4.10. The solid line represents the product of the likelihoods assuming conditional independence, while the dashed line represents the estimation determined from total tooth variance. The vertical line represents the known age of 15.2 years. Figure 4.10 conveys how problematic age
estimations can be when teeth that demonstrate lapsed root closure are observed. For example, while the dashed line representing the age estimation determined from total tooth variance presents a larger probability for age that includes the known age of 15.2 years, the solid line representing the product of the likelihoods assuming conditional independence presents a narrow probability distribution for age that does not include the known age of 15.2 years.

Figure 4.11 is a combined likelihood estimation distribution for case 5-09. The solid curve represents the product of the likelihoods assuming conditional independence, while the dashed curve represents the product of the likelihoods that recovers the between-tooth variance. The vertical line represents the known age of 11.2 years.

**Figure 4.10: Combined Likelihood Estimation Plots for Case 11-09**
(Female; 15.2 years)
Figure 4.11: Combined Likelihood Estimation Plots for Case 5-09
(Female; 11.2 years)

Figure 4.12 is a combined likelihood estimation distribution for case 43-09. The vertical line represents the known age of 19.5 years. The solid curve represents the product of the likelihoods assuming conditional independence, while the dashed line represents the product of the likelihoods taking into consideration the between tooth variance. It can be observed that for case 43-09, the inclusion of the between-tooth variance does not significantly contribute to increasing the accuracy of the maximum likelihood age estimation.
Figure 4.12: Combined Likelihood Estimation Plots for Case 43-09
(Male; 19.5 years)
CHAPTER 5: DISCUSSION

The purpose of this study is to assess whether or not differences in the timing and tempo of human dental development can be identified, and to what extent the rate of dental calcification between two contemporary Southeastern United States populations may vary. Analyses performed for this thesis sought to explore the possibility that frequently reported differences in timing of dental development among contemporary populations may be the result of inappropriate statistical analyses, rather than an indication of inter-population variation. By utilizing Bayesian analyses to interpret the data, statistical biases that are inherent in many methods of classical statistical analyses are removed.

As discussed, while many studies of age estimation in physical and biological anthropology seem to emphasize a need for population specific standards for dental age estimation, a limitation in existing comparative studies of the timing and patterning of dental development stages among populations is that many studies fail to take into account the underlying age structure of each population for which research samples represent (Konigsberg et al. 2008:542). Konigsberg et al. (2008:542) emphatically state the following in regard to the perceived need of population specific standards:

"Much ink has needlessly been shed in forensic and physical anthropology on the need for ‘population specific’ estimators, when in fact many of the perceived differences in aging between samples derive from the different age structures of the study populations." (Konigsberg et al. 2008:542).
The results of this thesis support assertions by Konigsberg et al. (2008) by demonstrating how predicted age parameters for target samples can change when an informed prior with a younger age distribution is utilized.

According to Hoppa and Vaupel (2002:1), the assessment of the “complete age structure of [a] population is absolutely imperative” in order to ensure accurate age estimations utilizing analysis of the skeleton or dentition. When utilizing dental mineralization stages to estimate age, the age distribution of the target sample is undeniably affected by the age structure of the reference population from which the dental mineralization standards have been devised (Millard and Gowland 2002:197). As a result, the target population often has the tendency to exhibit “age mimicry,” in which the age estimates of the unknown population mimic the structure of the known-age reference population rather than the entire population (Boldsen et al. 2002:73). Therefore, without an appropriate or thorough evaluation of age categories comprising a population, inconsistencies and variation in statistical modeling and sampling may influence authors’ perceptions of timing differences in the attainment of later dental development stages for individuals within various populations.

Supporters of transition analysis (Boldsen et al. 2002; Konigsberg et al. 2008) argue that graphical representations of probability density distributions produced by transition analyses provide a more accurate estimation of an individual’s age rather than a single point age estimate. Even after incorporating a Bayesian approach to the comparison of the timing of dental development between a contemporary Florida population and a contemporary Middle Tennessee population, and underestimation of age for individuals comprising the contemporary Florida population is apparent. This
underestimation of age can be observed in Figure 4.1 as 39 of the 59 known ages for individuals comprising the Florida sample fall below the line of best fit when utilizing dental development data from the contemporary Middle Tennessee population as an informed prior. In other words, individuals comprising the contemporary Middle Tennessee sample appear to be reaching advanced stages of dental development earlier than individuals comprising the contemporary Florida sample. However, this underestimation of age is to be expected as the Tennessee sample is considerably larger and is comprised of younger individuals than the Florida sample. Therefore, the results of this study suggest that even after incorporating a Bayesian approach to interpret the data, a difference in the timing of dental development between the two contemporary, Southern populations is apparent when an informed prior from a larger sample comprised of younger individuals is utilized.

