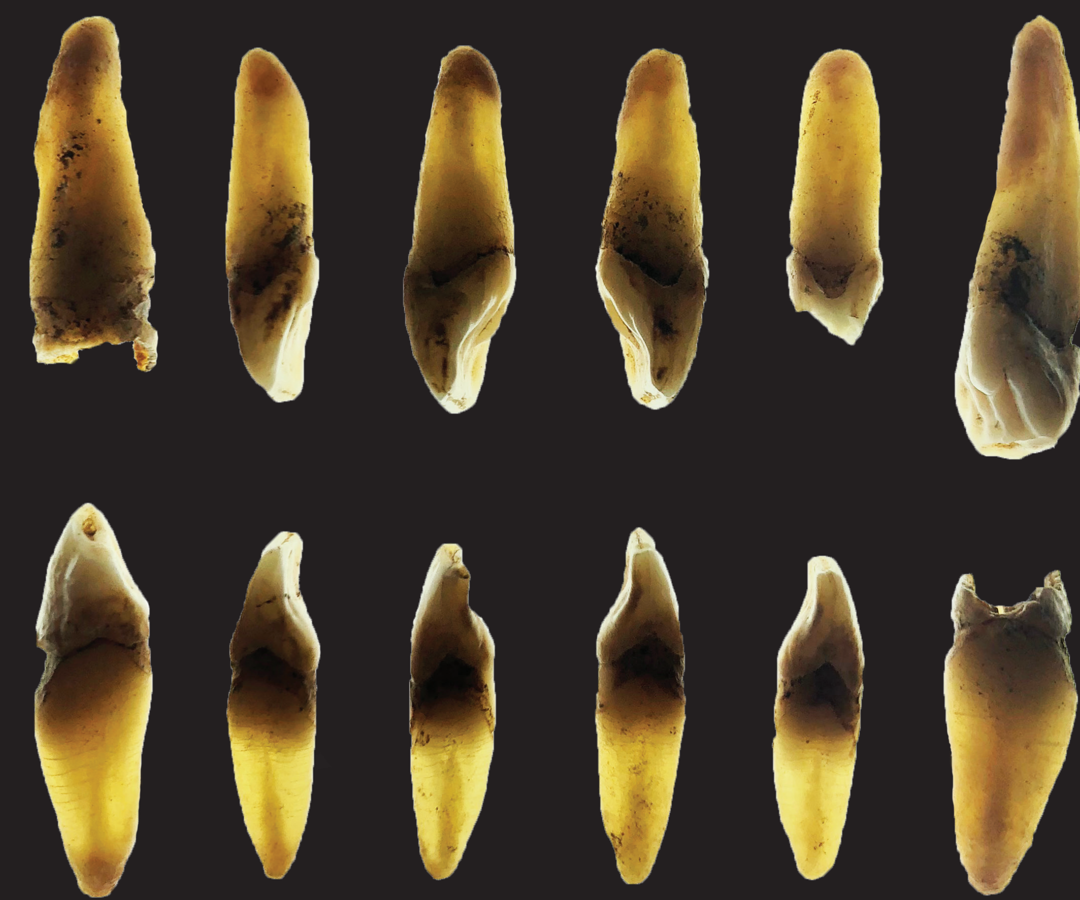
Age-at-Death Estimation using Dental Root Translucency (MSc Thesis) - Niels (N.J.H.) Sommers



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Niels (N.J.H.) Sommers

Master of Science Thesis - Archaeology

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Figure on Cover: The dental root translucency of a Middenbeemster' individual.

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1. Introduction

The role of an osteoarchaeologist is to establish the biological profile of an individual that has been archaeologically excavated, providing an insight into the life of past populations. The investigation gives understanding of burial practices, paleodemography and paleopathology (White *et al.* 2012, 379). The role of a forensic anthropologist is to identify the biological profile of an individual that is severely decomposed, burned or mutilated, which makes it difficult to identify the individual. Examples of these cases can be discovered at crime scenes, accidents, mass disaster sites, war crime scenes or even in living individuals when identity fraud is suspected (Randolph-Quinney *et al.* 2009, 1). Although the role of an osteoarchaeologist and forensic anthropologist are somewhat different, their techniques and methods are similar. Especially regarding the techniques and methods applied to estimate age-at-death, sex, and stature. While the methodologies for sex and stature estimations are very well established in adult skeletal remains (e.g. Buckberry and Chamberlain 2002; Meindl and Lovejoy 1985b; Brooks and Suchey 1990) each present a acceptable rate of accuracy especially when several methods are applied. However, age-at-death estimations still present very broad standard deviations. Most studies rely on age-at-death ranges/categories to make categorization of adult remains more valid. For example, adult individuals can be classified into three age groups: Young adult (20-35 years), Middle adult (35-50 years) and Old adult (50+ years). These adult age ranges are very broad compared to the non-adult age categories: Infant (0-3 years), Child (3-12 years) and Adolescent (12-18 years) (White *et al.* 2012, 385, 408, 418). This thesis will add an age-at-death estimation method to the toolbox of the osteoarchaeologist and make age-at-death estimation more accurate.

1.1 Osteoarchaeological Research

The research aims of an osteoarchaeologist are to compose a demographic profile of a population group(s), providing additional information about the sex, age-at-death and stature demographics of the population under study. Alongside this, skeletal pathological conditions (disease, trauma, congenital anomalies) and ancestral background can also be identified. With this information, an osteoarchaeologist can review the paleodemographic profile of the population. For example, life expectancy, birth rates, and populations size and/or density can be predicted. Although paleodemographic research is studied yearly, the reliability of these profiles depends on the accuracy of the methodology used to investigate the population and its effect on the demographic profile (White *et al.* 2012, 414-415). In the Netherlands, there are already issues since the clearing of a burial after 10-15 years is very common from at least the 17th century onwards (Spelde and Hoogland 2018, 312-313). Thus, only the latest burials will be excavated while the total of people buried on a graveyard (of which a number is cleared) can be considered as one population. In addition, the consideration taken into account is that more often than not, not all skeletons are excavated from an archaeological site due to time and funding issues. In the UK, Historic England even published a document on the best strategies of sampling a burial ground at or after excavation (Enticknap and Mays 2015).

Unfortunately, when age-at-death estimations (see Chapter 2) are not accurate or unreliable, the resulting demographic profile is questionable. The uniformitarian assumptions that humans of the past are biologically acting and reacting the same as present-day humans are considered within the assessment methods of age-at-death and sex in skeletal remains. This is also based on the assumption that these techniques are applicable to populations all over the world, often disregarding ancestral or geographical backgrounds. These uniformitarian assumptions are then included in the demographic profile of past populations (Chamberlain 2006, 81-89), so if the basics (age-at-death and sex) of such a profile are not re-evaluated using ‘new' archaeological samples to confirm the idea of uniformitarianism in humans, demographic profiles are perhaps not worth that much as (osteo)archaeologists might think. Here, this thesis will test an age-at-death estimation method using dental root translucency to see if this uniformitarianism is applicable to estimated age-at-death.

1.2 Dental Root Translucency Defined

A technique that is commonly used in forensic cases is based on dental root translucency, also called (dental) root transparency, apical translucency/transparency or root dentine sclerosis (Ackermann and Steyn 2014, 1; Hillson 2005, 254; Lewis and Kaspar 2018, 158; Prince and Konigsberg 2008, 578). This translucency occurs when all dental development has ceased and an individual is considered dentally mature. Thus, this translucency does not appear before the age of 20 (Prince and Ubelaker 2002, 107). At this point, degeneration starts to occur in other areas across the body, especially in cartilaginous joint areas (e.g. pubic symphyseal and auricular surface changes) and often these areas are used to determine age-at-death in skeletal remains. However, the degeneration of these areas is prone to extrinsic and intrinsic variables which can affect the rate of degeneration. This will vary between males and females, and their occupational lifestyle. Using root translucency as an age-at-death estimation method, these additional variables are avoided.

The theory behind a translucent root is that the older an individual gets; the more hydroxyapatite (calcium) crystals are deposited in the dentin tubuli (channels in dentine) of the root. This process starts at the apex of the root (Figure 1). These crystals are emphasized when a tooth is placed on a light source. When this translucency is measured and correlated to the root length of a tooth, it can be used to determine the age-at-death of an individual (Prince and Ubelaker 2002, 107).

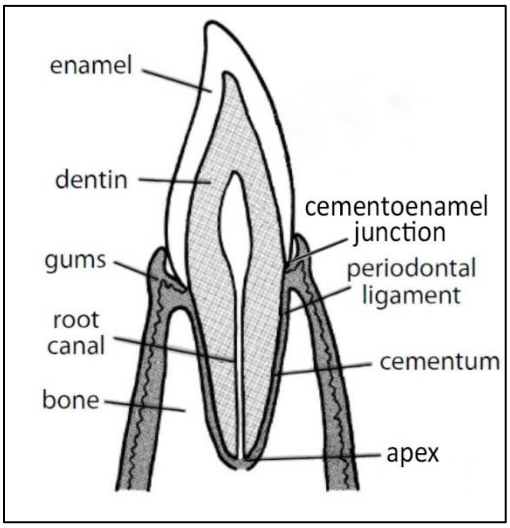

Figure 1: Anatomy of a tooth. After White et al. 2012, 104.

The first researcher that connected dental changes to age-at-death estimations was Gustafson (1947; 1950). Gustafson was a forensic odontologist and focussed on the forensic application of dentition in age-at-death methodologies. This was predominately used for severely decomposed human remains where only the dentition are amongst the (intact) remains. Gustafson (1950) also reports some drawbacks to the method: the total investigation takes up to seven days and some techniques (like the grinding of the roots) could only be done by skilled scientists (Gustafson 1950).

In 1963, Miles wrote a comparative paper in which contemporary research was compared with other studies from the years 1949 to 1960 (Miles 1963; Nalbandian and Sognnaes 1960; Pederson and Scott 1951; Scott *et al.* 1949; Zander and Hürzeler 1958). This study used parts of the Gustafson (1950) method as an age-at-death indicator. Miles (1963) wanted to improve the Gustafson (1950) method by making it less prone to subjective evaluation and more based on metric measurements. Also, Miles (1963) suggested an alteration in the six different dental changes that needed to be scored by adding or removing several of them. Combining this suggested change with the data from his research on 200 teeth, the conclusion was that root translucency was the best age indicator to work with in estimating age-at-death using dentition (Miles 1963, 260-262).

Almost all of Gustafson's (1950) dental change indicators were later discarded in adult dental age-at-death methods. Only root transparency (often combined with periodontosis) and secondary dentin deposition are marked as useful in adult age-at-death estimations. Several methods, such as Johanson (1971) and Maples (1978) use sectioned single-rooted teeth. While others like Bang and Ramm (1970), Lamendin *et al.* (1992), Prince and Ubelaker (2002), Schmitt *et al.* (2010) and Singhal *et al.* (2010) use intact (single rooted) teeth. The methods of Lamendin and colleagues (1992) and Prince and Ubelaker (2002) account for the observed amount of periodontosis in their research. Overall, the research in this area prefers the use of incisors and canines since these are single-rooted teeth. However, premolars and molars can be used, but usage is complicated because these teeth often have multiple roots (Lewis and Kaspar 2018, 158-162).

1.3 Problems in Archaeological Material

The applicability of root translucency as an age-at-death method on archaeological material has resulted in diverse results. Some researchers report doubts about the usability of root translucency in ancient materials due to soil conditions, dental wear and hygiene all influenced the amount of translucency (Lucy *et al.* 1995 423; Megyesi *et al.* 2006, 366; Sengupta *et al.* 1998, 1227-1228; Sengupta *et al.* 1999, 895-897). However, they all report that more research is needed in the archaeological application of this method, especially for intact teeth. Other researchers have opposed these statements and have stated that this method works well within archaeological material and is a good age-at-death estimation technique (Beyer-Olsen *et al.* 1994, 309; Drusini *et al.* 1991, 28; Maples 1978, 769; Marcsik *et al.* 1992, 537; Tang *et al.* 2014, 343-344). Noticeably is that the doubting group of researchers (Megyesi *et al.* 2006; Sengupta *et al.* 1999) used the two methods that account for periodontosis, while the other studies (Beyer-Olsen *et al.* 1994; Drusini *et al.* 1991; Maples 1978; Marcsik *et al.* 1992; Tang *et al.*

2014) relied mostly on methods that did not account for periodontosis, are the ones that give positive results.

Nonetheless, two methods (Lamendin *et al.* 1992, Prince and Ubelaker 2002) use periodontosis, also called paradentosis or gingival regression, as one of the parameters in the formulae. The line that marks this parameter is often difficult to distinguish in archaeological material but often described as an area with smooth root surface and a darkened, somewhat curved line on the root surface. Although the recognisability of this line depends on the soil conditions in which the teeth have been recovered (Megyesi *et al.* 2006, 366; Nikita 2016, 159).

Another problem is that only a few archaeological studies are applied to samples with known sex and age-at-death from historical sources (Drusini *et al.* 1991; Megyesi 2006; Sengupta *et al.* 1999; Tang *et al.* 2014) including collections like the 'Named Spitalfields Christchurch Collection', London, UK. Six of the previously mentioned studies (Beyer-Olsen *et al.* 1994; Lucy *et al.* 1995; Maples 1978; Marcsik *et al.* 1992; Megyesi *et al.* 2006; Sengupta *et al.* 1998) used archaeological human skeletal remains of unknown chronological age. In these six studies. age-at-death estimates were based on conventional techniques and methods used by osteoarchaeologists (e.g. pubic symphyseal changes, cranial suture closure, and sternal rib end estimates). An inadequacy in these six aforementioned studies is that the biological age-at-death estimates of the dental root translucency method are compared to biological age-at-death estimates of other methods, without knowing what the chronological age of the individuals was.

1.4 Current Research

The purpose of this thesis is to test the applicability of root translucency as an age-at-death estimation method in a known sex and age-at-death Dutch archaeological collection. This method will be tested on the Middenbeemster Collection housed at the Laboratory of Human Osteoarchaeology at the Faculty of Archaeology in Leiden University, The Netherlands. This collection consists of over 500 individuals which are provided with extensive historical sources. Because of these sources, sex and age-at-death of 124 individuals is known and therefore an appropriate sample to test age-at-death and sex estimation methods. Since root translucency research has a long history with several formulae developed, this thesis will test six of these formulae: Bang and Ramm (1970), Wegener and Albrecht (1980), Lamendin and colleagues (1992), Prince and

Ubelaker (2002), Schmitt and colleagues (2010) and Singhal and colleagues (2010). More information about the aforementioned will be given in the following chapter (see Chapter 2). This research will contribute to the knowledge of this method on a Dutch collection, but also on the possibility of using this as an age-at-death marker in universal archaeological material with the same ancestral background.

To give more insight into the usability of dental root translucency as an age marker, several research questions will be assessed:

- How accurate are the different formulae within the known sex and age-at-death collection of Middenbeemster?
- What difference in accuracy of age estimation is present when the mean of estimated ages per individual is used instead of one single tooth?
- Is a collection specific formula more accurate than the other formulae tested?
- What diagenetic/taphonomic factors could have had influenced the root translucency?
- What are the potentials of these methods in the Dutch archaeological work field?

This thesis wants to explore the feasibility of using root translucency as an age-at-death estimation method in archaeological context.

1.5 Thesis Structure

This thesis consists of 6 chapters. Here, the introduction is presented (Chapter 1), after which a background of age-at-death methods, especially those using root translucency will be given (Chapter 2). Next, the materials and methods used for the data collection will be described (Chapter 3). The results of the collected data will be presented in Chapter 4. In Chapter 5, there will be a discussion and interpretation of the results of this thesis within the reviewed literature and with comparable research. Limitations of this method will be considered here. Lastly, the conclusion will answer the research questions and the thesis results summarised (Chapter 6).

2. Estimating Age-at-Death

Developing methods for estimating the age-at-death of an individual is a topic that keeps physical anthropologists occupied for a long time, already from the mid-1800s. Because of this interest, several methods and techniques focussing on one or multiple age-at-death indicators, have been developed, trailed and tested (e.g. Acsádi and Nemeskéri 1970; Baccino *et al.* 1999; Brooks and Suchey 1990; Buckberry and Chamberlain 2002; Ferembach *et al.* 1980; Maat *et al.* 2002; Saunders *et al.* 1992). The human skeleton, especially the dentition, is often used as it is the most resistant to decomposition processes (Kemkes-Grottenthaler 2002, 48). This chapter will discuss the most commonly known adult age-at-death estimation methods using the cranium, the axial skeleton and finally, the dentition. This will then be focussed to review translucency methods.

Firstly, it is important to distinguish the difference between chronological age and biological age. Osteoarchaeologists use the estimated biological age derived from skeletal remains to predict the chronological age of an individual. However, age-at-death estimations lack precision due to the disassociation between these two. Chronological age is expressed in time, which is defined by the number of calendrical days, months and years have gone by from birth to death (Garvin *et al.* 2012, 202). So, the exact chronological age cannot be determined without the individuals birth date. Though, biological age is estimated by examining the physiological state of an individual as reflected in his/her skeletal remains. The biological age of an individual is affected by many factors, such as genetics, health, activity and environment. These factors may vary within and between populations at any given chronological age, which results in a different display of biological age in individuals of the same chronological age (Íşcan 1989, 335). Moreover, this results in a greater variation in biological age when chronological age increases, due to the variation in the accumulation of these extrinsic factors through life (Garvin *et al.* 2012, 203). This results in broader biological age estimates and less accurate chronological age determination.

2.1 Age-at-Death Estimation Methods Today

The Workshop of European Anthropologists (WEA) of 1980 accepted by commercial osteoarchaeologists as a methodology to estimate age-at-death by combining four common age indicators, called the Complex Method. This Europewide accepted methodology combines pubic symphyseal changes, cancellous bone changes in the femoral and humeral heads and the obliteration of endocranial suture lines. When all four indicators can be observed, it claims to have an interval of ± 2,5 years at an 80-85% confidence level. While two age indicators give age ranges of 10+ years (Ferembach *et al.* 1980; Maat *et al.* 2012, 12-28). Later studies using cross-checks suggests that the overall error of estimation lies above 10 years (Rösing *et al.* 2007, 84).

Research institutions, like the Laboratory of Human Osteoarchaeology at the Faculty of Archaeology in Leiden University (Schats 2012, 3) and the Department of Medical Biology of the Academic Medical Centre Amsterdam (A.E. van der Merwe, personal communication 12-06-2018), are currently using non-destructive methods to estimate age-at-death. Some of these methods include ectocranial suture closure, pubic symphyseal changes, auricular surface changes and sternal rib end morphology. All of these methods have age ranges of 15+ years, except for the sternal rib end method which has age ranges of less than 10 years (White *et al.* 2012, 392-404).