**Within Population Variation**

Since there are observed differences in the timing of dental development between the two Southern populations, it is important to discuss what factors may be contributing to this observed variation. Although environmental influences on the timing of dental development are often discussed in dental studies, discussions of the timing of dental development may not focus on environmental factors, such as malnutrition or disease, as possible contributors to the observed variation in timing between the populations due to the strong genetic component of human dental calcification. Therefore, in addition to population age distribution and sample size, it is imperative to explore possible evolutionary theories that may be contributing to the observed differences in the timing
of dental development between the contemporary Florida population and the contemporary Middle Tennessee population.

Though the results of this research indicate that individuals comprising the contemporary Florida population age at a different rate in comparison to individuals comprising the contemporary Middle Tennessee population, the observed differences in dental development timing may not necessarily suggest that there are evolutionary differences between two discrete, contemporary populations. The results of this thesis may suggest that there is evidence of an increased amount of variation within a single population than there is variation between populations.

According to Madrigal and Barbujani (2007:24), it is difficult to identify differences between populations since it has not been proven that populations are discontinuous. The authors assert that “variation is distributed in a continuous and overlapping manner among populations,” and therefore, it is problematic to present comparisons of human variation between populations, as it cannot be confirmed that between-populations analyses are not actually within-population analyses. Kittles and Weiss (2003:44), state that geographic distance within a population plays a more important role in structuring genetic variation than cultural characteristics and characteristics attributed to the concept of race. It is well known that the degree of human variation within populations is greater than the degree of variation between populations (Lewontin 1972:381). Since it cannot be assumed that the contemporary Florida population and the contemporary Middle Tennessee population samples analyzed in this research are indeed representative of two distinct populations due to their relatively close geographic proximity, and the likelihood of admixture between the two
samples, it can be suggested that observed differences in the timing of dental development between these two populations may be representative of a significant degree of within-population variation. Therefore, the author of this thesis supports criticisms (Konigsberg et al. 2008) that the results of existing studies (Harris and McKee 1990; Tompkins 1996; Blankenship et al. 2007; Kasper et al. 2009) of comparison in the timing of dental development among ancestral or perceived “racial” groups are by-products of inaccurate statistical analyses, and may not actually be representative of inter-population variation.

**Secular Change**

According to Eveleth and Tanner (1990:205), secular change is defined as the process of “children getting larger and growing to mature more rapidly” over time. The authors (Eveleth and Tanner 1990) suggest that such growth and development changes over time are often attributed to improvements in nutrition, as well as to the infrequent occurrence of infectious diseases as a result of improved access to healthcare. While secular changes have been observed in the body sizes and sexual maturation of children, the extent in which secular changes explain the differences in the timing of dental development among populations is unknown (Cardoso et al. 2010:791-792). According to Cardoso et al. (2010:792), “no study has been able to consistently and unequivocally show secular changes in dental maturation,” and that many studies that attempt to evaluate secular changes in dental development exhibit limitations. In order to appropriately analyze secular changes in dental development, there must be a significant amount of time separating the comparative samples, and appropriate statistical methods...
for estimating the mean age of attainment should be utilized. The significant amount of time between historic and modern samples should be large enough to reflect improvements in living and socioeconomic conditions of individuals included in the modern sample (Cardoso et al. 2010:792).

When comparing the timing of dental development of a historic Portuguese population with that of a modern Portuguese population, Cardoso et al. (2010:795) observed that earlier mean ages of attainment for root development were achieved in children comprising the modern population than the historic population. The authors assert that their results “demonstrate a consistent secular acceleration in tooth formation timing” (Cardoso et al. 2010:797). Therefore, a potential hypothesis to support the observed underestimation of age for the Florida sample when utilizing age parameters devised by Moorrees et al. (1963) could be the presence of secular change. However, secular change cannot be definitively assessed in this study since the Moorrees et al. (1963) sample, though reported in the 1960’s, is not considered to be an appropriate comparative sample to the Florida sample. Individuals comprising the sample collected by Moorrees, Fanning, and Hunt are individuals from the Northeastern United States. As suggested by Cardoso et al. (2010:792), in order to confidently assess secular change in the contemporary Florida population, a historic Florida sample should be utilized as a comparative sample.

**Total Tooth Variance**

While the maximum likelihood age estimations generally underestimated the age for individuals comprising the contemporary Florida sample, the results of this study
effectively demonstrate the importance of incorporating the between-tooth component, or
the total tooth variance, when utilizing human dental development to predict age. It can
be observed that, though age estimations were slightly younger than known ages, the
inclusion of the total tooth variance increased the likelihood that the known age would be
included in the maximum likelihood distribution. For example, it can be observed in
Figure 4.11 that the between-tooth variance should not be ignored since taking the
between-tooth variance into account generates a more inclusive and accurate maximum
likelihood estimation. The influence of total tooth variance in increasing the accuracy of
age estimations is a significant finding, as it is apparent that the rate at which each molar
in the oral cavity develops is not independent, but appears to be conditional on the rate of
development of other teeth in the dental arcade.

According to Parks (2006:214), the generation, transmission and recognition of
signals between cells function as essential components of human growth and
development. Many studies have produced insight into the contributions of hormonal
signaling to normal growth. For example, as stated by Moss-Salentijn and Hendricks-
Klyvert (1990:173), the initial stages of dental development are highly dependent on
interactions between mesenchymal components and the developing tooth germ. In other
words, proceeding histological stages of dental development cannot be reached unless the
appropriate signals for morphodifferentiation have been sent and received. Similarly,
research presented by Thesleff and Sharpe (1997:111) also suggests that the enamel knots
associated with the epithelial folding stages of morphogenesis that contribute to tooth
shape function as signaling centers that regulate tooth development. Therefore, it can be
suggested that similar signaling interactions that occur among initial components of the
tooth development while *in utero* continue to influence the attainment of calcification stages among various teeth in the oral cavity during postnatal dental development.

**Accuracy of Age Parameters Devised by Moorrees et al. (1963)**

One aim of this research is to assess the accuracy of dental age parameters devised by Moorrees *et al.* (1963) on a contemporary Florida population. Overall, the age estimations for the contemporary Florida population sample utilizing the age estimation standards of Moorrees *et al.* (1963) generated by analyses performed in “R” do not accurately represent the known ages of individuals comprising the sample. The results of this research indicate that there is an observed underestimation of age for individuals comprising the Florida population sample when utilizing the dental age parameters developed by Moorrees *et al.* (1963). Age predictions based on the standards of Moorrees *et al.* (1963) underestimated the ages for 50 individuals within the Florida sample. This underestimation of age is evident in Figure 4.2 as 50 of the 59 cases fall below the line of best fit, and in Figure 4.3 as 40 of the 59 cases do not intersect the line of best fit when 50.0% confidence intervals were calculated.

Though the sample size of the Florida population incorporated in this study may be considered small, Bayesian analysis is recognized for its applicability to smaller samples (Boldsen *et al.* 2002). The results of this thesis suggest that the dental age parameters of Moorrees *et al.* (1963) may not be universally applicable and may not yield accurate age estimations when utilized to predict age for individuals of a contemporary Florida population. However, it is important to note that the consistent underestimation of age for individuals comprising the Florida population is likely a result of the large
sample size and younger age distribution of the Middle Tennessee population that has been incorporated as an informed prior. Therefore, in response to the perceived need among researchers (Harris and McKee 1990; Tompkins 1996; Blankenship et al. 2007; Kasper et al. 2009) for population specific age estimation standards utilizing stages of dental calcification, the results of this research suggest that researchers should further consider the role of geography and the age distribution of samples rather than ancestral descent in the trend toward the development of population specific standards for age estimation.

**Research Methodology**

Numerous factors in research methodology may also contribute to the observed variation in the timing of dental development between the two contemporary Southern populations. For instance, the design of this research project relies significantly on the correct scoring of dental development stages of permanent teeth from dental radiographs. Failure to adhere to the protocol of dental development stages designed by Moorrees, Fanning, and Hunt (1963) during the initial stages of data collection for either population sample would certainly bare influence on the results of this research. Additionally, inter-observer errors in the ordinal scoring of dental development stages between the researcher and Drs. Harris and McKee may have also influenced the results of this research study. Moreover, the results of this study also demonstrate that missing dental data for particular teeth, such as the first permanent molar, significantly impacts the accuracy of age estimation utilizing observed stages of dental development. This undeniably supports the common understanding that the more developmental information
that is available for an individual improves the likelihood that an accurate and reliable age estimation can be obtained.