2.2 The Cranium

Ever since the beginning of the physical anthropological field, the human cranium has had an unparalleled attractive force for research on age-at-death (Blumenbach 1798; Brinton 1894; Dwight 1878, 36-39; Henschen 1966, 15; Welcker 1862). Thankfully, research has improved and changed since the 17th century as human skeletal remains are recovered in the best and most complete possible way. Although the full recovery of human skeletal remains is done today, the cranium is still important in the estimation of biological age-at-death of an individual.

2.2.1 Cranial Suture Closure

Reportedly used since the 16th century, cranial suture closure has been hailed and reviled as an age-at-death estimation method (Vesale 1542 in Galera *et al.* 1998, 933; Meindl and Lovejoy 1985, 57). After being systematically used at the end of the 19th and the first half of the 20th century, it was rejected in the 1950s as an age-at-death estimation method. New methods using cranial suture closure were developed in the second half of the 20th century of which the Acsádi and Nemeskéri (1970) and Meindl and Lovejoy (1985) method became the most used. Although both are not quite precise, the first one is standardly used in Europe, while the latter is standardly used in the United States (Ruengdit *et al.* 2018, 79-80).

The Acsádi and Nemeskéri (1970) method uses ten suture sites that have to be observed endocranially. The study used 285 European crania, but only 71% was used in the study since the other 29% was removed for being atypical (Meindl and Lovejoy 1985, 64). The sites have to be scored on a scale of 0-4, where 0 represents an open suture and 4 represents an obliterated suture line (Acsádi and Nemeskéri 1970; Ferembach *et al.* 1980, 533). After closure observation, the mean closure must be calculated which gives age ranges with intervals of 25-30 years. This method is part of the earlier mentioned Complex Method that is accepted by the European Anthropological Association in 1980 (Ferembach *et al.* 1980).

The Meindl and Lovejoy (1985) methodology uses two separately usable suture site lists that have to be observed ectocranially, one of the cranial vault and one of the lateral-anterior sutures. The cranial vault has seven suture sites to observe, the lateral anterior has five of which two are overlapping with the cranial vault suture sites. A total of 236 crania of the Hamann-Todd Collection were selected based on the reliability of the known age-at-death. The correlation coefficients per observed cranial site are ranging between 0.29 and 0.51 (Meindl and Lovejoy 1985, 61) The sites have to be scored from 0-3, where 0 represents an open suture and 3 represents an obliterated suture. After observing the vault and lateral-anterior suture sites, the scores have to be added together to get the composite closure score and this gives age ranges with intervals of 24-53 years (Meindl and Lovejoy 1985, 63).

Both of these methods were later tested by Key and colleagues (1994). This study included 183 crania from the Christ Church, Spitalfields Collection from London. For the Acsádi and Nemeskéri (1970), this gave age ranges with intervals of 37-57 years (Key *et al.* 1994, 196), this is significantly higher than the original method. The Meindl and Lovejoy (1985) methodology gave age ranges with intervals of 21-77 years which is again much higher than the original study. This proves that original studies have to be tested on other populations since the original and new study can give a lot of discrepancies between the given results of different studies.

2.2.2 Maxillary Suture Closure

Another suture closure age-at-death estimation method focusses on the obliteration of several maxillary sutures. The Mann and colleagues (1991) revised method focusses on five sutures of the maxilla in this order: the incisive, posterior median palatine, greater palatine foramen, transverse palatine suture, and the anterior median palatine (Mann *et al.* 1991). Firstly, the incisive suture is examined the level of obliteration: 0 (0%), 1 (1-25%, 2 (26-50%), 3 (51-75%) or 4 (76-100%). After that, the next suture in line is examined until a suture is not obliterated at all. This is the suture that defines the age estimation. It can occur that a suture further in line has some obliteration while a suture before has not (e.g. greater palatine foramen has obliteration, but the posterior median palatine has not). In that case, the age-at-death estimation is based on the last one with obliteration. This leads to the following age ranges: 20-24 years, 25-29 years, 30-34 years, 35-50 years and 50+ years. Several researchers have achieved an accuracy of over 85% in a Greek (Apostolidou *et al.* 2011), Canadian (Ginter 2005) and Japanese (Sakaue and Adachi 2007) populations when the same age ranges are used to categorise the individuals.

2.3 The Postcranial Skeleton

In the postcranial skeleton (all bones except cranium and mandible), the focus of age-at-death estimation methods is mostly on the degeneration and metamorphosis of the human skeleton, including both macroscopic and microscopic methods (White *et al.* 2012, 406-407). In the Netherlands, most commercial osteoarchaeologists still use a destructive method, amongst other methods (Baetsen 2008, 56; Hoven 2016, 17-18; van Genabeek and van der Linde 2004, 24; Kootker and Baetsen 2009, 4; van der Linde 2016, 62), while non-destructive methods are on the rise (Bergsma and Stokkel 2009, 37; Lemmers *et al.* 2013, 37; Schats 2012, 4; Veselka 2016, 2; de Wit and Bergsma 2011, 23-25).

2.3.1 Destructive Methods

The first method examines the spongiosa (cancellous bone) of the proximal portion and heads of the femur and humerus. It is part of the previously mentioned Complex method of the Workshop of European Archaeologists (Ferembach *et al.* 1980) and is widely used by Dutch osteoarchaeologists. This method was originally designed to be used with radiographs or a sagittal cut through the central axis of the diaphysis, although the radiograph method was later discarded since creating distinctive criteria was difficult (Nemeskéri *et al.* 1960; Maat *et al.* 2012, 12; Walker and Lovejoy 1985, 67). The method of Nemeskéri and colleagues (1960) is based on the fact that the cancellous bone, the medullary cavity and cortex changes as biological age progresses. These changes are classified in six stages (I to VI) for the femur and humerus and give age ranges with intervals of 17-30 years (femur) and 30-37 years (humerus).

Another method developed by Kerley (1965) focusses on the amount of cortical bone that has been remodelled. A ground section of the femur, tibia or fibula is collected, and this ground section is examined under the microscope. The number of osteons, the number of fragmented old osteons, and the number of non-Haversian canals have to be counted, together with the percentage of circumferential lamellar bone. Regression formulae are derived to estimate age with these data. The original article claims to estimate age-at-death within ten years of the chronological age in more than 95% of the individuals (Kerley 1965, 158-159).

A revision on this method was suggested by Maat and colleagues (2006), partly because age-at-death estimation on dissected bodies lead to serious mutilation and technical advances made the use of bone remodelling as an age-at-death method is rapid and cheap. With this method, the focus lies on the determination of the amount of non-remodelled bone in 1 mm^2 of the bone section, to make determination faster (Maat *et al.* 2006, 231-232). Again, regression formulae are derived to estimate age-at-death. The standard deviations range from 9.162 to 14.786 years (Maat *et al.* 2006, 233).

2.3.2 Non-Destructive Methods

Already studied at the beginning of the 20th century by Todd (1920), the pubic symphyseal face is a well-known age-at-death marker. Two methods are in general use today: the Acsádi-Nemeskéri method as part of the Complex method (Nemeskéri *et al.* 1960, 78-80; Acsádi and Nemeskéri 1970, 532-533) and the Suchey-Brooks method (Brooks and Suchey 1990). These methods rely on the morphological changes of the pubic symphysis, that degenerates when chronological age increases. The Acsádi-Nemeskéri method (1970) used 105 autopsied European individuals (61 males, 44 females) ranging from 23 to 93 years with a majority of older (50+ years) individuals. The study classified the morphological changes in five stages (I to V), provided with descriptive texts and depictions per stage. These stages have age ranges with intervals of 20-27 years. The study did not give any accuracy rates. The Suchey-Brooks method (1990) used 1225 autopsied North American (presumably Whites and Blacks) individuals (739 males, 273 females) and classified morphological six stages (I to VI), provided with separate male and female depictions of the begin and end phase of the different stages, together with a description per stage. These six stages give age ranges with intervals of 9-58 years in females and intervals of 8-54 years in males. Both methods are only accurate in the early phases (Acsádi-Nemeskéri: SD ± 1.76, Suchey-Brooks: SD ± 2.1 in males, ± 2.6 in females) (Acsádi and Nemeskéri 1970, 126; Brooks and Suchey 1990, 233).

The auricular surface of the ilium (os coxa) has been recognized as a possible indicator of biological age-at-death since the 1930s (Sashin 1930, 891). However, it was Lovejoy and colleagues (1985a and 1985b) who were the first to develop a method of age-at-death estimation on the morphological changes of the auricular surface. This study included 500 os coxae from the Hamann-Todd Collection, 250 from the historical Libben population (Native American) and fourteen forensic cases (Lovejoy *et al.* 1985a, 17). After the development of the methodology, it was tested on another part of the Hamann-Todd Collection. The changes of the auricular surface appear due to degeneration of the sacroiliac joint. This method (Lovejoy *et al.* 1985a; 1985b) divides the morphological changes into eight stages (1 to 8), provided with pictures and descriptions per stage. Every stage represents an age range of five years starting at twenty years (e.g. stage 1 = 20-24 years), with the eighth stage being estimated at 60+ years (Lovejoy *et al.* 1985a, 27). The study had a Pearson's correlation coefficient of 0.71 using the eight stages (Lovejoy *et al.* 1985b, 9). The age ranges of five years were found too small because the morphological changes were too variable and that interobserver error was high (Murray and Murray 1991, 1168-1169; Saunders *et al.* 1992, 114).

Nonetheless, Buckberry and Chamberlain (2002) revised the methodology to estimate age-at-death using the auricular surface by assessing 180 os coxae from the historical, known age-at-death, collection of Christ Church Spitalfields, London. A quantitative scoring system was implemented to establish a more objective methodology. The features have to be scored from 1 to 3 (microporosity, macroporosity and apical changes) or 1 to 5 (transverse organization and surface texture), the composite score of these features corresponds to one of the seven stages (I to VII) and gives age ranges with intervals of 3-59 years (Buckberry and Chamberlain 2002, 233-237). When all five features are taken into consideration, this gives a correlation coefficient of 0.609 (Spearman's correlation) (Buckberry and Chamberlain 2002, 236).

Íşcan, Loth and Wright (1984; 1985) developed an age-at-death estimation method using the sternal rib end of the fourth rib of white males and females. The method observes the amount of ossification of the costal cartilage, by looking at the cavity of the sternal end of the ribs, based on cavity depth, cavity shape and rim/wall configurations (Íşcan *et al.* 1984, 1094). Six stages (0-5) were described for these three features, which subsequently can be subdivided into nine stages resulting in age ranges with intervals of 3-9 years in males and intervals of 2-7 years in females (Íşcan *et al.* 1984; Íşcan *et al.* 1985). Later, sex-specific stage descriptions and plastic casts were developed (Íşcan and Loth, 1993). Loth (1995) tested the method on 36 males and 38 females of the collection Christ Church Spitalfields, London, to see if the method was also applicable to archaeological material. It did not publish exact accuracy rates but concluded that the sternal rib end methodology is accurate and that it "may be the most accurate technique for archaeological skeletons" (Loth 1995, 470).

2.4 Dentition

Brothwell (1989) derived a classification system for dental wear/attrition, especially molar wear, in British human skeletal remains. The wear classification system was based on cusp wear, dentine exposure and crown wear and supposed to be applicable to British populations from the Neolithic to Medieval period (Brothwell, 1989, 71-73). Since dental wear widely differs in different populations, it is important to use a population-specific wear/age chart, which happened through numerous population specific editions (Rose and Ungar 1998, 353). For Dutch populations, four specific wear patterns have been drafted for pre-Medieval populations and populations from the periods, 1275-1572 AD, 1650-1800 AD and 1830-1858 (Maat 2001, 18-21; Maat *et al.* 2002, 39-40). Overall, caution has to be taken when using dental wear as an age-at-death estimation method, since there are many factors that influence dental wear (Rösing and Kvaal 1998, 450).

After being applied to both land and sea mammals for decades, cementum annulations were firstly used as an age-at-death estimation method in human remains by Stott and colleagues (1982, 814). This destructive method predicates upon the assumption that one thin layer of cementum, with a darker and lighter zone, is deposited around the root every year (Rösing and Kvaal 1998, 454). So, these layers of cementum can be counted as done in year rings of a tree. The number of layers has to be added to the eruption age range of the tooth under investigation since these layers start to form after tooth eruption (Stott *et al.* 1982, 814-815).

2.5 Root Translucency and Related Studies

Root translucency is a physiological feature that appears after the age of 20 due to the deposition of hydroxyapatite crystals within the dentinal tubules (Figure 2) (Lewis and Kasper 2018, 163). As chronological age increases, the dentine of the root becomes progressively translucent, starting at the apex, due to the occlusion of these dentinal tubules. This occlusion gives the tubules a similar refractive index as the intertubular dentinal matrix, allowing light to pass unscattered, giving it the translucent appearance, while the unoccluded tubules have a different refraction index in contrast to the intertubular dentinal matrix, giving it an opaque appearance (Kinney *et al.* 2005, 3364; Tang *et al* 2014, 333).

2.5.1 The First Dental Studies

Studies on the usability of dental features in age-at-death estimation methodology began with the earlier mentioned Gustafson (1950) study. Gustafson (1950) firstly tried to examine age-at-death based on a general impression of a prepared sectioned tooth observing the features attrition, periodontosis, secondary dentin formation and cementum apposition, giving unsatisfactory results (Gustafson 1950, 45-46).

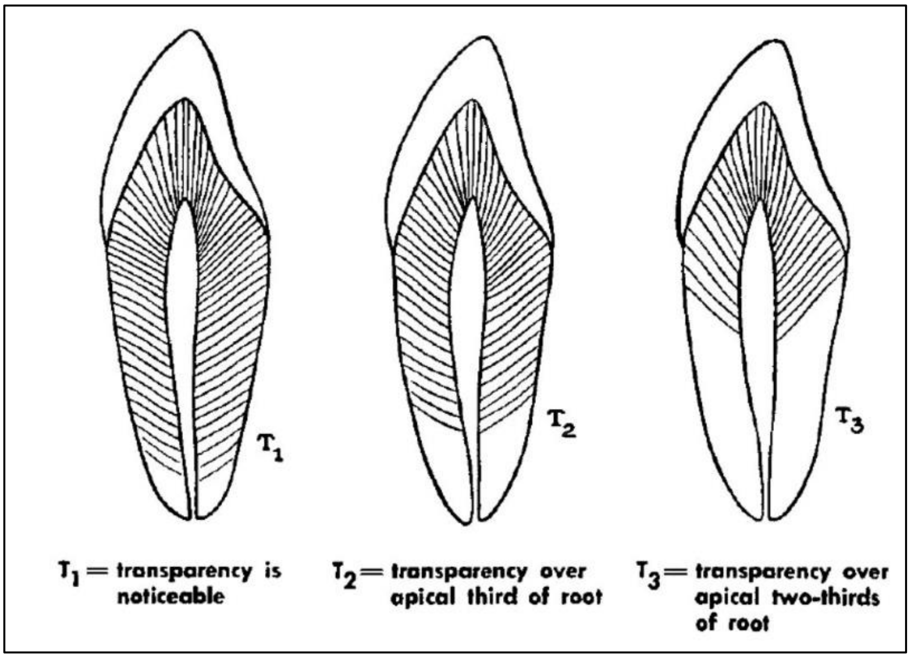

Figure 2: First staging system for root translucency, the radial lines 'represent' the dentinal tubule structure (Gustafson 1950, 49).

The six features had to be scored on a range of 0 to 3 and inserted into a formula which is applicable to all teeth, except for the third molar (Gustafson 1950). The dental features that are reported in the Gustafson (1950) method are:

1. Attrition or dental wear of the incisal or occlusal surface. Seen both macroscopically and microscopically.
2. Periodontosis, non-pathological loosening of the tooth due to gingival recession (retraction of mandibular/maxillary bone. Seen both macroscopic- and microscopically.
3. Secondary dentin development on the pulp cavity due to wear and caries. Seen in a microscopical section.
4. Cementum apposition, which is deposited at the outside of a root. Seen in a microscopical section.
5. Root resorption, which may happen in both the dentin of the root itself as well as in the cementum.
6. Transparency of the apex of the root, seen both in sectioned and intact teeth. Only one mentioned as being not closely related to pathological conditions or treatment.

Following, a new method was developed that accounted for six features that had to be observed in sectioned teeth. It combined the four features with root resorption and root transparency and implemented four stages per feature (0-4), provided with drawings and descriptions per stage (figure 2) (Gustafson 1950, 47-49). The sum of the six feature stages (X) had to be entered in the formula (SD = ± 10.9 years):

$$\text{Age} = 11.43 + 4.56X$$

In the years after 1950, research was focussing on the relation between the six features and the chronological age-at-death and trying to implement measurements instead of a staging system (Miles 1963, 260-261). To do so, Miles (1963) examined 200 teeth using the Gustafson (1950) method. The best feature for both measurement and age-at-death estimation was found to be root translucency (Miles 1963, 261). The study used 118 incisor teeth to derive a regression line between the amount of translucency (mm) and biological age, together with a formula to estimate age-at-death using sectioned incisors (Miles 1963, 262). In the formula X = amount of translucency in millimetres (SD = ± 10.93):

$$\text{Age} = 21.857 + 4.6169X$$

Johanson (1971) revised the methodology of Gustafson (1950). The study evaluated 162 sectioned teeth from 46 individuals. The same six features as Gustafson (1950) were used: attrition (A), periodontosis (P), secondary dentin formation (S) and cementum apposition (C), root resorption (R) and root transparency (T). Although, the four stages per feature (0-4) were increased to seven by including 0.5, 1.5 etc. to the grading system together with a new formula (Johanson 1971 in Lewis and Kasper 2018, 161):

$$Age = 11.02 + 5.14A + 2.30S + 4.14P + 3.71C + 5.57R + 8.98T$$

2.5.2 Studies on Root Translucency

Bang and Ramm (1970) were the first to extensively and solely study the relation between root translucency and chronological age-at-death. In the study, 1013 teeth (incisors, canines, premolars and molars) were collected from 201 mental institution patients and from 64 autopsies (West-European origin), of which 926 teeth were suitable for examination. All intact, restored and decayed teeth were included, except for root-filled teeth (Bang and Ramm 1970, 4). The amount of root translucency was buccally measured twice in front of a constant light source, once using the intact root and once using a longitudinal section of the root (Bang and Ramm 1970, 8). Although measuring root translucency in premolars and molars was deemed to be more difficult in comparison to incisors and canines, tooth specific regression values were derived (Bang and Ramm 1970, 21). The basic formula consists of four components (Bang and Ramm 1970, 20-21): B_0 (constant), B_1 (regression coefficient 1), B_2 (regression coefficient 2) and X (amount of translucency in millimetres):

$$Age = B_0 + B_1 * X + B_2 * X^2$$

Different values are available for intact and sectioned teeth. Also, when the amount of translucency exceeds 9 mm, other constants, and regression coefficients per tooth are derived (Bang and Ramm 1970, 22-24) resulting in the next formula:

$$Age = B_0 + B_1 * X$$

The standard deviations for X = ≤9 mm range between ± 9.48-13.80 years and for X = >9 mm range between ± 9.32-13,60 years (Bang and Ramm 1970, 21-23).