Additionally, since the statistical biases of the analyses performed for this thesis have been removed, it is imperative to investigate what additional components of research methodology may account for the observed differences in the rate of dental calcification between the contemporary Florida population and the contemporary Middle Tennessee population. While ancestral data were not available for the contemporary Florida population, there are several identifiable components of the methodology utilized by Drs. Harris and McKee in collecting ancestral data for the contemporary Middle Tennessee samples that could have a significant impact on the results presented in this thesis. For example, Harris and McKee (1990:860) state that the variable of “race” was assigned to individuals comprising the Middle Tennessee research samples based on “cultural and physical criteria.” As stated by Madrigal and Barbujani (2007:26), there is no guarantee that had the individuals comprising the research sample been asked, they would have presented the same ancestral information that was assigned to them by the observers. Therefore, it cannot be denied that the assignment of “races” to individuals comprising the authors’ research samples presents a problematic interpretation of any perceived differences between the Middle Tennessee population of European descent and the Middle Tennessee population of African descent.

Significance of Research

The results of this study present significant contributions within the disciplines of biological anthropology, paleodemography, and forensic anthropology. Biological
anthropologists are able to gain further insight into the extent in which human variation is represented in contemporary populations. While it is known that variation in skeletal growth and development can be observed among individuals comprising various populations, biological anthropologists are now encouraged to explore the manner in which genetic influences impact the timing and tempo of human dental development. Furthermore, the results of this research contribute to the field of paleodemography as many researchers within paleodemography are interested in the development of population age distributions. Population age distributions of various contemporary and archaeological populations can be utilized by paleodemographers as informed priors for estimating age of individuals comprising similar geographic, archaeological, or contemporaneous populations.

Finally, the results of this research impact the forensic community by presenting data related to estimating appropriate dental ages for unknown juveniles and young adults utilizing advanced stages of molar development. The accurate estimation of age utilizing molar development can have important legal implications for living individuals for which chronological age is unknown since the observation of advanced mineralization stages in permanent third molars can provide insight into whether or not an individual is likely to have reached 18 years of age. This information can assist courts within The United States in determining whether or not an individual is legally considered a minor or an adult.
Suggestions for Future Research

The results of this thesis indicate that individuals comprising the Middle Tennessee population exhibit advanced timing in dental development in comparison to individuals comprising the contemporary Florida population. Previous studies (Harris and McKee 1990; Koshy and Tandon 1998; Kasper et al. 2009) in the comparison of the timing of dental development have incorporated traditional methods in statistical analysis to conclude that differences in the timing of dental development among populations are evident. However, this research incorporates methods in Bayesian analyses to remove the statistical biases inherent in classical methods of statistical analysis. While the results of this thesis suggest possible differences in timing in the attainment of dental calcification stages between two geographic populations of the Southeastern United States, the incorporation of Bayesian analyses to assess differences in the timing of dental development provides a more comprehensive assessment of perceived variation (Buck et al. 1996:2). In other words, the incorporation of the known age structure of a Middle Tennessee population as an informed prior serves to remove statistical biases, such as age mimicry (Aykroyd et al. 1999:57-58), that result in a more reliable evaluation of the timing of dental development for a contemporary Florida population.

Therefore, this research supports Bayesian analysis as a valid contribution to comparative studies within biological anthropology. Future research should continue to apply methods in Bayesian analyses to address questions of population variability in order to determine whether or not observed differences among populations are evident, or are statistical byproducts. Statistical analyses utilized in this thesis should also be performed on research samples representative of other contemporary populations of the
United States in order to evaluate if differences in the timing of dental development can be observed between other contemporary populations. Additionally, future research should compare historic and modern samples to assess whether or not secular change in the timing of dental calcification can be observed within a Florida population. Finally, future research should provide a more thorough evaluation of the possible evolutionary and genetic factors that may contribute to this observed variation in dental development timing between the contemporary Florida population and the contemporary Middle Tennessee population, and to what extent these factors may influence the timing of dental development.
CHAPTER 6: CONCLUSION

Previous research has suggested that, while mineralization patterning generally remains the same, the timing and tempo of dental development varies among populations (Harris and McKee 1990; Tompkins 1996). However, it must be determined whether or not observable differences in the timing of dental development among populations are the result of biases in popular methods of statistical analyses. This study is an effort to show how differences in population age structure can influence age estimations in hopes of producing more accurate age parameters utilizing postnatal dental development.