Wegener and Albrecht (1980) did a comparative study on 613 intact teeth (incisors, canines, premolars and molars) from 50 individuals (German/West European). The measurements were conducted in a dark room using a fluorescent tube as a light source and the amount of translucency was measured in millimetres (Wegener and Albrecht 1980, 30-31). Again, a general formula with tooth specific variables was established, C (constant), RC (regression coefficient) and X (amount of translucency in millimetres) with standard deviations between ± 10.8-16.1 years and a general formula for every tooth (SD ± 15,3) (Wegener and Albrecht 1980, 32):

$$\text{Age (tooth specific)} = C + RC*X$$

$$\text{Age (general)} = 23.8 + 4{,}5X$$

Little more than a decade later, Lamendin and colleagues (1992) developed a new age-at-death estimation method only using root transparency and periodontosis as age markers. The study examined 306 single rooted intact teeth (incisors, canines and premolars) of 208 individuals (198 Caucasians and 10 Blacks) of French descent on periodontosis and root translucency Lamendin *et al.* 1992, 1373). A new feature that is considered in the following formula is the root height, which is measured from the cementoenamel junction to the apex of the tooth (Lamendin *et al.* 1992, 1374-1376). The formula of Lamendin and colleagues (1992, 1378-1379) accounts for the relative periodontosis (P = (periodontosis (mm) * 100)/root height (mm)) and relative translucency (T = (translucency (mm) * 100)/root height (mm)) with a mean error of approximately 10 years:

$$\text{Age} = 25.53 + 0.18P + 0.42T$$

Prince and Ubelaker (2002) initially tested the Lamendin and colleagues (1992) methodology and formula on 400 single-rooted teeth from 359 individuals (age 25-99 years, 94 black females, 72 white females, 98 black males and 98 white males) from the Terry Collection of the Smithsonian’s National Museum of Natural History in the US. This led to an overall mean error of 8.23 years and a standard deviation of 6.87 years using the Lamendin *et al.* (1992) formula (Prince and Ubelaker 2002, 108). The collected data were also analysed on the effect of sex and ancestry on the accuracy of age-at-death estimation using Lamendin’s formula, which resulted in four new sex and ancestry-specific formulae using the relative periodontosis (P) and relative translucency (T) in the same way as Lamendin *et al.* (1992), in addition root height (RH) was incorporated in the formula (Prince and Ubelaker 2002, 108, 112). Two of these new formulae are applicable in this thesis:

$$\text{White females (SD = 6.21 years): Age} = 11.82 + 1.10RH + 0.31P + 0.39T$$

$$\text{White males (SD = 5.92): Age} = 23.17 + 0.15RH + 0.29P + 0.39T$$

An evaluation of the statistical methods in age-at-death estimation using root translucency and periodontosis was carried out by Schmitt and colleagues (2010). This was done since the correlation between the two features periodontosis and translucency, and chronological age-at-death is low in both Lamendin *et al.* (1992) and Prince and Ubelaker (2002) (Schmitt *et al.* 2010, 590). Several statistical prediction systems (least square regression, multinomial logistic regression and Bayesian method) were applied on the single rooted teeth (incisors and canines) from 214 individuals (114 males and 100 females), measuring periodontosis, root translucency and root height (Schmitt *et al.* 2010, 590). No significant difference between age-at-death estimation between males and females was found. The linear (least square) regression method gave the best results, despite the low correlation of periodontosis and translucency with chronological age-at-death (Schmitt *et al.* 2010, 596). The linear (least square) regression gave the following formula, where relative periodontosis (P) and relative translucency (T) is calculated the same as Lamendin *et al.* (1992):

$$\text{Age} = 20.591 + 0.516T + 0.336P$$

In the same year, Singhal and colleagues (2010) studied fifty mandibular central incisors from fifty individuals (27 males and 23 females) from Indian descent. The teeth were sectioned, dyed and the area, as well as the length of the translucency, were examined (Singhal *et al.* 2010, 18-19). The study found a strong linear correlation between the amount of translucency and chronological age, where translucency length was preferred over translucency area (Singhal 2010, 20). This resulted in the following formula (T = amount of translucency in millimetres, RH = root height in millimetres):

$$\text{Age} = 22.25 + 77.04 * (T/RH)$$

2.5.3 Archaeological Application of Root Translucency

The Bang and Ramm (1970) and Lamendin and colleagues (1992) formulae have been tested on archaeological material several times. Marcsik and colleagues (1992) tested the Bang and Ramm (1970) formulae on 200 intact teeth from the 8^{th} century and the estimated translucency age-at-death was compared with the estimated age-at-death using the Complex Method. No further statistical information is given on the accuracy of the translucency, but it is concluded that root translucency can be used in archaeological populations (Marcsik *et al.* 1992, 537). Vodavonić and colleagues (2011) tested the Bang and Ramm (1970) formulae, amongst other age-at-death estimation methods, on 192 individuals from the St. Theresa's Cathedral in Požega (Croatia). Again, no statistical information was given in the results, but the study concludes that root translucency can be used when combined with at least one other age indicator (Vodavonić *et al.* 2011, 17-18). Tang and colleagues (2014) tested the Bang and Ramm (1970) formulae on 297 individuals (146 males, 146 females, 6 unknown) of the collection from Christ Church Spitalfields, London, of which 162 individuals (76 males, 82 females, 3 unknown) could be used in age-at-death estimation and 12 individuals (8 males, 4 females) from the All Hallows (London) collection. This gave correlation coefficients of 0.45 in single teeth estimations and 0.46 in the average estimations of an individual (Tang *et al.* 2014, 335). Overall, the researchers conclude that root translucency as an age-at-death estimation marker has to be used with caution in archaeological material (Tang *et al.* 2014, 344).

Megyesi and colleagues (2006) tested the Lamendin and colleagues (1992) formulae on 176 individuals (89 males, 87 females) with 951 teeth from Christ Church Spitalfields, London, and 44 individuals (20 males, 24 females) with 237 teeth from St. Bride's, London (all individuals with known age and sex). This resulted in a mean error of 15.4 years (all teeth) and 13.2 years (when decalcified and poorly conserved teeth were excluded) for the Spitalfields individuals and 16.7 years (all teeth) and 13.3 years (when decalcified and poorly conserved teeth were excluded) for the St. Bride's individuals which was higher than the original Lamendin *et al.* study (Megyesi *et al.* 2006, 364-366).

2.5.4 Light Conditions

Adserias-Garriga and colleagues (2017) researched the influence of light on the accuracy of the formulae of Lamendin *et al.* (1992) and Prince and Ubelaker (2002). The study included 19 upper incisors of 11 males and 8 females and 36 upper and lower canines of 19 males and 17 females that were independently examined in three different light settings: 6500 lux, 3000 lux and 1600 lux (Adserias-Garriga 2017, 638). Although the study does not mention how the different light settings are set and monitored or what defines the lux emission (e.g. the lamp's specifications, illuminance measurement at the surface of the lamp or illuminance measurement at eye height), the conclusion is that the 1600 lux light intensity is significantly better to use than the other two light intensities (Adserias-Garriga 2017, 639-640).

This chapter has provided an overview of several of the most used age-at-death estimation methods used in forensic and osteoarchaeological context. Several methods and techniques to determine the chronological age-at-death by estimating the biological age-at-death have been developed on different areas of the human skeleton. This thesis will focus on the use of root translucency as an estimation marker for age-at-death in archaeological skeletal remains. The following chapter will present a review of the materials and methods used in this study.

3. Materials and Methods

The first part of this chapter focusses on the background, history and archival data of the Middenbeemster Human Skeletal Collection that is used in this thesis. The exact number of teeth will be mentioned together with the equipment and methods used. After that, there will be a focus on the methodology for measuring root translucency and the used formulae will be fully explained. Lastly, a review of the statistical analysis will be presented.

Before that, ethical considerations are important to discuss. Cultures, both contemporary and former cultures, treat their deceased in different ways, and (osteo)archaeologists should respect this. The ethical treatment of human remains is a delicate issue in archaeology, but common to encounter during excavation. Not until 1989, on the World Archaeology Congress in South-Dakota, a universal ethical code (The Vermillion Accord on Human Remains) was approved. The first rule of this ethical code was: “Respect for the mortal remains of the dead shall be accorded to all, irrespective of origin, race, religion, nationality, custom and tradition” (World Archaeology Congress 1989, rule 1). The Dutch Law on Funerals (Wet op Lijkbezorging) should be considered when archaeological human remains are studied, according to the Behavioural Code for Professional Archaeologists (NVvA 2001, 10-13). This means that human remains should be handled with dignity and respect during excavation and research.

3.1 Middenbeemster Collection

During the summer of 2011, the Faculty of Archaeology at Leiden University and Hollandia Archaeology excavated the former graveyard of the Keyserkerk in Middenbeemster (Figure 3). During the excavations, roughly 400 primary burials were exhumed and a total of over 500 skeletons were excavated on an area of approximately 250 m^2 (Lemmers *et al.* 2013, 35). The Middenbeemster church was in use from 1617 AD until 1866 AD, when it was prohibited by law to bury individuals on church property. Although people were buried here for 250 years, the majority of the exhumed individuals are most likely from the period 1829-1866 AD since historical documentation of the graveyard from this exact period registered over 600 individuals. Age-at-death, sex, burial location and often occupation are mentioned in this historical documentation.

3.1.1 Historical Overview

This historical overview is a resume of the historical overview from Falger and colleagues (2012). The Beemster Lake was drained and reclaimed between 1609 and 1613 by wealthy merchants who saw investment opportunities to increase the agricultural area and regulate water management. Within the newly created polder, a systematic rectangular grid used to divide the land into plots. Flax, cereals and rapeseed were cultivated at first, but eventually, the farmers mostly focussed on dairy/cheese production. Other occupations are known from the historical records: tailors, merchants, carpenters, servants etc.

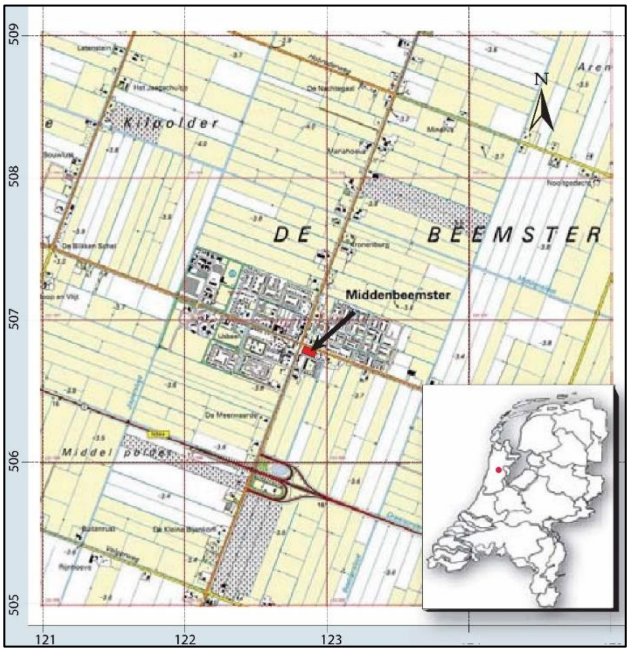

Figure 3: Location in Middenbeemster where excavation took place (Hakvoort 2013, 11).

Originally, five churches were planned to be built in the Beemster polder, but only one church, at the intersection of two main roads in the middle of the polder, was finished in 1621 AD. This church was ceremoniously consecrated in 1621 AD, the 'Keyserkerk' of Middenbeemster (midden = in the middle). Two annexes and a tower heightening the Keyserkerk were built in the following years. People were buried inside the church during the period 1638 to 1829 AD while the graveyard was used from at least 1617 AD until 1866 AD. From 1829 onwards, the Beemster civil administration managed the Keyserkerk graveyard and made it into a communal graveyard, meaning that all deceased were buried there regardless of their beliefs.

3.1.2 Historical Documentation

The burial records of over 600 individuals are still consultable in the provincial archives. These records are transcribed, translated and linked to the exhumed skeletons of the 2011 excavation. This archival work is mostly done by the historical association *Beemster* (Falger 2011, 22). This proved to be difficult since historical records are not coherent and burial plots were consecutively rented out to multiple individuals. Individuals were also placed between known burial plots and several burials were placed on top of each other, making identification more difficult. Nevertheless, approximately 120 excavated individuals have been linked to the burial records and name, age-at-death, sex and often occupation is known.

3.2 Used Materials from Middenbeemster

Only incisors and canines were used in this thesis since these teeth have preference and are mostly used in comparable studies (Adserias-Garriga *et al.* 2017, 638; Foti *et al.* 2001, 101; Lewis and Kasper 2018, 158-165; Sarajlić *et al.* 2006, 79; Ubelaker and Parra 2008, 609). The premolars and molars were not included in this study because these teeth are more often still intact in the maxilla and/or mandible. Alongside this, premolars and molars have multiple roots that complicate the proper measurement of root translucency (Bang and Ramm 1970, 12, 19). For this reason, only the single rooted anterior teeth (incisors and canines) were included in this study.

A preliminary investigation was completed to ensure that there were enough individuals of known sex and age-at-death that had teeth available to study. A list of the 124 known sex and age-at-death individuals was provided without the archival data to ensure blind testing. This preliminary investigation gave a list of 78 individuals with 615 teeth. However, when teeth were still intact in the maxilla or mandible, extraction of these teeth was not permitted. This resulted in a total of 580 loose teeth (Table 1) from 77 individuals that were available for research. All loose incisors and canines were examined (N=580). Teeth with substantial or severe wear, caries into the pulp chamber and pipe smokers' notches were noted but still included in this study.

Table 1: Distribution of the number of loose teeth for this study.

Tooth type	Total no.
Maxillary incisors	180
Maxillary canines	81
Mandibular incisors	221
Mandibular canines	110

3.2.1 Equipment

Measurements were carried out with an HBM Machines 150 mm Digital Sliding Calliper (accuracy: two decimal places). A 6000K cold white LED-panel (20 watts) was used as a light source. This LED-panel had a light power of 1700 lumen, measuring 200.000 lux above the panel and 2800 lux at eye-level. The amount of lux was measured with a Wetekom Digital Illuminance Light (Lux) Meter (accuracy: 1 lux). This digital lux meter was also regularly used to ensure consistent light conditions.

3.3 Methodology

This section of the chapter covers the technical aspects of human skeletal analysis and root translucency age-at-death estimation methods.

3.3.1 Skeletal Analysis

Approximately 400 primary burials were analysed to estimate sex, age-at-death, stature, body mass and pathological conditions for adult individuals. Also, the completeness and conservation of the skeletal material were registered. This analysis was performed in the Laboratory for Human Osteoarchaeology of the Faculty of Archaeology at Leiden University by Human Osteoarchaeology MSc students under the supervision of Dr Andrea Waters-Rist. Later, the historical documentation was linked to the data of the analyses. Only the methods used for sex and age-at-death estimation and (dental) pathological conditions will be discussed since these are applicable to this study.

3.3.1.1 Adult Age-at-Death Estimation

Age-at-death was estimated by analysing suture closure (Meindl and Lovejoy 1983) the auricular surface morphology (Buckberry and Chamberlain 2002), the pubic symphyseal face morphology (Brook and Suchey 1990), sternal rib end morphology (Íşcan *et al.* 1984) and dental attrition (Maat 2001). Also, several epiphyseal fusion sites that fuse after the age of 18 years are observed, such as the fusion sites at the medial clavicle, sternum and sacrum (Scheuer and Black 2000). Based on the results of these analyses, individuals were assigned to one of the osteological age categories: Early young adult (18-25 years), Late young adult (26-35 years), Middle adult (36-49 years) or Old adult (50+ years).

3.3.1.2 Sex Estimation

Sex estimation was done based on the recommendations of the Workshop of European Anthropologists (Ferembach *et al.* 1980, 517-527), the methodology of Buikstra and Ubelaker (1994) and Phenice (1969). The WEA method uses a weighted scoring system of cranial, mandibular and pelvic traits. The traits were scored as female (-2), probable female (-1), indeterminate (0), probable male (1) or male (2) and multiplied by the weight of the trait (1, 2 or 3). The cranial, mandibular and pelvic degree of sexualization was calculated separately. The same traits were scored according to the Buikstra and Ubelaker (1994) method, using the scoring system: female (F), probable female (PF), indeterminate (I), probable male (PM) or male (M). The Phenice (1969) traits only focus on the morphology of the pubic bone (*os pubis*), especially on the ventral arc, ischiopubic ramus and subpubic concavity. Additional to this, several osteometric traits (such as maximal humeral head diameter, clavicular maximal length, maximal length of the scapula) were measured to substantiate the first three sex estimation methods (Lemmers *et al.* 2013, 36-37).

3.3.1.3 (Dental) Pathological Conditions and Trauma

Pathological condition observation was done by macroscopic examination of each skeletal element per individual, for example trauma (like fractures), diseases or nutrient deficiencies. Although only long-term or chronic conditions leave marks on skeletal material, and even these long-term conditions do not always appear in the skeletal material. For example, tuberculosis is chronic when it is longer than one month, but it only shows skeletal lesions in 1% of the diseased (Mann and Hunt 2005, 97). This is in big contrast with a healing fracture which is directly visible in the skeletal material. For archaeological material establishing a cause of death is difficult without clear evidence of lesions on the bone (Waldron 2009, 1). Regarding dental diseases and deficiencies (like caries, abscesses, periodontitis, linear enamel hypoplasia), they are more often visible in the skeletal material. This is mostly caused by the fact that enamel and (primary) dentine do not remodel, so dental pathological conditions leave permanent marks on teeth unless these are *ante-mortem* lost (Hillson 2005, 185).

3.3.2 Dental Measurements

Dentition was identified by using White and Folkens' (2005) Human Bone Manual and by refitting the teeth in their former tooth sockets. The worldwide designation system for teeth (ISO 3950:2016) was used for identification of the teeth. When loose incisors and canines were identified in the correct anatomical order (Figure 4), three measurements were taken on the labial/buccal side. The first measurement taken was the dental root height (RH) in millimetres (Figure 5). The second measurement taken was the amount of periodontosis (P) in millimetres (Figure 5) using laboratory light. The third and last measurement taken, was the amount of transparency (T) in millimetres (Figure 6) using the LED-panel.

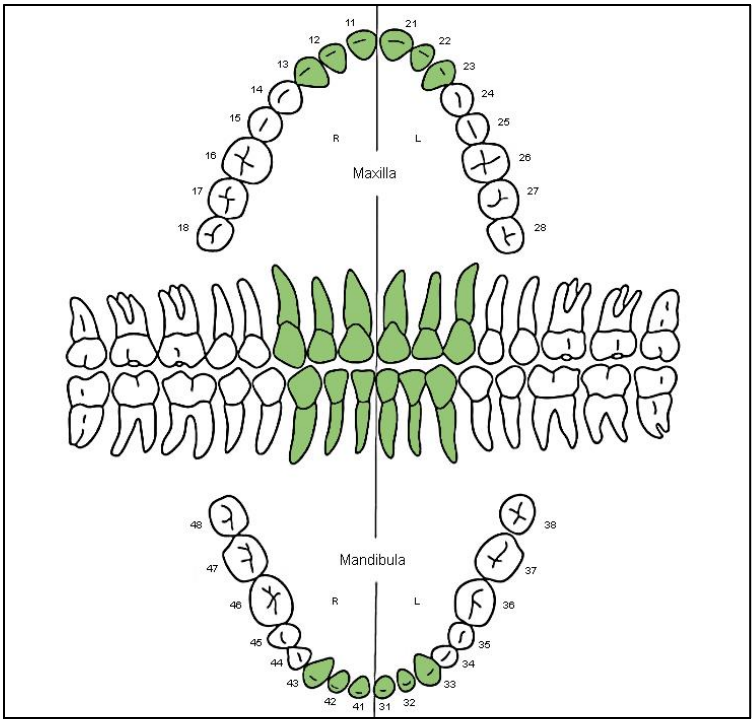

Figure 4: Dental designation system (ISO 3950:2016) and the teeth examined in this thesis.

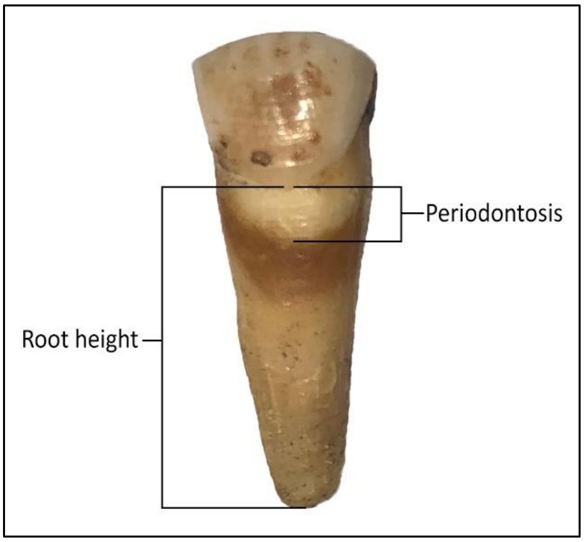

Figure 5: Indication of root height (RH) and periodontosis (P).

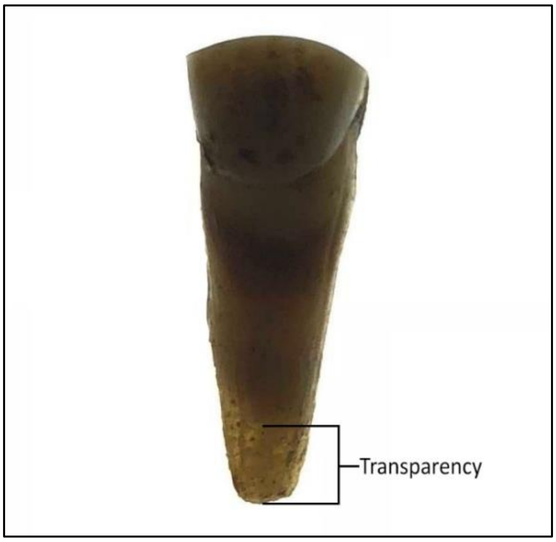

Figure 6: Indication of root transparency (T).

These measurements were entered in an Excel-sheet, registering feature number, tooth number, root height in millimetres (mm) transparency in mm, periodontosis in mm and remarks. Also, in this Excel-sheet are the formulae used for age-at-death estimation using root transparency (and periodontosis). Since dental roots and root translucency borders are not always straight, the measuring standards of Wegener and Albrecht (1980, 30) were applied to get consistent measurements (Figure 7).

This thesis tested the formulae for intact teeth from Bang and Ramm (1970), Wegener and Albrecht (1980) (general formula and tooth specific formulae), Lamendin and colleagues (1992), Prince and Ubelaker (2002) and Schmitt and colleagues (2010). All these formulae can be found in Table 2 and Table 3. The formula of Singhal and colleagues (2010) is also used, even though it is intended for sectioned teeth. This was done because of the simplicity of the formula, the simplicity of the observation of translucency in intact teeth (Rösing and Kvaal 1998, 453; Sengupta *et al.* 1998, 1227) and because the formula has successfully been used on intact teeth as well (Santoro *et al.* 2015, 1314).

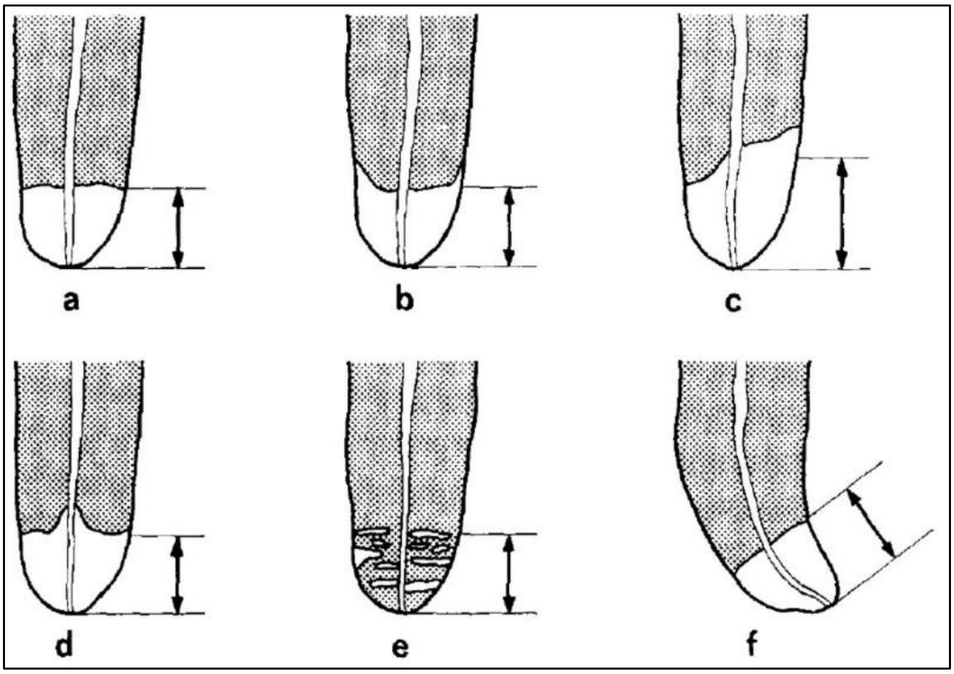

Figure 7: Measuring standards of root translucency, always measuring on the buccal side of the tooth (Wegener and Albrecht 1980, 30).

*Table 2: Overview of the different methodologies/formulae used in this thesis. [1] General formula, [2] Tooth specific formulae. Standard Deviation (SD) or Standard Error of the mean (SE). All measurements done in millimetres. In Lamendin et al., Prince and Ubelaker and Schmitt et al. T is Translucency*100/Root Height and P is Periodontosis*100/Root Height.*

Root translucency method	Formulae	RH	T	P	Precision in years
Bang and Ramm (1970)	$T \le 9$ mm: Age = $B_0 + B_1(T) + B_2(T)^2$ $T > 9$ mm: Age = $B_0 + B_1(T)$		X		9.71-13.80 (SD)
Wegener and Albrecht[1] (1980)	Age = 23.8 + 4.5(T)		X		15.30 (SD)
Wegener and Albrecht[2] (1980)	Age = C + RC(T)		X		12.70-15.80 (SD)
Lamendin *et al.* (1992)	Age = (0.18 * P) + (0.42 * T) + 25.53	X	X	X	5.86/7.31 (SD)
Prince and Ubelaker (2002)	Male: Age = 0.15(RH) + 0.29(P) + 0.39(T) + 23.17 Female: Age = 1.10(RH) + 0.31(P) + 0.39(T) + 11.82	X		X	5.93/6.21 (SD)
Schmitt *et al.* (2010)	Age = 20.591 + 0.516(T) + 0.336(P)	X	X		13.67 (SE)
Singhal *et al.* (2010)	Age = 22.25 + 77.04 * (T/RH)	X	X		Not given

Table 3: The additional tooth specific formula data for Bang and Ramm (1970) and Wegener and Albrecht[2] formulae.

Bang and Ramm (1970) reference table ($T \le 9$ mm)					Bang and Ramm (1970) reference table ($T \le 9$ mm)			Wegener and Albrecht (1980) Tooth specific		
Tooth no.	B_0	B_1	B_2	SD	B_0	B_1	SD	C	RC	SD
11	20.30	5.74	0.00	10.42	20.34	5.74	10.42	22.8	6.1	13.8
12	18.80	7.10	-0.164	10.83	22.06	5.36	10.73	28.9	3.0	12.7
13	26.20	4.64	-0.044	12.59	28.13	4.01	12.39	17.5	5.3	15.8
21	24.30	6.22	-0.119	9.71	26.78	4.96	9.58	25.2	4.5	14.9
22	20.90	6.85	-0.223	9.77	25.57	4.38	9.81	29.5	3.7	15.7
23	25.27	4.58	-0.073	13.80	27.59	3.65	13.60	22.5	4.1	14.3
31	23.16	9.32	-0.539	12.27	29.00	4.23	11.85	25.5	4.8	15.2
32	18.58	10.25	-0.538	10.08	38.81	2.81	12.43	26.6	4.6	15.4
33	27.45	7.38	-0.289	10.22	37.80	3.50	11.24	22.4	5.2	15.8
41	9.80	12.61	-0.711	10.91	37.56	2.94	12.84	34.4	2.7	15.2
42	26.57	7.81	-0.383	11.95	33.65	3.53	11.12	24.9	4.3	15.9
43	23.30	8.45	-0.348	10.52	41.50	2.84	10.74	24.9	4.7	15.6

3.3.3 Light Conditions

Six weeks after the initial data collection, ten individuals were remeasured at a different illumination strength (lux) to test if this has an influence on the taken measurements. As tested in the Adserias-Garriga and colleagues (2017) article. These results are presented in Chapter 4 (section 4.3).

3.3.4 Statistical Analysis

Statistical analysis was performed with Microsoft Excel 2016 and IBM SPSS (Statistical Package for the Social Sciences) statistics software version 24. Two regression analyses were performed, one applied to the *transparency ratio* (Transparency/Root Height) and one applied to transparency height (in mm) in relation to the known chronological age to derive a formula for the Middenbeemster collection. A paired T-test was done to see the accuracy between the chronological age and the estimated biological age that was calculated per tooth for every formula. Subsequently, these age-at-death estimations were grouped per individual (mean age-at-death estimation), per tooth group (incisors/canines), per sex. The same paired T-test was applied to the estimated ages per individual. Additionally, a Pearson's correlation analysis was done on the single tooth age-at-death estimations, mean age-at-death estimations, per tooth group and per sex. Also, the two newly developed formulae are tested on thirteen individuals from the Middenbeemster Collection that do not have a known age-at-death but do have an estimated osteological age category, as described in this chapter (Section 3.3.1.1).

3.4 Testing the New Formulae

The new formulae were tested on 21 randomly selected individuals from the Middenbeemster Collection. These individuals only have an estimated age-at-death that is translated into an osteological age category as described in section 3.3.1.1. Another 20 randomly selected individuals were examined from the Arnhem Collection (*Eusebiuskerk*). These individuals from Arnhem (Figure 8) were buried in the 17th to early 19th century, but further little is known about these individuals (e.g. social status) since no final report has been made on the excavations (van Alfen 2018). Both were used to test if the formulae were also applicable to estimate age-at-death for other individuals than the ones used for developing the formulae.

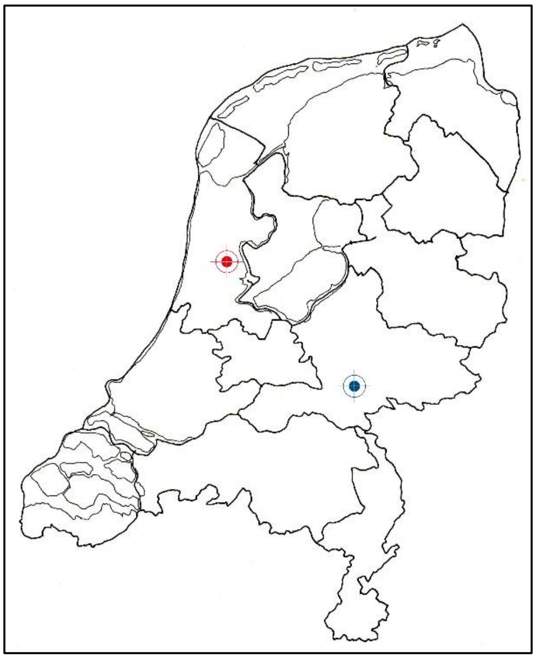

Figure 8: Map of The Netherlands with the two excavation locations of the used samples. Red: Middenbeemster. Blue: Arnhem.

The next chapter will present the results of this study, especially the results of the statistical analysis. The accuracy of the existing formulae will be presented, as well as the newly developed formulae.

4. Results

Statistical analysis is a crucial part of a study on human osteological data. The analyses are applied to support the answering of the research question with numerical evidence. It provides possibilities to derive additional information from the presented data in a clear and comparable way. This chapter will show the statistical analysis per formula, a total of nine formulae. In addition, it will present the statistical analysis for data that is grouped on sex (male and female) and tooth type (incisors and canines), to study possible differences between those variables.

The total of 588 intact loose teeth of 77 individuals were all examined on tooth root translucency and periodontosis, whereof 458 teeth (Table 4) could produce an age-at-death estimation in 67 individuals (27 males, 40 females) using root translucency. By the use of the combination of root translucency and periodontosis, 430 teeth could produce an age-at-death estimation in 65 individuals (25 males, 40 females). A total of 133 teeth could not produce an age-at-death estimation, whereof 125 teeth were marked as decalcified (Figure 9), four teeth had such severe wear that all enamel was worn away and one tooth had a resorbed open root. The collected data and the age-at-death estimations per tooth are presented in Appendix 1. The mean of the age-at-death estimations per individual and per formula are presented in Table 5.

Table 4: The distribution of teeth that produced an age-at-death estimation.

Tooth no.	Total no.	Tooth no.	Total no.	Tooth no.	Total no.	Tooth no.	Total no.
11	40	**21**	37	**31**	39	**41**	45
12	28	**22**	31	**32**	44	**42**	47
13	34	**23**	29	**33**	42	**43**	42

Figure 9: Example of all examined teeth of an individual being decalcified. The structure of the root is different from Fig. 5 and 6. When examined for translucency, no translucent zone will appear.

Table 5: The mean age-at-death estimations (in years) per individual and per formula. P.&U. = Prince and Ubelaker, B.&R. = Bang and Ramm, W.&A.[1] = Wegener and Albrecht (general formula), W.&A.[2] = Wegener and Albrecht (tooth-specific formulae). Formula 1 and 2 are presented below.

Feature no.	Known age	Lamendin	P.&U.	Schmitt	Singhal	B.&R.	W.&A.[1]	W.&A.[2]	Formula 1	Formula 2
45	47	39,33	43.70	37.46	42.38	50.14	41.64	43.48	43.80	45.32
47	21	29.03	30.58	23.94	28.19	29.99	28.50	29.80	27.78	27.26
51	74	56.36	55.83	50.62	74.04	68.78	69.50	66.08	65.74	66.49
53	55	42.29	47.71	45.00	43.23	50.16	41.31	43.41	44.65	45.07
59	38	40.88	41.32	37.98	45.87	49.47	43.89	44.74	46.06	46.77
60	26	30.17	32.03	25.95	29.30	31.69	29.53	31.37	29.32	29.00
88	50	47.30	53.35	48.74	52.66	54.48	51.52	49.66	52.15	54.42
92	59	44.59	46.85	47.92	46.49	51.84	42.59	44.25	47.88	46.55
93	67	42.67	44.42	43.72	45.34	50.77	43.62	46.51	46.21	47.18
100	75	53.99	54.64	51.96	66.83	67.48	61.93	70.50	62.39	63.18
101	39	41.32	43.00	45.58	39.67	38.30	34.91	36.95	41.17	36.89
149	25	29.34	29.85	27.21	26.07	26.71	26.28	28.23	24.88	23.70
151	27	33.35	35.61	31.45	32.51	35.18	31.72	35.21	33.27	32.38
153	57	46.25	47.63	45.96	52.44	56.28	51.07	51.96	52.65	54.74
155	54	55.70	59.01	54.76	68.69	66.37	61.71	63.79	63.32	62.89
158	60	50.45	51.97	51.03	58.63	62.65	55.00	58.03	57.22	57.91
160	28	36.98	39.18	38.65	35.35	36.06	33.57	35.63	35.52	33.70
174	45	46.94	50.14	44.92	55.12	56.39	51.28	53.40	54.89	55.07
194	58	42.61	46.56	48.71	40.76	49.41	43.78	45.37	42.00	47.16
195	54	44.72	49.22	43.83	53.91	55.54	49.43	48.85	52.85	52.93
213	22	40.81	39.47	32.82	46.86	49.96	44.05	43.11	48.17	48.16
236	24	29.37	29.04	23.87	29.10	31.01	29.61	31.74	29.01	29.05
239	23	33.80	34.28	30.42	34.56	39.18	35.19	37.25	35.48	37.04
243	62	48.48	51.97	47.24	56.90	57.67	52.44	54.11	55.99	56.13
246	19	31.05	31.29	27.94	28.52	29.20	27.90	29.36	27.23	26.24
285	71	43.51	43.23	38.60	52.01	53.66	48.96	53.26	52.68	53.28
302	73	61.19	61.00	51.75	85.31	74.41	74.26	75.81	65.98	65.15
303	44	37.20	39.04	32.43	41.46	45.73	39.38	42.37	43.00	42.66
306	31	34.72	34.25	29.27	37.92	40.78	36.77	38.40	39.34	39.26
307	21	37.15	36.00	31.16	41.93	41.32	37.52	38.72	43.38	40.22
309	58	43.05	48.59	43.50	46.51	48.37	45.81	52.63	47.96	50.17
310	35	37.84	38.45	35.62	40.23	44.76	38.95	40.00	41.79	41.97
313	46	48.61	48.39	44.20	60.01	61.23	54.21	56.29	57.94	57.59
324	54	47.69	47.58	42.49	58.95	64.95	58.64	61.44	57.08	60.57
325	36	33.44	33.29	27.66	36.09	41.64	37.57	39.63	37.24	40.13
327	31/37	36.50	36.05	31.27	40.69	41.05	36.83	38.11	42.19	39.33
337	68	52.08	52.37	48.38	65.74	65.10	62.37	63.40	61.00	62.58
338	33	30.90	32.15	26.43	30.73	32.51	30.41	32.34	31.13	30.41
339	64	49.10	49.39	44.76	60.76	56.32	51.14	51.89	58.29	55.13
342	75	41.49	41.63	36.38	48.85	57.33	52.03	54.74	49.04	53.89
346	59	44.78	51.65	48.18	46.75	48.71	46.75	47.75	47.86	50.36
347	56	40.48	42.53	41.65	42.43	49.05	42.92	44.76	43.94	46.67
350	23	26.47	29.52	23.28	22.25	22.59	23.80	24.50	20.18	19.83
359	46	57.24	62.37	59.01	68.83	66.58	63.61	62.99	62.75	63.04
363	61	40.78	40.92	37.09	46.49	50.03	44.74	47.60	47.48	48.05
369	30	31.07	32.24	27.39	30.32	31.35	30.28	31.97	30.45	29.94
374	80	-	-	-	75.06	80.43	78.61	97.10	66.15	68.86
381	68	-	-	-	57.71	52.56	49.09	57.08	56.97	53.48
383	55	45.51	44.06	38.03	57.61	54.66	48.38	50.62	56.18	52.29
385	25	31.61	32.99	28.17	31.00	32.60	30.42	32.04	31.40	30.37
386	61	52.33	52.46	45.60	67.69	62.93	58.51	58.72	61.50	59.94
390	71	46.18	48.52	40.02	58.86	61.48	55.48	55.15	57.01	58.32
394	58	46.30	48.30	41.03	56.94	51.74	52.78	48.90	56.43	56.81
413	39	36.70	38.22	32.02	40.52	43.44	38.35	40.32	42.04	41.41