Researchers suggest that the Bayesian approach to analyzing data permits the “incorporation of relevant prior knowledge” and thus facilitates a more comprehensive interpretation of the data (Buck et al. 1996:2). In other words, the results of studies in which mean ages of attainment comprise the basis for comparison between populations may be inaccurate as entire age distributions of reference and target populations are not taken into consideration.

However, the preliminary results of this study indicate that there is a consistent underestimation of age for a contemporary Florida population utilizing data from a contemporary Tennessee population as an informed prior. The results of this study also suggest that dental development is correlated among various teeth in the oral cavity, and therefore, dental development per tooth is not independent. The results of this
preliminary study are promising, in that there is an observable difference in timing of dental development between two contemporary populations of the Southeastern United States after removing the limitation of a statistical bias. Future research will address to what extent population variation may influence the timing of dental development, and will further assess the perceived need for population specific age estimation standards.

This research has important applications within the field of forensic anthropology. The accurate estimation of age utilizing stages of dental calcification will aid in obtaining positive identifications for living and deceased juveniles and young adults. Additionally, the accurate estimation of age given stage of permanent molar development can have important legal implications for living individuals for which chronological age is unknown since the observation of advanced mineralization stages in permanent third molars can provide insight into whether or not an individual is likely to have reached 18.0 years of age. This information can assist courts in the United States in determining whether or not an individual of unknown age is legally considered a minor or an adult.


Appendix A: Protocol for Data Collection

Mineralization Patterns of the Deciduous and Permanent Dentitions

Data Collection Protocol
May 2009
Meryle A. Dotson

Introduction:
Data is collected from radiographs of deciduous and permanent dentitions for individuals with observable mineralization stages.

Definitions
Mineralization - process by which the soft tissue tooth germ develops into hard tissue characteristic of mature teeth
Clinical Eruption – tooth has emerged from the gingiva
Alveolar Eruption – tooth has emerged from the alveolar portion of the mandible or maxilla

Permanent Tooth Identification (Universal Numbering System)
1. Right Maxillary Third Molar
2. Right Maxillary Second Molar
3. Right Maxillary First Molar
4. Right Maxillary Second Premolar
5. Right Maxillary First Premolar
6. Right Maxillary Canine
7. Right Maxillary Lateral Incisor
8. Right Maxillary Central Incisor
9. Left Maxillary Central Incisor
10. Left Maxillary Lateral Incisor
11. Left Maxillary Canine
12. Left Maxillary First Premolar
13. Left Maxillary Second Premolar
14. Left Maxillary First Molar
15. Left Maxillary Second Molar
16. Left Maxillary Third Molar
17. Left Mandibular Third Molar
18. Left Mandibular Second Molar
19. Left Mandibular First Molar
20. Left Mandibular Second Premolar
21. Left Mandibular First Premolar
22. Left Mandibular Canine
23. Left Mandibular Lateral Incisor
24. Left Mandibular Central Incisor
25. Right Mandibular Central Incisor
26. Right Mandibular Lateral Incisor
Appendix A: Protocol for Data Collection (Continued)

27. Right Mandibular Canine
28. Right Mandibular First Premolar
29. Right Mandibular Second Premolar
30. Right Mandibular First Molar
31. Right Mandibular Second Molar
32. Right Mandibular Third Molar

Deciduous Tooth Identification (Universal Numbering System)
A. Right Maxillary Second Molar
B. Right Maxillary First Molar
C. Right Maxillary Canine
D. Right Maxillary Lateral Incisor
E. Right Maxillary Central Incisor
F. Left Maxillary Central Incisor
G. Left Maxillary Lateral Incisor
H. Left Maxillary Canine
I. Left Maxillary First Molar
J. Left Maxillary Second Molar
K. Left Mandibular Second Molar
L. Left Mandibular First Molar
M. Left Mandibular Canine
N. Left Mandibular Lateral Incisor
O. Left Mandibular Central Incisor
P. Right Mandibular Central Incisor
Q. Right Mandibular Lateral Incisor
R. Right Mandibular Canine
S. Right Mandibular First Molar
T. Right Mandibular Second Molar