422	29	39.14	39.41	35.32	43.81	45.36	39.20	41.04	45.13	42.31
427	27	32.04	32.22	29.17	31.19	29.79	30.03	32.34	30.96	29.30
430	30	32.35	35.19	29.23	31.93	34.58	32.02	33.50	32.50	32.64
436	64	43.57	46.06	39.71	53.06	54.90	49.81	50.03	53.45	54.03
441	23	31.50	34.09	26.80	31.94	34.90	32.17	33.46	32.47	32.87
457	57	44.26	47.68	46.06	47.30	53.69	43.02	44.60	48.68	47.12
461	28	33.34	34.62	32.93	28.84	29.68	28.39	29.82	28.61	27.16
466	43	35.96	39.06	35.99	35.12	40.12	33.76	36.17	36.23	35.27
473	42	35.01	35.85	32.85	35.49	40.23	35.83	38.39	36.65	38.08
476	31	34.01	34.86	29.49	35.93	37.12	34.44	36.24	37.13	36.08
482	36	33.48	33.09	28.82	35.16	37.40	33.51	35.61	36.32	34.91
487	29	27.53	25.64	26.34	32.44	36.10	31.11	32.04	32.23	30.71
521	69	35.09	34.92	29.67	38.41	43.65	38.94	40.10	39.85	41.98

4.1 Regression Analysis

In the studied collection, the correlation coefficient (r) between chronological age and translucency ratio (translucency in mm/root length in mm) is r = 0.70, and between chronological age and translucency (in mm) is r = 0.73. The regression analyses focussed on linear regression, as done by Wegener and Albrecht (1980) and Singhal *et al.* (2010) and on quadratic regression as done by Bang and Ramm (1970) by using translucency ratio (translucency in mm/root length in mm) and the translucency length (in mm) as variable, resulted in two formula. Based on the Middenbeemster data, quadratic regression gave the best results. The first formula was acquired using translucency ratio ($p = <0.001$) (Figure 10), resulting in the following formula with a coefficient of determination (R^2) of 0.519:

Formula 1: Age = 20.179 + 106.215(T/RH) + -57.122*$(T/RH)^2$

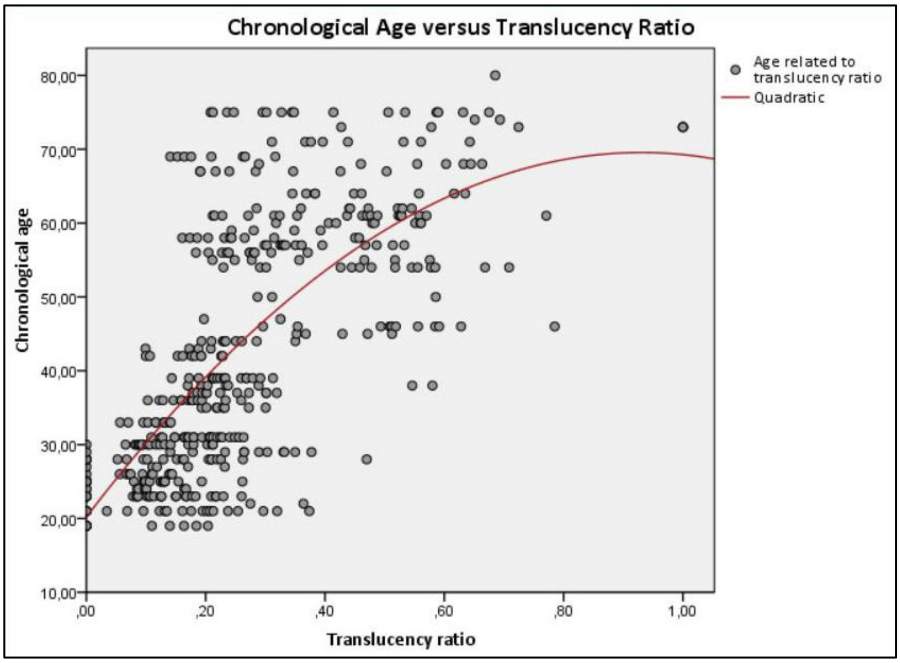

Figure 10: A scatterplot with the chronological age on the y-axis and translucency ratio on the x-axis and the line of the quadratic regression formula.

The other quadratic formula was based on translucency length (in mm) ($p = <0.0001$) (Figure 11), resulting in the following formula with a coefficient of determination (R^2) of 0.540:

$$\text{Formula 2: Age} = 19.832 + 7.667*T + -0.299*T^2$$

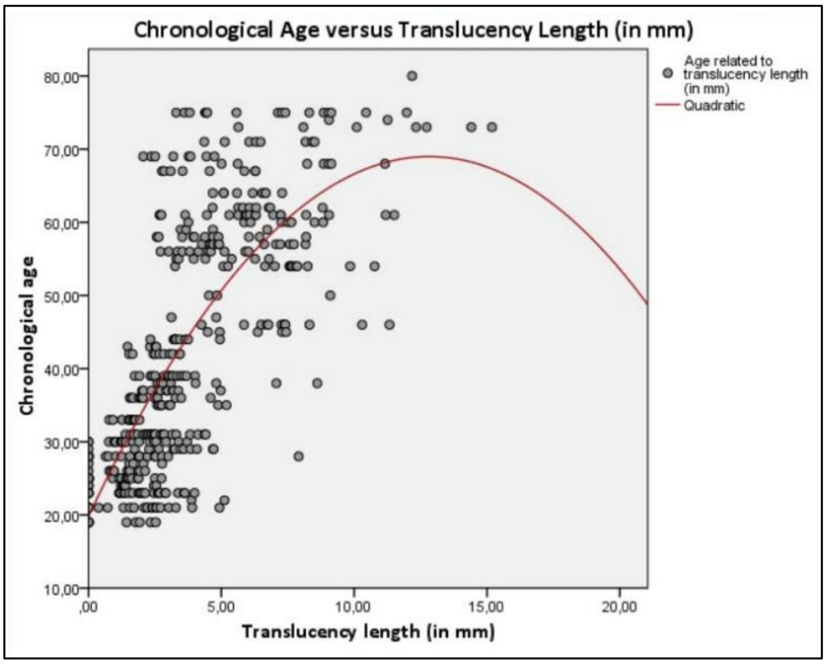

Figure 11: A scatterplot with the chronological age on the y-axis and translucency length (in mm) on the x-axis and the line of the quadratic regression formula.

4.2 The Formulae

To analyse the accuracy of the formulae a paired T-test was performed. If the estimated age obtained by the formulae is in agreement with the chronological age, the result of the paired T-test is expected to be non-significant. Furthermore, to estimate the correlation of the chronological age with the estimated biological age, a Pearson's correlation test has been performed for every formula. In addition, this correlation test was used to see the difference in correlation per tooth group and sex. A correlation of 1 describes a perfect correlation, while a correlation of 0 describes no correlation.

4.2.1 Bang and Ramm (1970) Formulae

The age-at-death that was estimated per tooth with the Bang and Ramm (1970) formulae showed a mean difference of -2.51 years (95%CI: -3.56 – -1.47), and a standard mean error of 0.53. There was a significant difference ($p = <0.001$) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be $r = 0.75$. On the total number ($N = 458$, 100%) of age-at-death estimations, 17.5% ($N = 80$) of the estimations deviates only ± 2 years or less of the chronological age, 39.7% (N = 182) deviates ± 5 years or less and 65.5% (N = 300) deviates ± 10 years or less. For incisors, the analysis resulted in a significant (p = 0.011) mean difference of -1.68, a standard mean error of 0.66 and a correlation coefficient of r = 0.72. For canines, this resulted in a non-significant (p = 0.606) mean difference of -4.27, a standard mean error of 0.87 and a correlation coefficient of r = 0.80. There was a significant (p <0.001) difference in accuracy between females (N = 262) and males (N = 196). The correlations between the sexes show a strong correlation although they were not similar, namely r = 0.79 in females and r = 0.70 in males.

The mean age-at-death that was estimated with all teeth available per individual using these formulae showed a non-significant (p = 0.248) mean difference of -1.41 years (95%CI: -3.83 - 1.00), with a standard mean error of 1.21 and a correlation coefficient of r = 0.83. On the total number (N = 67, 100%) of mean age-at-death estimations, 22.4% (N = 15) of the estimations deviates only ± 2 years or less of the chronological age, 41.8% (N = 28) deviates ± 5 years or less and 65.5% (N = 50) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 27), there was a non-significant (p = 0.083) difference in accuracy. The correlations were high and relatively similar, namely r = 0.84 in females and 0.83 in males. Indicating that the accuracy and correlation of these formulae slightly increase by use of data that is grouped per individual.

4.2.2 Wegener and Albrecht (1980) General Formula

The age-at-death that was estimated per tooth with the Wegener and Albrecht (1980) general formula showed a mean difference of 1.47 years (95%CI: 0.41 – 2.53), and a standard mean error of 0.54. There was a significant difference (p = 0.007) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be r = 0.75. On the total number (N = 458, 100%) of age-at-death estimations, 20.5% (N = 94) of the estimations deviates only ± 2 years or less of the chronological age, 44.8% (N = 205) deviates ± 5 years or less and 67.0% (N = 307) deviates ± 10 years or less. For incisors, the analysis resulted in a significant (p = 0.003) mean difference of -1.99, a standard mean error of 0.66 and a correlation coefficient of r = 0.72. For canines, this resulted in a non-significant (p = 0.705) mean difference of 0.36, a standard mean error of 0.94 and a correlation coefficient of r = 0.76. There was a significant (p <0.001) difference in accuracy between females (N = 262) and males (N = 196). The correlations between the sexes show a high correlation although they were not similar, namely r = 0.79 in females and r = 0.68 in males.

The mean age-at-death that was estimated with all teeth available per individual using this formula showed a significant (p = 0.036) mean difference of 2.72 years (95%CI: 0.18 – 5.26), with a standard mean error of 1.27 and a correlation coefficient of r = 0.81. On the total number (N = 67, 100%) of mean age-at-death estimations, 20.9% (N = 18) of the estimations deviates only ± 2 years or less of the chronological age, 43.3% (N = 29) deviates ± 5 years or less and 68.7% (N = 46) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 27), there was a non-significant (p = 0.060) difference in accuracy. The correlations were high and relatively similar, namely r = 0.82 in females and 0.81 in males. The results indicate that the accuracy and correlation of this formula neither increase nor decrease by use of data that is averaged per individual.

4.2.3 Wegener and Albrecht (1980) Tooth Specific Formulae

The age-at-death that was estimated per tooth with the Wegener and Albrecht (1980) formulae for individual teeth showed a mean difference of -0.27 years (95%CI: -1.33 – -0.80), and a standard mean error of 0.54. There was a non-significant difference (p = 0.620) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be r = 0.74. On the total number (N = 458, 100%) of age-at-death estimations, 20.1% (N = 92) of the estimations deviates only ± 2 years or less of the chronological age, 40.4% (N = 185) deviates ± 5 years or less and 67.5% (N = 309) deviates ± 10 years or less. For incisors, the analysis resulted in a non-significant (p = 0.384) mean difference of -0.59, a standard mean error of 0.67 and a correlation coefficient of r = 0.70. For canines, this resulted in a non-significant (p = 0.660) mean difference of 0.40, a standard mean error of 0.91 and a correlation coefficient of r = 0.78. There was a significant (p <0.001) difference in accuracy between females (N = 262) and males (N = 196). The correlations between the sexes were high although not similar, namely r = 0.78 in females and r = 0.68 in males.

The mean age-at-death that was estimated with all teeth available per individual using these formulae showed a non-significant (p = 0.248) mean difference of 0.75 years (95%CI: -1.76 – 3.94), with a standard mean error of 1.26 and a correlation coefficient of r = 0.81. On the total number (N = 67, 100%) of mean age-at-death estimations, 17.9% (N = 12) of the estimations deviates only ± 2 years or less of the chronological age, 43.3%

(N = 29) deviates ± 5 years or less and 68.7% (N = 46) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 27), there was a non-significant (p = 0.206) difference in accuracy. The correlations were high and relatively similar, namely r = 0.83 in females and 0.79 in males. Indicating that the accuracy and correlation of these formulae neither increase nor decrease by use of data that is grouped per individual, with the exception of the difference in the accuracy of age-at-death estimation between the two sexes.

4.2.4 Lamendin *et al.* (1992) Formula

The age-at-death that was estimated per tooth with the Lamendin and colleagues (1992) formula showed a mean difference of 3.47 years (95%CI: 2.31 – 4.65), and a standard mean error of 0.59. There was a significant difference (p = <0.001) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be r = 0.72. On the total number (N = 430, 100%) of age-at-death estimations, 18.6% (N = 80) of the estimations deviates only ± 2 years or less of the chronological age, 40.7% (N = 175) deviates ± 5 years or less and 64.2% (N = 276) deviates ± 10 years or less. For incisors, the analysis resulted in a significant (p = <0.001) mean difference of 2.28, a standard mean error of 0.72 and a correlation coefficient of r = 0.68. For canines, this resulted in a significant (p = <0.000) mean difference of 4.83, a standard mean error of 1.02 and a correlation coefficient of r = 0.76. There was a significant (p <0.001) difference in accuracy between females (N = 247) and males (N = 183). The correlations between the sexes were high although not similar, namely r = 0.79 in females and r = 0.65 in males.

The mean age-at-death that was estimated with all teeth available per individual using this formula showed a significant (p = 0.001) mean difference of 4.89 years (95%CI: 1.96 – 7.83), with a standard mean error of 1.47 and a correlation coefficient of r = 0.78. On the total number (N = 65, 100%) of mean age-at-death estimations, 13.8% (N = 9) of the estimations deviates only ± 2 years or less of the chronological age, 35.4% (N = 23) deviates ± 5 years or less and 58.5% (N = 38) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 25), there was a significant (p = 0.034) difference in accuracy. The correlations were high and relatively similar, namely r = 0.81 in females and 0.79 in males. Indicating that the accuracy and correlation of these formulae decrease by use of data that is grouped per individual in both sexes.

4.2.5 Prince and Ubelaker (2002) Formulae

The age-at-death that was estimated per tooth with the Prince and Ubelaker (2002) formulae showed a mean difference of 2.28 years (95%CI: 1.11 – 3.45), and a standard mean error of 0.60. There was a significant difference (p = <0.001) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be r = 0.71. On the total number (N = 430, 100%) of age-at-death estimations, 16.0% (N = 69) of the estimations deviates only ± 2 years or less of the chronological age, 37.0% (N = 159) deviates ± 5 years or less and 66.3% (N = 285) deviates ± 10 years or less. For incisors, the analysis resulted in a significant (p = 0.006) mean difference of 2.02, a standard mean error of 0.73 and a correlation coefficient of r = 0.67. For canines, this resulted in a significant (p = 0.008) mean difference of 2.82, a standard mean error of 1.04 and a correlation coefficient of r = 0.73. There was a significant (p <0.001) difference in accuracy between females (N = 247) and males (N = 183). The correlations between the sexes were not similar, namely r = 0.78 in females and r = 0.66 in males.

The mean age-at-death that was estimated with all teeth available per individual using these formulae showed a significant (p = 0.023) mean difference of 3.39 years (95%CI: 0.47 – 6.31), with a standard mean error of 1.46 and a correlation coefficient of r = 0.76. On the total number (N = 65, 100%) of mean age-at-death estimations, 7.7% (N = 5) of the estimations deviates only ± 2 years or less of the chronological age, 36.9% (N = 24) deviates ± 5 years or less and 64.6% (N = 42) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 25), there was a significant (p = 0.007) difference in accuracy. The correlations were high and relatively similar, namely r = 0.83 in females and 0.79 in males. Meaning that the accuracy and correlation of these formulae do not increase or decrease by use of data that is grouped per individual or sex.

4.2.6 Schmitt *et al.* (2010) Formula

The age-at-death that was estimated per tooth with the Schmitt and colleagues (2010) formula showed a mean difference of 6.52 years (95%CI: 5.32 – 7.71), and a standard mean error of 0.61. There was a significant difference (p = <0.001) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be r = 0.67. On the total number (N = 430, 100%) of age-at-death estimations, 22.6% (N = 97) of the estimations deviates only ± 2 years or less of the chronological age, 39.1% (N = 168) deviates ± 5 years or less and 63.7% (N = 274) deviates ± 10 years or less. For incisors, the analysis resulted in a significant ($p = <0.001$) mean difference of 5.50, a standard mean error of 0.76 and a correlation coefficient of $r = 0.63$. For canines, this resulted in a significant ($p = <0.000$) mean difference of 8.61, a standard mean error of 1.01 and a correlation coefficient of $r = 0.75$. There was a significant ($p <0.001$) difference in accuracy between females (N = 247) and males (N = 183). The correlations between the sexes were high although not similar, namely $r = 0.71$ in females and $r = 0.62$ in males.

The mean age-at-death that was estimated with all teeth available per individual using this formula showed a significant ($p = 0.036$) mean difference of 7.56 years (95%CI: 4.59 – 10.53), with a standard mean error of 1.49 and a correlation coefficient of $r = 0.74$. On the total number (N = 65, 100%) of mean age-at-death estimations, 21.5% (N = 14) of the estimations deviates only ± 2 years or less of the chronological age, 32.3% (N = 21) deviates ± 5 years or less and 58.5% (N = 38) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 25), there was a significant ($p = 0.040$) difference in accuracy. The correlations were high and relatively similar namely $r = 0.77$ in females and 0.74 in males. Indicating that the accuracy and correlation of this formula do not increase or decrease by use of data that is grouped per individual or sex.

4.2.7 Singhal *et al.* (2010) Formula

The age-at-death that was estimated per tooth with the Singhal and colleagues (2010) formula showed a mean difference of -0.34 years (95%CI: -1.49 – 0.80), and a standard mean error of 0.58. There was a non-significant difference ($p = 0.558$) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be $r = 0.71$. On the total number (N = 458, 100%) of age-at-death estimations, 19.9% (N = 91) of the estimations deviates only ± 2 years or less of the chronological age, 41.7% (N = 191) deviates ± 5 years or less and 65.9% (N = 302) deviates ± 10 years or less. For incisors, the analysis resulted in a non-significant ($p = 0.294$) mean difference of -0.75, a standard mean error of 0.71 and a correlation coefficient of $r = 0.68$. For canines, this resulted in a non-significant ($p = 0.606$) mean difference of 0.52, a standard mean error of 1.01 and a correlation coefficient of $r = 0.73$. There was a significant ($p <0.001$) difference in accuracy between females (N = 262) and males (N = 196). The correlations between the sexes were high although not similar, namely $r = 0.79$ in females and $r = 0.64$ in males.

The mean age-at-death that was estimated with all teeth available per individual using this formula showed a non-significant (p = 0.725) mean difference of 0.47 years (95%CI: -2.17 – 3.11), with a standard mean error of 1.32 and a correlation coefficient of r = 0.78. On the total number (N = 67, 100%) of mean age-at-death estimations, 22.4% (N = 15) of the estimations deviates only ± 2 years or less of the chronological age, 44.8% (N = 30) deviates ± 5 years or less and 68.7% (N = 46) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 27), there was a non-significant (p = 0.060) difference in accuracy. The correlations were high and relatively similar namely r = 0.81 in females and 0.80 in males. Indicating that the accuracy and correlation of this formula increase by use of data that is grouped per individual.

4.2.8 Formula 1 based on Translucency Ratio

The age-at-death that was estimated per tooth with the first formula (Formula 1) which was presented in this thesis, based on translucency ratio, showed a mean difference of 0.004 years (95%CI: -1.08 – 1.09), and a standard mean error of 0.55. There was a non-significant difference (p = 0.994) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be r = 0.73. On the total number (N = 458, 100%) of age-at-death estimations, 21.2% (N = 97) of the estimations deviates only ± 2 years or less of the chronological age, 39.3% (N = 180) deviates ± 5 years or less and 66.4% (N = 304) deviates ± 10 years or less. For incisors, the analysis resulted in a non-significant (p = 0.518) mean difference of -0.44, a standard mean error of 0.67 and a correlation coefficient of r = 0.70. For canines, this resulted in a non-significant (p = 0.331) mean difference of 0.94, a standard mean error of 0.96 and a correlation coefficient of r = 0.76. There was a significant (p <0.001) difference in accuracy between females (N = 262) and males (N = 196). The correlations between the sexes were high although not similar, namely r = 0.79 in females and r = 0.68 in males.

The mean age-at-death that was estimated with all teeth available per individual using this formula showed a non-significant (p = 0.377) mean difference of 1.15 years (95%CI: -1.43 – 3.72), with a standard mean error of 1.29 and a correlation coefficient of r = 0.81. On the total number (N = 67, 100%) of age-at-death estimations, 19.4% (N = 13) of the estimations deviates only ± 2 years or less of the chronological age, 38.8% (N = 26) deviates ± 5 years or less and 70.1% (N = 47) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 27), there was a significant (p = 0.015) difference in accuracy.

The correlations were high and relatively similar namely r = 0.82 in females and 0.83 in males. Indicating that the accuracy and correlation of this formula do not increase or decrease by use of data that is grouped per individual or sex.

4.2.9 Formula 2 based on Translucency Length

The age-at-death that was estimated per tooth with the second formula (Formula 2) which was presented in this thesis, based on translucency length, showed a mean difference of -0.0005 years (95%CI: -1.02 – 1.02), and a standard mean error of 0.52. There was a non-significant difference (p = 0.999) between the chronological age and the estimated biological age. In addition, the correlation between the chronological age with the estimated biological age was found to be r = 0.77. On the total number (N = 458, 100%) of age-at-death estimations, 19.4% (N = 89) of the estimations deviates only ± 2 years or less of the chronological age, 42.6% (N = 195) deviates ± 5 years or less and 68.1% (N = 312) deviates ± 10 years or less. For incisors, the analysis resulted in a non-significant (p = 0.442) mean difference of 0.49, a standard mean error of 0.63 and a correlation coefficient of r = 0.74. For canines, this resulted in a non-significant (p = 0.257) mean difference of -1.03, a standard mean error of 0.91 and a correlation coefficient of r = 0.79. There was a significant (p <0.001) difference in accuracy between females (N = 262) and males (N = 196). The correlations between the sexes were high although not similar, namely r = 0.80 in females and r = 0.71 in males.

The mean age-at-death that was estimated with all teeth available per individual using this formula showed a non-significant (p = 0.354) mean difference of 1.13 years (95%CI: -1.28 – 3.54), with a standard mean error of 1.21 and a correlation coefficient of r = 0.84. On the total number (N = 67, 100%) of age-at-death estimations, 23.9% (N = 16) of the estimations deviates only ± 2 years or less of the chronological age, 44.8% (N =30) deviates ± 5 years or less and 74.6% (N = 50) deviates ± 10 years or less. With respect to sex (female N = 40, male N = 27), there was a non-significant (p = 0.068) difference in accuracy. The correlations were high and relatively similar namely r = 0.84 in females and 0.85 in males. Indicating that the accuracy and correlation of this formula increase by use of data that is grouped per individual.

4.2.10 Summary of the Formulae

The results of the statistical analysis are summarised in two tables, one with the data considering all (N = 458) age-at-death estimations of single teeth (Table 6) and one with the data considering the mean age-at-death estimations per individual (Table 7). Both of the tables are arranged in the order of giving the best estimations of age-at-death in relation to the chronological age.

Table 6: Summary of the statistical analyses of the different formula considering all (N = 458) age-at-death estimations of single teeth. The formulae are in the order of giving the best to worst age-at-death estimations in relation to the chronological age, based on the mean difference and percentage correct within ±2 years and ±5 years.

Estimations per tooth	Mean difference	p-value	Std. mean error	Correlation (r)	Difference between sex	% in ±2 years	% in ±5 years	% in ±10 years
Formula 2 (translucency length)	0.0005	0.999	0.52	0.76	Yes	19.4%	42.6%	68.1%
Formula 1 (translucency ratio)	0.004	0.994	0.55	0.72	Yes	21.2%	39.3%	66.4%
Wegener and Albrecht[2] (1980)	-0.27	0.620	0.54	0.73	Yes	20.1%	40.4%	67.5%
Wegener and Albrecht[1] (1980)	1.47	0.007	0.54	0.73	Yes	20.5%	44.8%	67.0%
Singhal *et al.* (2010)	-0.34	0.558	0.58	0.70	Yes	19.9%	41.7%	65.9%
Bang and Ramm (1970)	-2.51	<0.001	0.53	0.75	Yes	17.5%	39.7%	65.5%
Prince and Ubelaker (2002)	2.28	<0.001	0.60	0.69	Yes	16.0%	37.0%	66.3%
Lamendin *et al.* (1992)	3.47	<0.001	0.59	0.71	Yes	18.6%	40.7%	64.2%
Schmitt *et al.* (2010)	6.52	<0.001	0.61	0.66	Yes	22.6%	39.1%	63.7%

Table 7: Summary of the statistical analyses of the different formula considering the mean age-at-death estimations per individual (N = 67). The formulae are in the order of giving the best to worst age-at-death estimations in relation to the chronological age, based on the mean difference, difference between sexes (yes or no) and percentage correct within ±2 years and ±5 years.

Average estimation per individual	Mean difference	p-value	Std. mean error	Correlation (r)	Difference between sex	% in ±2 years	% in ±5 years	% in ±10 years
Formula 2 (translucency length)	1.13	0.354	1.21	0.84	No	23.9%	44.8%	74.6%
Singhal *et al.* (2010)	0.47	0.725	1.32	0.78	No	22.4%	44.8%	68.7%
Bang and Ramm (1970)	-1.41	0.248	1.21	0.83	No	22.4%	41.8%	65.5%
Wegener and Albrecht[2] (1980)	0.75	0.248	1.26	0.81	Yes	17.9%	43.3%	68.7%
Wegener and Albrecht[1] (1980)	2.72	0.036	1.27	0.81	No	20.9%	43.3%	68.7%
Formula 1 (translucency ratio)	1.15	0.377	1.29	0.81	No	19.4%	38.8%	70.1%
Prince and Ubelaker (2002)	3.39	0.023	1.46	0.76	Yes	7.7%	36.9%	64.6%
Lamendin *et al.* (1992)	4.89	0.001	1.47	0.78	Yes	13.8%	35.4%	58.5%
Schmitt *et al.* (2010)	7.56	0.036	1.49	0.74	Yes	21.5%	32.3%	58.5%

4.3 Testing the New Formulae

The newly developed formulae were tested on the single rooted dentition (N = 133) of 21 individuals (11 [probable] males, 9 [probable] females), consisting of three early young adults (18-25 years), six late young adults (26-35 years), eight middle adults (35-50 years) and four old adults (50+ years) from the Middenbeemster Collection. Five age-at-death estimations did not match the assigned osteological age category when using

Formula 1, three deviated more than ± 2 years from the assigned age category. Four age-at-death estimations did not match the assigned osteological age category when using formula 2, but only one deviated more than ± 2 years from the assigned age category. In contrast, the Singhal and colleagues (2010) formula also produced five wrong estimations in the current study of which again three deviated more than ± 2 years from the assigned age category.

These formulae were also tested on another Dutch osteoarchaeological Collection, from Arnhem. It consisted of the single rooted teeth (N = 158) of 20 individuals (10 [probable] males and 10 [probable] females), consisting of consisting of three early young adults (18-25 years), four late young adults (26-35 years), nine middle adults (35-50 years) and four old adults (50+ years). Five age-at-death estimations did not match the assigned osteological age category when using Formula 1, two deviated more than ± 2 years from the assigned age category. Three age-at-death estimations did not match the assigned osteological age category when using formula 2, but only one deviated more than ± 2 years from the assigned age category. In contrast, the Singhal and colleagues (2010) formula also produced five wrong estimations in the current study of which again three deviated more than ± 2 years from the assigned age category.

4.4 Light Conditions

Adserias-Garriga and colleagues (2017) hypothesized that the level of illumination (in lux) influences the accuracy of translucency measurements. In order to test this hypothesis, the translucency was measured again several weeks after data collection at a lower light intensity. The first measurement of translucency was performed at a light intensity of 2800 lux at eye height, the second time the root translucency was 1850 lux at eye height for 39 teeth of five individuals. This resulted in a statistically significant ($p = 0.022$) difference of maximal ± 0.84 mm. This results in a maximal age-at-death estimation difference of 1.5-6 years, depending on the amount of translucency the tooth already had.

The next chapter will discuss the results that are obtained during this study and compare those results with similar studies previously done. It will focus on what formula is best used for Dutch archaeological human remains. In addition, the limitations of this thesis will be discussed.

5. Discussion

Chronological age-at-death determination by estimating the biological age-at-death is an important and basic parameter in both archaeological and forensic human remains. The use of dental root translucency has been validated in estimating the age-at-death of an individual, especially in present-day populations, but also proven to be applicable to archaeological human remains for several times. This chapter presents the accuracy of the tested methodology in comparison to other studies and presents several aspects that influence age-at-death estimation (i.e. the effects of dental disease, sex, geographical background and light conditions). Furthermore, the use of dental root translucency is compared with the earlier mentioned Complex Method.

5.1 Caution taken with Archaeological Known Age-at-Death Individuals

Before going into detail about the applicability of age-at-death estimation using dental root translucency, a point of thought has to be discussed. The concept of 'known age-at-death' is used in this study, but is this 'known age-at-death' really that known? This problem is already addressed by Saunders and colleagues (1992) when working with an osteoarchaeological sample from Belleville, Ontario (Canada), of which 80 individuals were identified (name, age-at-death and sex) by the coffin nameplates and written burial record. However, no legal documentation of the age-at-death of individuals is available, such as birth or death certificates (Saunders *et al.* 1992, 115-116). Transcription errors in the burial records or coffin plates are neither detectable. Other issues can be taken into consideration when using the Middenbeemster Collection; burial records can hold several names on one grave slot, multiple individuals could have been buried in a different grave than registered in the burial records, individuals or family of deceased individuals could have lied (willingly or accidentally) about their actual age or diagenetic changes could lead to the commixture of individuals. One example of the first issue occurred in the Middenbeemster Collection, the burial slot connected to feature 327 (Appendix 1 and Table 5) registered two females individuals with ages-at-death of 31 and 37 years. The female individual found in feature 327 could not be identified as the 31 years' individual, but neither as the 37 years' individual. This clearly shows the limitations of current age-at-death estimation of archaeological human remains in osteoarchaeological research. Remarkably, most formulae tested pointed towards 37 years of age. Suggesting that root translucency resolved the age-at-death issue for the individual of feature 327.

Nevertheless, the author does not think that these issues invalidate the research presented in this study. Particularly because all individual have previously been osteoarchaeologically studied, thus validated to the historical records and vice versa, by the Laboratory of Human Osteoarchaeology at the Faculty of Archaeology of Leiden University.

5.2 The Accuracy of the Formulae

The nine (sets of) formulae that were tested can be subdivided into three groups; One, formulae using translucency and periodontosis as parameters in multiple linear regression (Lamendin *et al.* 1992; Prince and Ubelaker 2002; Schmitt *et al.* 2010). Two, formulae using translucency as the parameter in single linear regression (Singhal *et al.* 2010; Wegener and Albrecht 1980). Three, formulae using translucency as the parameter in quadratic regression (Bang and Ramm 1970, and the two formulae presented in this thesis). The use of quadratic regression is considered to be the best regression model since this virtually eliminates the problem with linear regression to overestimate younger individuals and underestimates older individuals (Martrille *et al.* 2007, 304; Ackermann and Steyn 2014). This is also supported by the observation that the formation of dental root translucency progresses more slowly when chronological age increases (Bang and Ramm 1970, 11), suggesting that a curved regression model is necessary to reduce the over- and underestimation of individuals.

Several things have to be considered when using root translucency as an age-at-death estimation methodology regardless of which formula(e) is used. Firstly, a good light source has to be used in order to make the translucency properly visible. Older publications used a negatoscope (Foti *et al.* 2001, 102; González-Colmenares *et al.* 2007, 1157; Megyesi 2006, 364) while newer light sources, like a LED-light, can also be used (Lewis and Kasper 2018, 163). A 6000K cold white 30x30cm LED-panel with a light power of 1700 lumen was used in this thesis. However, a smaller 6000K cold white panel with a significantly lower amount of lumen will also suffice, because the amount of lumen in LED-panels increases by the size of the panel. An accurate measuring tool has to be used to ensure a constant light intensity. Secondly, the correct teeth have to be used, the single-rooted incisors and canines are utilized in this thesis. The reasons for this decision are presented in the background (Chapter 3) and materials and methods (Chapter 4), but the most important reason are that these teeth are often found loose or disarticulated from the maxilla and mandible. Additionally, these teeth do not have multiple roots. Teeth with multiple roots (e.g. molars) make the determination of root translucency more difficult. Thirdly, measurements have to be carried out in a correct and consistent way. This thesis used the measuring instructions from Wegener and Albrecht (1980) as presented in Figure 7, where the measurements were always carried out on the buccal side of the tooth. Fourthly, the teeth that are examined have to be clean. This sounds obvious but often there is filth on the teeth that cannot be seen with the naked eye due to of the colour which can affect the measurement of translucency.

An overall problem that is seen in several of the tested formulae (Bang and Ramm 1970; Lamendin *et al.* 1992; Prince and Ubelaker 2002; Wegener and Albrecht 1980), at least partly, have a constant value much higher than 20 years, while the appearance of translucency is considered to start around the age of 20 years (Lamendin *et al.* 1992, 1374). Therefore, the lowest age estimation that can be achieved with for example the Lamendin formula is 25.53 years. This contributes to the overestimation of the age-at-death of younger individuals. This is less applicable to the formula of Singhal and colleagues (2010) (constant: 22,25 years) and not applicable to the new formula presented in this thesis, with constants of 20.18 years (formula 1) and 19.83 (formula 2).

5.2.1 Formulae using Translucency and Periodontosis

The first group of formulae, using translucency and periodontosis relative to root length as parameters, resulted in the worst age-at-death estimations. For the Lamendin formula, this is confirmed by Ackerman and Steyn (2014) in present-day human remains and Megyesi and colleagues (2006) archaeological human remains. Both studies report a significantly higher mean absolute error compared to the original mean absolute error of ± 10 years (Ackermann and Steyn 2014, 192.e3; Lamendin *et al.* 1992, 1378; Megyesi *et al.* 2006, 366). This thesis reaffirms that the Lamendin formula should not be used on archaeological material since this resulted in the second worst mean absolute error within the Middenbeemster Collection (± 9.79 years). The Prince and Ubelaker formulae for white females and males reported a standard mean error of respectively 0.62 and 0.60 (Prince and Ubelaker 2002, 115). The standard mean error in this thesis using these formulae is 0.60 for the sexes combined. The Schmitt formula has not yet been tested in a new study but was considered to be the worst formula tested in this thesis since it had the lowest correlation coefficient, highest standard mean error and highest mean difference.