Mineralization Stages (Moorrees et al. 1963. See proposal for full reference)
Based on Attainment of consecutive stages, choose all that apply for each tooth

1. Initial cusp formation ($C_i$)
2. Coalescence of cusps ($C_{co}$)
3. Cusp outline complete ($C_{oc}$)
4. Crown $\frac{1}{2}$ complete ($C_{-\frac{1}{2}}$)
5. Crown $\frac{3}{4}$ complete ($C_{-\frac{3}{4}}$)
6. Crown complete ($C_{-c}$)
7. Initial root formation ($R_i$)
8. Initial cleft formation ($Cl_{-i}$)
9. Root length $\frac{1}{4}$ ($Rl_{-\frac{1}{4}}$)
10. Root length $\frac{1}{2}$ ($Rl_{-\frac{1}{2}}$)
Appendix A: Protocol for Data Collection (Continued)

11. Root length $\frac{3}{4} (R_{l} \frac{3}{4})$
12. Root length complete ($R_{c}$)
13. Apex $\frac{1}{2}$ closed ($A_{c} \frac{1}{2}$)
14. Apical closure complete ($A_{c}$)

DEMOGRAPHIC INFORMATION:

OBS. 01: Sex 1=Male 2=Female

OBS. 02: Age (years)

OBS. 03: Ancestry:
1=Caucasian 4=Hispanic 6=Other (list)
2=African-American 5=American-Indian 99=Unknown
3=Asian

OBS. 04: Individual’s Residence
1=West Florida (List City) 4=North Florida (List City) 99=Unknown
2=South Florida (List City) 5=Out of State (List State)
3=East Florida (List City) 6=Other (List)

INDIVIDUAL TOOTH INFORMATION:

OBS. 05: Tooth Identification Number (Universal Numbering System)
1=Right Maxillary Third Molar 17=Left Mandibular Third Molar
2=Right Maxillary Second Molar 18=Left Mandibular Second Molar
3=Right Maxillary First Molar 19=Left Mandibular First Molar
4=Right Maxillary Second Premolar 20=Left Mandibular Second Premolar
5=Right Maxillary First Premolar 21=Left Mandibular First Premolar
6=Right Maxillary Canine 22=Left Mandibular Canine
7=Right Maxillary Lateral Incisor 23=Left Mandibular Lateral Incisor
8=Right Maxillary Central Incisor 24=Left Mandibular Central Incisor
9=Left Maxillary Central Incisor 25=Right Mandibular Central Incisor
10=Left Maxillary Lateral Incisor 26=Right Mandibular Lateral Incisor
11=Left Maxillary Canine 27=Right Mandibular Canine
12=Left Maxillary First Premolar 28=Right Mandibular First Premolar
13=Left Maxillary Second Premolar 29=Right Mandibular Second Premolar
14=Left Maxillary First Molar 30=Right Mandibular First Molar
15=Left Maxillary Second Molar 31=Right Mandibular Second Molar
16=Left Maxillary Third Molar 32=Right Mandibular Third Molar

A=Right Maxillary Second Molar K=Left Mandibular Second Molar
B=Right Maxillary First Molar L=Left Mandibular First Molar
C=Right Maxillary Canine M=Left Mandibular Canine
Appendix A: Protocol for Data Collection (Continued)

<table>
<thead>
<tr>
<th>Tooth Position</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Right Maxillary Lateral Incisor</td>
</tr>
<tr>
<td>E</td>
<td>Right Maxillary Central Incisor</td>
</tr>
<tr>
<td>F</td>
<td>Left Maxillary Central Incisor</td>
</tr>
<tr>
<td>G</td>
<td>Left Maxillary Lateral Incisor</td>
</tr>
<tr>
<td>H</td>
<td>Left Maxillary Canine</td>
</tr>
<tr>
<td>I</td>
<td>Left Maxillary First Molar</td>
</tr>
<tr>
<td>J</td>
<td>Left Maxillary Second Molar</td>
</tr>
<tr>
<td>N</td>
<td>Left Mandibular Lateral Incisor</td>
</tr>
<tr>
<td>O</td>
<td>Left Mandibular Central Incisor</td>
</tr>
<tr>
<td>P</td>
<td>Right Mandibular Central Incisor</td>
</tr>
<tr>
<td>Q</td>
<td>Right Mandibular Lateral Incisor</td>
</tr>
<tr>
<td>R</td>
<td>Right Mandibular Canine</td>
</tr>
<tr>
<td>S</td>
<td>Right Mandibular First Molar</td>
</tr>
<tr>
<td>T</td>
<td>Right Mandibular Second Molar</td>
</tr>
</tbody>
</table>

**OBS. 06: Mineralization Stages Attained**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial cusp formation (C_i)</td>
</tr>
<tr>
<td>2</td>
<td>Coalescence of cusps (C_co)</td>
</tr>
<tr>
<td>3</td>
<td>Cusp outline complete (C_oc)</td>
</tr>
<tr>
<td>4</td>
<td>Crown ½ complete (Cr – ½)</td>
</tr>
<tr>
<td>5</td>
<td>Crown ¾ complete (Cr – ¾)</td>
</tr>
<tr>
<td>6</td>
<td>Crown complete (Cr – c)</td>
</tr>
<tr>
<td>7</td>
<td>Initial root formation (R_i)</td>
</tr>
<tr>
<td>8</td>
<td>Initial cleft formation (Cl – i)</td>
</tr>
<tr>
<td>9</td>
<td>Root length ¼ (Rl – ¼)</td>
</tr>
<tr>
<td>10</td>
<td>Root length ½ (Rl – ½)</td>
</tr>
<tr>
<td>11</td>
<td>Root length ¾ (Rl – ¾)</td>
</tr>
<tr>
<td>12</td>
<td>Root length complete (R_c)</td>
</tr>
<tr>
<td>13</td>
<td>Apex ½ closed (A – ½)</td>
</tr>
<tr>
<td>14</td>
<td>Apical closure complete (A_c)</td>
</tr>
</tbody>
</table>

**OBS. 07: Has the tooth clinically erupted?**

0 = No  
1 = Yes  
99 = Unknown

**OBS. 08: Has the tooth erupted from the alveolar region?**

0 = No  
1 = Yes  
99 = Unknown

**OBS. 09: Is a pathology present (Corrected or uncorrected)?**

0 = No  
1 = Yes  
99 = Unknown

**OBS. 10: If a pathology is present, what type is it (Select all that apply)?**

0 = None  
1 = Carries  
2 = Abscess  
3 = Other (list)  
4 = Decay  
5 = Developmental Abnormality  
6 = Trauma  
99 = Unknown

**OBS. 11: Is a restoration present?**

0 = No  
1 = Yes  
99 = Unknown

**OBS. 12: If a restoration is present, what type is it?**

0 = None  
1 = Filling  
2 = Sealant  
3 = Inlay  
4 = Onlay  
5 = Crown  
6 = Other (list)  
99 = Unknown

**OBS. 13: Additional Comments**
Appendix B: Data Collection Form

Mineralization Patterns of the Deciduous and Permanent Dentitions

Data Collection Form

<table>
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<th>Case Number:</th>
<th>Date of Radiograph:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of Record:</td>
<td>Dr. Barry Lipton’s Office, Suite 108; Genesis Dental Software</td>
</tr>
<tr>
<td>Observer:</td>
<td>M.A. Dotson</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observation</th>
<th>Code</th>
</tr>
</thead>
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<td>1 2</td>
</tr>
<tr>
<td>OBS 2</td>
<td></td>
</tr>
<tr>
<td>OBS 3</td>
<td>1 2 3 4 5 6 99</td>
</tr>
<tr>
<td>OBS 4</td>
<td>1 2 3 4 5 6 99</td>
</tr>
<tr>
<td>OBS 5</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 A B C D E F G H I J K L M N O P Q R S T</td>
</tr>
<tr>
<td>OBS 6</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 99</td>
</tr>
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<td>OBS 7</td>
<td>0 1 99</td>
</tr>
<tr>
<td>OBS 8</td>
<td>0 1 99</td>
</tr>
<tr>
<td>OBS 9</td>
<td>0 1 99</td>
</tr>
<tr>
<td>OBS 10</td>
<td>0 1 2 3 4 5 6 7 99</td>
</tr>
<tr>
<td>OBS 11</td>
<td>0 1 99</td>
</tr>
<tr>
<td>OBS 12</td>
<td>0 1 2 3 4 5 6 99</td>
</tr>
<tr>
<td>OBS 13</td>
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