The main reason to discard these three formulae is the fact that it uses periodontosis as a marker of age. Firstly, because the use of this marker is already contested by Miles (1963), who found that especially root translucency was a good age marker, dismissing the other age-at-death markers as suggested by Gustafson (1950) of which periodontosis was one of the markers (Miles 1960, 261). But also, in more recent studies which still developed formulae incorporating periodontosis, while acknowledging in the same publication that this is a poor age-at-death indicator (Borrman *et al.* 1995, 185; Foti *et al.* 2001, 102; Prince and Konigsberg 2008, 582; Prince and Ubelaker 2002, 116; Solheim 1992). Secondly, because periodontosis is difficult to measure in present-day human remains (Maples 1978, 765) as well as in archaeological human remains (Megyesi *et al.* 2006, 366; Tang *et al.* 2014, 333). The latter is supported by this thesis since the authors experienced difficulties with the exact measurement of the degree of periodontosis and could therefore not measure periodontosis in 6.0% of the teeth that could produce an age-at-death estimation using root translucency.

5.2.2 Formulae using Translucency in Linear Regression

There is a small difference between the formulae that are grouped here, Singhal and colleagues (2010) provides one formula using translucency ratio (translucency in mm/root height in mm) while Wegener and Albrecht (1980) use translucency length (in mm) as x-value with tooth specific formulae. Both have not been tested in other populations, neither contemporary nor archaeological human remains. The formula proposed by Singhal and colleagues (2010) was tested and showed promising results, namely a mean difference of -0.34. Even better than the formula proposed by Singhal and colleagues (2010) when looking at single tooth age-at-death estimation, are the Wegener and Albrecht (1980) formulae. The formulae for individual teeth achieved better results than the general formula, although the differences in the accuracy of age-at-death estimation are meticulously (the same standard mean error and correlation coefficient) and mostly seen in the mean difference (tooth specific: -0.27, general: 1.47). Notable is that in case the estimated age-at-deaths of all teeth of an individual are averaged, the Singhal formula achieves much better results, especially in comparison with the Wegener and Albrecht (1980) formulae.

5.2.3 Formulae using Translucency in Quadratic Regression

The only previously developed formulae using quadratic regression, tested in this thesis, is the work of Bang and Ramm (1970). As mentioned previously, those researchers used quadratic regression to overcome the problem of over- and underestimation of the age-at-death of respectively younger and older individuals. This especially improved the results for younger individuals as application of the formulae on new teeth studied (Bang and Ramm 1970, 32). The other two formulae using quadratic regression are the ones generated in this thesis. The study of Lamendin and colleagues (1992) suggested that a bigger correlation between translucency ratio and chronological age-at-death compared to translucency length and chronological age-at-death, however, this has only been investigated once (Lamendin *et al.* 1992, 1375; Sengupta *et al.* 1999, 891). Ever since these studies, most recent studies used transparency ratio as a parameter but did not look at transparency length (in mm) as a parameter (Prince and Konigsberg 2008, 580-581; Prince and Ubelaker 2002, 108; Schmitt *et al.* 2010, 591; Singhal *et al.* 18-19). Although, the results of this thesis found a better correlation between translucency length and chronological age-at-death instead of translucency ratio and chronological age-at-death. This is supported by other studies on root translucency as an age-at-death estimation method (Solheim 1989, 194). In addition, Ackermann and Steyn reported that root height is possibly negatively correlated with age, which influences the estimation of age-at-death that includes root height as a parameter (Ackermann and Steyn 2014, 192.e3).

5.2.4 Testing the New Formulae

Although caution must be taken when testing the new formulae on individuals with estimated ages-at-death, the two newly derived formulae were tested on 21 individuals with an age-at-death estimation from the Middenbeemster Collection based on the techniques described in the Materials and Methods chapter (Chapter 3). This worked well for both formulae, though Formula 2 (based on translucency length) was found to be more accurate. Although the accuracy was tested by comparing the age-at-death estimation to the assigned osteological age category, this suggests that the formulae work population-wide for the Middenbeemster Collection. In addition, these new formulae were tested on 20 individuals from another Dutch osteoarchaeological collection from Arnhem. Again, both formulae performed well in this sample. However, Formula 2 accomplished considerable better results. This strongly suggests that the applicability of the formulae could be proven for all Dutch Collections by using Formula 2 (based on translucency length). While Formula 1 is a little less accurate and achieving comparable results as the formula of Singhal and colleagues (2010).

5.3 Effects of Dental Diseases

Since dentition is used for age-at-death estimation, its reliability is contested in teeth that are diseased (e.g. having caries) although Gustafson (1950) concluded that dental pathologies did not severely affect translucency (Gustafson 1950, 47). Later research either concluded that more research had to be done on the consequence of disease on root translucency (Meinl *et al.* 2008, 104; Santoro *et al.* 2015, 1314) or that disease does merely affect the amount of root translucency in dentition (Azaz *et al.* 1977, 577; Johnson 1968; Lewis and Kasper 2018, 163; Nalbandian *et al.* 1960, 606; Rösing and Kvaal 1998, 453; Saunders 1965, 36; Singhal 2010, 18). The dentition of a sample study (N = 72) of the Middenbeemster Collection was described as "terrible" with a lot of caries (20.6%) and abscesses (30.4%), and at least 13 individuals with pipe notches indicating the use of tobacco (Lemmers *et al.* 2013, 49-50, 59).

In the dentition (N = 458) of the individuals (N = 67) in this thesis that produced an age-at-death estimation, 22.7% (N = 104) teeth out of 41.8% (N = 28) of the individuals had either caries into the pulp chamber, severe wear (more than ⅔ of the enamel worn) or pipe notches. Additionally, at least three individuals showed the presence of linear enamel hypoplasia. Despite this large number of individuals affected by dental pathological conditions, the accuracy of several of the formulae is satisfactory. The presence of pathological root translucency was observed only in one individual which had an average translucency measurement of 8.42 mm (age-at-death estimation: ± 60 years) while having a known age of 21. Taken together, this suggests that dental pathological conditions do not affect the presence and amount of root translucency, at least not enough to obstruct proper age-at-death estimation. The exceptions are individuals with pathological root translucency of which the cause is unclear, however, these individuals will show other age-at-death estimations using other techniques.

5.4 Effects of Sex

The first to study the influence of sex on root translucency in age-at-death estimation were Bang and Ramm (1970), who reported no sexual dimorphism which was supported by later studies (Bang and Ramm 1970, 32; Lamendin *et al.* 1992; Drusini 1991, 636; Ermenc 1997, 223; Gonzales-Colmenares 2007, 1157; Schmitt *et al.* 2010, 595; Tang *et al.* 2014, 335; Ubelaker and Parra 2008, 610; Zorba *et al.* 2017, 20). Either, some studies found that there were differences between males and females, where males had more translucency at the same age as their female counterparts (Prince and Ubelaker 2002, 115; Solheim 1989, 196). Solheim suggested this difference was caused by the generally larger teeth of males and greater functional forces on teeth of male individuals.

All of the tested formulae showed differences in the accuracy of age-at-death estimation between males and females, where females consequently gave better results. Most likely this difference is caused by the underrepresentation of teeth of male individuals (N = 196) versus teeth of female individuals (N = 262) as well as the presence of several old male individuals that can be designated as outliers. Notable for several formulae (Bang and Ramm 1970; Formula 1 and Formula 2), is that the significant discrepancy between males and females disappears when the mean of age-at-death estimations per individual is evaluated. This supports the idea that using all possible dental measurement of one individual to estimate age-at-death, of which the mean of these age-at-death estimations should be used as a definitive translucency age-at-death estimation.

5.5 Effects of Taphonomic and Diagenetic Change

A study on the biochemical composition of contemporary versus archaeological human teeth found that the protein was disappeared in ancient material while the inorganic material (including hydroxyapatite crystals) was still present in both poorly and well-preserved teeth (Beely and Lunt, 1980, 377). Bell, Boyde and Jones (1991) studied the microscopic diagenetic changes to archaeological human teeth. They found distinct diagenetic changes to the periphery of the dentine of the root, but this only affected biochemical and aDNA research (Bell *et al.* 1991, 177, 182). Studies on archaeological material using sectioned teeth, often found changes to the internal macrostructure of the root, obliterating the root translucency (Lucy *et al.* 1995, 423; Sengupta *et al.* 1999, 896). Vlcek and Mrklas (1975) tested the Gustafson (1950) method and warned that root translucency and periodontosis could not be evaluated properly in archaeological human remains, because of *post-mortem* taphonomic changes. Later research found that in archaeological material, about 35% of the teeth did not show any transparency apparently due to taphonomic changes (Marcsik *et al.* 1992, 530; Megyesi *et al.* 2006, 366; Tang *et al.* 2014, 334). Nevertheless, the authors of both studies do not mention that root translucency develops at various rates in the dentition of one individual. This loss of transparency, often called decalcified teeth, manifests itself as an opaque chalky root Tang *et al.* 2014, 334). One study found that these diagenetic changes already could appear after only 16 years interment in the soil (Angelis *et al.* 2015, S180-S181). In this thesis, the oldest individual that did not show translucency in one of the individual's studied teeth had a known age of 30 years, as seen in other research (Drusini 1991, 633). Tang and colleagues (2014) stated that the way of burial (e.g. wooden coffin burial) could affect the expression of root translucency in archaeological human remains. The expression of root translucency seemed not to be affected by further diagenetic changes (Tang *et al.* 2014, 342).

The results of this thesis, together with the abovementioned studies, strongly suggests that taphonomic and diagenetic changes have an effect on the dentition of archaeological human remains. A total of 21.3% of the investigated teeth was marked as decalcified which is lower than the earlier mentioned 35%. Possibly this is caused by the different taphonomic and diagenetic factors in the Middenbeemster soil. For example, many of the teeth marked as decalcified in this thesis show a comparable root surface (Figure 8) with a case of 'moderate diffuse hypercementosis' which is not taphonomically or diagenetically influenced (D'Incau *et al.* 2015, 297). Overall, the factors and processes affecting dental root translucency are not consistent in all teeth on a populational or interpopulational level and the factors and processes are still little understood. More research on this subject is needed to evaluate which factors affect the amount of dental root translucency visible in archaeological material.

5.6 Effects of Geographical Background

The geographical background of an age-at-death estimation methodology is very important. Nevertheless, most of the currently used age-at-death methods are based on the same collections, such as the Hamann-Todd Collection (Buckberry and Chamberlain 2002, 231; Lovejoy *et al.* 1985, 17; Meindl and Lovejoy 1983, 58; Todd 1920, 289). These methods are applied without knowing if the geographical background has an influence on this, partly because skeletal collections with known age, sex and ancestry are scarce, especially in Europe (Rissech *et al.* 2012, 145-146). Alongside this, there are some characteristics that define a perfect reference collection to which virtually no skeletal collection can meet. Such a characteristic is that very often the registered age-at-death of an individual can be wrong since this was a self-reported age or that most collections are a select subset of all individuals of a population (Usher 2002, 31).

The examples of two age-at-death estimation methods are given to illustrate this geographical dissimilarity. The Suchey-Brooks (1992) method, focussing on the pubic symphyseal face morphology, is universally used and is considered to be the best age-at-death estimation method for American samples (Rissech *et al.* 2011, 146). Although, when this methodology was tested in validation studies on modern French individuals (Baccino *et al.* 1999, 935), Portuguese (Santos 1996, 29) and Italians (Hens *et al.* 2008, 1043) and historical Canadian pioneers (Saunders *et al.* 1992, 113), all showed biased age-at-death estimates and a difficulty of estimating age-at-death over 35 years. Another methodology with the same difficulties is relatively new, but often validated, work of Rissech and colleagues (2006), who looked at seven features of the acetabulum in the 19th and 20th century Portuguese Coimbra Collection. This methodology was tested in several validation studies on collections from Lisbon, Barcelona and London from the 18th to the 20th century (Rissech *et al.* 2007, 774). Showing that the method worked well in other Mediterranean populations but is less accurate in the Anglo-Saxon population (Rissech *et al.* 2007, 777). Later research on the collection from London found an even bigger discrepancy with the original method (Mays 2012, 489-490).

The same can be concluded for the use of root translucency as an age-at-death marker; it is a feature that is observable in all humans, but its rate of age-related change varies among populations of different geographical regions (Schmitt *et al.* 2010, 591). Whittaker and Bakri (1996) studied the difference in root translucency in Malaysian, Chinese, Indian and Welsh (UK) contemporary individuals. The study showed significant differences in the progression of translucency in relation to age between the four geographical populations (Whittaker and Bakri 1996, 19). Gonzalez-Colmenares and colleagues (2007) registered a better result with the ancestry-specific formulae of Prince and Ubelaker (2002) in contrast to the formula of Lamendin and colleagues (1992). They stress the importance of taking ancestry and geographical background into account when using dental root translucency as an age marker (Gonzalez-Colmenares 2007, 1159). Therefore, it is deemed important that when using dental root translucency, a (set of) formula from a comparable geographical region is used.

5.7 Effects of Light Conditions

Although there are several things to consider when reading the study of Adserias-Garriga and colleagues (2017), the general idea of the study is correct. The amount of light, the illuminance, will influence the measurements an observer will take. Nevertheless, it does not mention what light sources were used to mimic microscopic light, negatoscope light or the daily sunlight. The authors neither mentioned how the amount of lux was measured (Adserias-Garriga *et al.* 2017). In this thesis, teeth of five individuals were remeasured which showed a maximal difference of 6 years with the initial measurement. It is possible that these differences are caused by the difference in illumination, although the results of the new measurements were not necessarily more accurate. Therefore, the differences between the measurements could at least partly be caused by interobserver error. Other researchers reported a comparable difference considering intra-observer error (Lopes *et al.* 2014, 19; Prince and Ubelaker 2002, 115).

5.8 Effects of using Mean Age-at-Death Estimations

Bang and Ramm (1970) already stress the potential and importance of measuring as many teeth available of an individual, while other researchers tended to develop methodologies incorporating only one single tooth per individual (Bang and Ramm 1970, 31; Schmitt 2010, 590). The fact that measuring many teeth of one individual and averaging the age-at-death estimations of these different teeth gives better results in age-at-death estimation is confirmed by this thesis. Except for the Schmitt and colleagues (2010) formula, all formulae performed better when the mean of the age-at-death estimations was statistically compared to the chronological age-at-death per individual. Notably, the statistical differences between males and females in single tooth age-at-death estimations were significant while this difference disappears for five formulae, including the newly presented formulae of this thesis. This underlines the importance of using the mean of the age-at-death estimations per individual.

5.9 Comparison to the Complex Method

As already stated in this thesis, a lot of the commercial osteoarchaeological studies in The Netherlands are based on the Complex Method as suggested by the Workshop of European Anthropologists [WEA] (Ferembach *et al.* 1980), though limitations of the technique were reported soon after publication (Molleson *et al.* 1993, 168). This method is based on the publication of Acsádi and Nemeskéri (1970) and it consists of the observation of endocranial suture obliteration, pubic symphyseal changes and cancellous bone changes in the femoral and humeral heads. The methodology promises an age-at-death estimation method within ± 2.5 years of the chronological age when three or four of the features is observed. Nevertheless, control studies reported average errors way above ± 10 years (Rösing *et al.* 2007, 84). The only control study on archaeological material even reported that less than 30% of the individuals could be estimated within ± 5 years of the known chronological age and only 50% could be estimated within ± 10 years of the known chronological age (Molleson *et al.* 1993, 169). They also reported an under-ageing of individuals in 58% of the cases (Molleson *et al.* 1993, 167). The Bang and Ramm (1970) formulae were tested on the same sample as the one from Molleson and colleagues (1993) and got 29% of the individual's age-at-death estimations within ± 5 years and 58% of the individual's age-at-death estimations within ± 10 years of the known chronological age (Tang *et al.* 2014, 335). The percentages of the Complex Method are considerably worse compared to the percentages obtained in this thesis with only one age-at-death feature (root translucency). Even the formula that statistically produced the worst age-at-death estimations scored better results than the archaeological control study using the Complex Method. This again proves the potential and great applicability of dental root translucency in archaeological human remains.

That is why a newly composed method should be developed including dental root translucency as one of the features. It could still look at the three age-at-death features that are proposed by the WEA (cranial suture obliteration and pubic symphyseal changes) while the 'cancellous bone changes' needs to be discarded because it is destructive, and its reliability is doubted. Additionally, the method should include the observation of the auricular surface changes of Buckberry and Chamberlain (2002) and several late epiphyseal fusion sites. If these five age-at-death estimation methods are combined, age-at-death estimation could prove to be very 'accurate' when using the earlier mentioned adult osteological age categories, maybe with a new category of 60+ or 65+ years. Eventually, it could very well be possible to assign age-at-death estimations in ranges of a decade for adult individuals.

5.10 Advantages and Disadvantages

There are four main advantages to the use of dental root translucency as an age-at-death estimation method. The first advantage is practical: it is cheap, simple, rather objective, non-destructive, fast and no special training or materials are needed (except for a LED-light, max. €30). The second advantage is that the formulae enable a higher upper limit on estimating age-at-death, thus applicable to adults of all age categories while other skeletal methods have an upper age-at-death estimation limit of ± 45 years (Gonzalez-Colmenares *et al.* 2007, 1159). Also, in comparison with the use of sectioned teeth, which take a lot more time and money and is destructive, equal results were obtained (Drusini 1991, 634; Solheim 1989, 191). The third advantage is that root translucency is negligibly affected by dental diseases, sex or genetic differences in populations as stated above. This is found to be different in other age-at-death estimation methods, as studies by Mays (2015). He concluded that age-at-death estimation using the pubic symphysis, the auricular surface, sternal rib ends, and cranial sutures is highly influenced by both intrinsic and extrinsic factors (Mays 2015, 338). The fourth advantage is that its applicability is already proven in archaeological human remains (Beyer-Olsen *et al.* 1994, 309; Drusini *et al.* 1991, 28; Maples 1978, 769; Marcsik *et al.* 1992, 537; Tang *et al.* 2014, 343-344), especially when only using root translucency as a single parameter of age-at-death and periodontosis is excluded.

There are not many disadvantages to age-at-death estimation using dental root translucency, but the main disadvantage is that old individuals in past populations very often lost all their teeth before death, making this root translucency age-at-death estimation method ineffective. This is especially unfortunate for this method because it makes it possible to produce reliable age-at-death estimations on individuals of 50+ years. Another disadvantage is that measuring root translucency in teeth with thick roots, like the canines, is tentative to a subjective measurement since the border between translucent and opaque root dentin is not clear.

5.11 Limitations of this Study

There are several limitations of this thesis that need to be discussed. Of the roughly 400 primary burials with over 500 individuals exhumed on the Middenbeemster graveyard, only 124 individuals have known sex and age-at-death documentation. Only 77 individuals from the known sex and age-at-death sample had single-rooted teeth to study and of these individuals no more than 67 individuals had teeth not affected by decalcification or excessive wear. This means that only 13.4% of the original Middenbeemster Collection is incorporated in a study to test and develop formulae for age-at-death estimation using dental root translucency. Together with the 20 newly studied individuals, still only 19.4% (N = 97) of the total Middenbeemster Collection is studied in this thesis. Therefore, the representativeness of the individuals used in relation to the total Middenbeemster Collection, or even the total population of Middenbeemster, can be contested. Even after testing the new formulae on 20 individuals from the Middenbeemster Collection that only has estimated age-at-death and sex with good results. A side-note related to this is that old individuals are underrepresented in this study since, as already mentioned, older individuals tend to lose more/all teeth before death.

Another limitation is related to the application of other techniques in using dental root translucency as an age-at-death estimation method. A simple one is suggested by Solheim (1989), who tested thirteen ways of recording root translucency including measuring in intact dry teeth, intact moist (formaldehyde solution) teeth, area of translucent zone and sectioned dry teeth. The results of the intact moist teeth were slightly better than the intact dry teeth (Solheim 1989, 192), this is something that could have been tested if the formaldehyde solution was not corrosive. Already discussed is the use of sectioned teeth instead of intact teeth, the sectioning of teeth was not performed in this study. The results of intact versus sectioned teeth are indistinct, especially on archaeological human remains, so if sectioning was performed in this thesis it could have contributed to this indistinctness. These two techniques could not be performed because the Middenbeemster Collection does not allow the appliance of destructive methods. Another technique that could have been utilised is a digital approach, as done by Drusini and colleagues (1991) and Gupta and colleagues (2017). The first used an image analysis system to measure root translucency in intact teeth while the latter used this technique on sectioned teeth. Although no better results were achieved, the advancement of digital image analysis could achieve more objective results on a semi-automatic basis (Drusini *et al.* 1991, 28; Gupta *et al.* 2017, 42).

The last limitation of this study is that the applicability of this age-at-death estimation methodology could not be tested on archaeological human remains that are cremated. A German study found that the hardness of dentition prevented alterations to the structure of teeth when exposed to extreme heat as in a cremation (Großkopf and Hummel 1992, 567-569). An Italian pilot study exposed groups of 26 extracted teeth to three different temperatures (50°C, 100°C and 200°C) for several hours and found that with increasing temperatures, the measured root translucency either decreased or disappeared in an increasing number of teeth, up to 77% at 200°C (Gibelli *et al.* 2014, 220-221). Notable is that they acknowledge the fact that teeth would normally be covered in both soft tissue and the maxillary or mandibular bone when cremated, although the authors expect that this will not change the proven changes to the measurement of root translucency in cremated teeth (Gibelli *et al.* 2014, 222-223). These two studies evoke the need for more research on cremated remains. Especially since age-at-death estimation in cremated human remains is difficult and cremated remains are often found in an archaeological context.

5.12 Future Research

Future research must mainly focus on the limitations of this study. Although this is hard to accomplish, more archaeologically excavated individuals with known age-at-death should be included in the development of root translucency formulae. New archaeological excavations will possibly uncover human remains of which burial records are still present, or for example, uncover coffin plates with personal information on it to establish known sex and age-at-deaths for the excavated individuals. These yet to be found individuals could be included to try to develop a more accurate formula or to sufficiently test the accuracy of the formulae presented in this study. This especially is needed for old individuals who are slightly underrepresented in this thesis.

Another subject for future research has to focus on testing the accuracy of the new formulae on individuals with an estimated age-at-death or osteological age category. Although it is doubtful to test age-at-death methodologies since comparing old estimations with new estimations, this is the best way of testing age-at-death estimation methods in archaeological material. Mostly, this is caused by the absence of big known sex and age-at-death archaeological collections. Testing the method on future samples with known age-at-death individuals as well as individuals with estimated age-at-death can be done within the Laboratory of Human Osteoarchaeology at the Faculty of Archaeology in Leiden University, but other Dutch (or even Belgian) universities with osteoarchaeological collections can contribute to this research.

The effects of cremation on dental root translucency also has to be studied in more detail. These effects are barely studied in both present-day and archaeological human remains, resulting in questionable measurability of dental root translucency in cremated human remains. When these effects are properly studied, the applicability of root translucency in age-at-death estimation can be examined. One disadvantage is that there are no known sex and age-at-death osteological collections with cremated remains, especially none with archaeological human remains.

Lastly, future research should focus on developing a new age-at-death estimation method that combines several age-at-death markers just as the Complex Method. There are five age-at-death markers that could be combined in this method: dental root translucency, cranial suture closure, pubic symphyseal change, auricular surface changes and late epiphyseal fusion sites. Although other recent methodologies that achieve good results could be included or replacing either cranial suture closure or auricular surface changes, such as acetabular morphological changes by San-Millán, Rissech and Turbón (2016). Ideally, cranial suture closure and pubic symphyseal change will be included in this new methodology to still enable the comparison osteological studies using the 'old' Complex Method (or parts of it) with future osteological studies using the 'new' combined method. The focus of the methodology should be that an individual could be estimated in the correct lustrum or decade of age-at-death up to 60 years of age, thus 20-25, 25-30, 30-40, 40-50 etc.

The next chapter will present the conclusion of this thesis by giving a short summary of the thesis. The research questions will be answered concisely, together with some final remarks.

6. Conclusion

Although the cause of a tooth root becoming translucent is still unclear, the translucency progresses when the chronological age of an individual increases. Therefore, dental root translucency is useable as an age-at-death estimation marker as already proven in both forensic and archaeological human remains. This thesis certainly proves that this age-at-death estimation marker is also usable in estimation age-at-death in Dutch osteoarchaeological human remains. This is especially important since age-at-death estimation still is a difficult section of osteoarchaeological studies, especially in contrast to sex or stature estimation. This research is especially limited by using only 67 individuals to produce a sample specific formula for the Middenbeemster Collection (500+ individuals), although the results are still promising and good.

Seven already existing (sets of) formulae were tested on 77 known sex and age-at-death individuals with 588 loose teeth resulting in a total of 458 teeth that could produce an age-at-death estimation distributed over 67 individuals. The remaining 130 teeth were probably mainly affected taphonomic and/or diagenetic alteration, resulting in so-called decalcified teeth. Three (Lamendin *et al.* 1992, Prince and Ubelaker 2002; Schmitt *et al.* 2010) of the seven tested formulae had a second parameter in the equation, these also accounted for the amount of periodontosis present. The other four formulae (Bang and Ramm 1970; Singhal *et al.* 2010; Wegener and Albrecht 1980) only accounted for root translucency, either with a measurement in millimetres or as a ratio of the total root length and either plotted in a linear or quadratic formula. The formulae with two parameters (translucency and periodontosis) produced the worst age-at-death estimations and should not be used in archaeological material, partly because measuring periodontosis is very difficult on archaeological human remains. All these four (sets of) formulae presented better results when the average of all age-at-death estimation per individual (mean age-at-death estimation) was used as the final age-at-death estimation. Of the seven tested formulae, the Singhal and colleagues (2010) formula provided the best results. This was the case in the single tooth age-at-death estimation as well as in the mean age-at-death estimations.

The measurements of the earlier mentioned 67 individuals were used to develop a formula that would be applicable to at least the Middenbeemster Collection, but ideally applicable to all Dutch osteoarchaeological human remains. Quadratic regression delivered the best results, both when translucency length in millimetres and translucency ratio were used. Although the differences in accuracy between Formula 1 (translucency ratio) and Formula 2 (translucency length in mm) are not large, the use of Formula 2 obtained better results in both single tooth age-at-death estimation and mean age-at-death estimations. Testing both formulae on 41 individuals (21 from the Middenbeemster Collection and 20 from Arnhem, *Eusebiuskerk*) with an estimated age-at-death converted to an osteological age category, confirmed this difference in accuracy and even proved the applicability of the formula in another Dutch archaeological human remains sample. Thus, the dental root translucency formula that should be used when working with Dutch archaeological human remains is (T = translucency measurement in mm):

$$Age = 19.832 + 7.667*T + -0.299*T^2$$

Dental root translucency should be considered as a standard age-at-death estimation method throughout the Dutch osteoarchaeological work field. This is due to several advantages, especially in contrast with other age-at-death estimation methods. The first advantage is that the methodology is accurate in all osteological age categories (44.8% in ± 5 years and 74.6% in ± 10 years) while other methodologies especially tend to overestimate young individuals and underestimate old individuals (resulting in large age estimation ranges). The second is that the dental root translucency still progresses after about 50 years of age, making age-at-death estimation possible above 50 years while other age-at-death methods cannot estimate age-at-death above the age of 45-50 years. One side-note to the second point is that older individuals tend to have lost all of their teeth, making translucency observation impossible. The third advantage is that the progress, amount and measurability of dental root translucency do not seem to be affected by the following factors: dental disease, sex, taphonomy/diagenesis (except decalcified teeth). The geographical background does seem to affect the way that dental root translucency progresses in an individuals' dentition, although not that much that formulae developed on a population from another geographical region are not usable anymore as this thesis proved with the Singhal and colleagues (2010) formula (developed on a present-day Indian population). The effects of light conditions should be studied more intensively since there were measurement differences between two levels of illuminance (in lux), but these differences could also appear due to intra-observer error.

Abstract

Dental root translucency (also root transparency, apical translucency or transparency or root dentine sclerosis) has long been used to estimate age-at-death in forensic as well as archaeological human remains but has never been tested on a Dutch archaeological collection with known sex and age-at-death individuals. This thesis tested seven already existing (sets of) formulae using dental root translucency as a parameter, that were developed on samples from various geographical regions, on the known sex and age-at-death sample from the Middenbeemster Collection housed at the Laboratory of Human Osteoarchaeology at the Faculty of Archaeology in Leiden University, The Netherlands. A total of 77 individuals were studied, resulting in age-at-death estimations for 67 of these individuals. To test if a more accurate formula could be developed for the Middenbeemster Collection, and even Dutch osteoarchaeological human remains, several new formulae were trailed resulting in the following formula (T = translucency in mm): Age = 19.832 + 7.667*T + -0.299*T^2. With this formula, no statistical difference was found between males and females and seemed not to be affected by dental disease. The new formula was tested on twenty-one new individuals from the Middenbeemster Collection and twenty individuals from Arnhem, *Eusebiuskerk*, all only having an estimated osteological age category. The newly derived formula performed well in the forty-one newly studied individuals, bringing the total number of studied individuals with an age-at-death estimation to 108 individuals. The small sample size and slight underrepresentation should be addressed in future research that either has to enlarge the known age-at-death sample and/or enlarge the estimated age-at-death sample to test the presented formula of this thesis.

Samenvatting

De mate van transparantie van de tandwortel wordt al lange tijd gebruikt voor sterfteleeftijdschatting in zowel forensische als archeologische menselijke resten. Echter, het is nooit getest op een Nederlandse archeologische collectie met individuen waarvan het geslacht en de leeftijd bekend is uit historische bronnen. Deze scriptie testte zeven reeds bestaande (sets van) formules voor sterfteleeftijdschatting, op basis van de mate van transparantie van de tandwortel, op de volwassen individuen van de Middenbeemster-collectie waarvan geslacht en sterfteleeftijd bekend is (gehuisvest in het Laboratorium voor Menselijke Osteoarcheologie aan de Faculteit der Archeologie van de Universiteit Leiden). Van de in totaal 77 individuen die zijn bestudeerd, kon er voor 67 individuen een sterfteleeftijdschatting vastgesteld worden.

Verschillende nieuwe formules werden ontwikkeld op basis van de 67 gemeten individuen, om te testen of een meer accurate formule kon worden ontwikkeld voor de Middenbeemster-collectie of zelfs voor Nederlandse archeologische menselijke resten. De volgende dient gebruikt te worden in de Nederlandse fysische antropologie/archeologie (T = mate van transparantie in mm): Leeftijd = 19,832 + 7,667 * T + -0,299 * T^2. Deze formule toont geen statistisch verschil tussen mannen en vrouwen en lijkt niet te worden beïnvloed door tandheelkundige aandoeningen als cariës. De nieuwe formule is getest op eenentwintig nieuwe individuen uit de Middenbeemster-collectie en twintig individuen uit Arnhem (Eusebiuskerk), welke allemaal alleen een geschatte osteologische leeftijdscategorie (bijv. jongvolwassene 18-25 jaar) hebben. De nieuwe formule presteerde zeer goed in de eenenveertig nieuw bestudeerde individuen, waarmee het aantal onderzochte individuen met een sterfteleeftijdschatting op een totaal van 108 individuen kwam.

Deze scriptie toont aan dat de toepasbaarheid van deze methode en formule ook werkt op Nederlandse archeologische menselijke resten, anderzijds zal toekomstig onderzoek zich moeten richten op het vergroten van de sampleomvang en op het vergroten van het aantal oudere individuen (50+ jaar). Ook moet het zich richten op het testen van de formule gepresenteerd in deze scriptie op individuen met een bekende sterfteleeftijd of individuen met een geschatte sterfteleeftijd.

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Table 4: The distribution of teeth that produced an age-at-death estimation.

Table 5: The mean age-at-death estimations (in years) per individual and per formula. P.&U. = Prince and Ubelaker, B.&R. = Bang and Ramm, W.&A.1 = Wegener and Albrecht (general formula), W.&A.2 = Wegener and Albrecht (tooth-specific formulae). Formula 1 and 2 are presented below.

Table 6: Summary of the statistical analyses of the different formula considering all age-at-death estimations of single teeth. Summary of the statistical analyses of the different formula considering all (N = 458) age-at-death estimations of single teeth. The formulae are in the order of giving the best to worst age-at-death estimations in relation to the chronological age, based on the mean difference and percentage correct within ±2 years and ±5 years.

Table 7: Summary of the statistical analyses of the different formula considering the mean age-at-death estimations per individual (N = 67). The formulae are in the order of giving the best to worst age-at-death estimations in relation to the chronological age, based on the mean difference, difference between sexes (yes or no) and percentage correct within ±2 years and ±5 years.

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Appendix 1: The age-at-death estimations of all measured teeth per individual with known sex and age-at-death.

Appendix 2: The mean age-at-death estimations of the individuals with estimated sex and age-at-death from the Middenbeemster Collection and from Arnhem (*Eusebiuskerk*).

Appendix 1

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
45	41	14.78	4.81	2.39	Female	47	42.11	45.78	39.87	47.32	54.00	45.45	47.39	48.70	46.01
45	43	15.82	3.12	2.40	Female	47	36.54	41.62	35.05	37.44	46.28	37.84	39.56	38.90	37.95
47	11	11.08	0.38	0.00	Female	21	26.97	25.35	21.74	24.89	22.48	25.51	25.12	23.75	22.78
47	12	12.70	1.56	0.00	Female	21	30.69	30.58	24.72	31.71	29.48	30.82	33.58	32.36	29.64
47	13	16.02	0.00	0.00	Female	21	25.53	29.44	20.59	22.25	26.20	23.80	17.50	20.18	20.46
47	21	10.51	0.72	0.00	Female	21	28.41	26.05	22.89	27.53	28.72	27.04	28.44	27.19	24.80
47	22	12.57	2.21	0.00	Female	21	32.91	32.50	26.50	35.79	34.95	33.75	37.68	37.09	33.21
47	23	16.15	0.00	0.71	Female	21	26.32	30.95	22.86	22.25	25.27	23.80	22.50	20.18	20.46
47	31	13.80	1.32	0.00	Female	21	29.55	30.73	23.80	29.62	34.52	29.74	31.84	29.82	28.28
47	32	14.74	0.00	0.81	Female	21	26.52	29.74	23.43	22.25	18.58	23.80	26.60	20.18	20.46
47	33	15.76	2.54	0.54	Female	21	32.92	36.50	27.77	34.67	44.33	35.23	35.61	35.81	34.96
47	41	12.67	1.71	0.55	Female	21	31.98	32.37	27.37	32.65	29.28	31.50	39.02	33.47	30.47
47	42	14.94	0.00	0.00	Female	21	25.53	28.25	20.59	22.25	26.57	23.80	24.90	20.18	20.46
47	43	15.98	2.10	0.00	Female	21	31.05	34.52	25.01	32.37	39.51	33.25	34.77	33.15	32.61
51	41	13.90	9.05	1.71	Male	74	55.09	54.21	48.82	72.41	64.17	64.53	58.84	65.12	61.81
51	42	16.24	11.26	2.69	Male	74	57.63	57.45	52.43	75.67	73.40	74.47	73.32	66.36	67.55
53	32	15.92	3.96	4.11	Female	55	40.62	47.04	42.27	41.41	50.73	41.62	44.82	43.06	42.08
53	41	12.33	4.40	4.88	Female	55	47.64	51.57	53.00	49.74	51.52	43.60	46.28	50.81	44.14
53	42	15.65	3.31	3.65	Female	55	38.61	44.51	39.73	38.54	48.22	38.70	39.13	40.09	38.91
59	13	16.66	4.81	1.70	Male	38	39.49	39.89	35.56	44.49	47.50	45.45	42.99	46.08	46.01
59	21	13.77	2.80	1.17	Male	38	35.60	35.63	31.81	37.92	40.78	36.40	37.80	39.41	36.32
59	22	14.01	2.70	1.29	Male	38	35.28	35.46	31.82	37.10	37.77	35.95	39.49	38.53	35.80
59	31	13.24	3.10	2.46	Male	38	38.71	39.68	38.05	40.29	46.87	37.75	40.38	41.92	37.85
59	32	15.25	2.59	2.31	Male	38	35.39	36.47	34.11	35.33	41.52	35.46	38.51	36.57	35.22
59	33	16.95	4.03	2.37	Male	38	38.03	39.04	35.79	40.57	52.50	41.94	43.36	42.20	42.41
59	41	12.94	7.07	2.49	Male	38	51.94	52.00	48.88	64.34	63.41	55.62	53.49	61.16	55.21

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
59	42	14.84	8.61	2.22	Male	38	52.59	52.36	47.80	66.95	65.42	62.55	61.92	62.58	60.46
60	11	12.66	0.94	1.00	Female	26	30.07	31.09	27.16	27.97	25.70	28.03	28.53	27.75	26.09
60	12	13.84	0.00	1.27	Female	26	27.18	29.89	25.33	22.25	18.80	23.80	28.90	20.18	20.46
60	13	17.15	0.96	0.92	Female	26	28.85	34.53	25.24	26.56	30.61	28.12	22.59	25.95	26.21
60	21	11.93	0.86	0.71	Female	26	29.63	29.60	26.08	27.80	29.56	27.67	29.07	27.54	25.63
60	22	14.01	1.56	1.78	Female	26	32.49	35.51	30.89	30.83	31.04	30.82	35.27	31.30	29.64
60	31	13.80	1.94	0.50	Female	26	32.09	33.61	27.18	33.08	39.21	32.53	34.81	33.98	31.74
60	32	14.81	2.13	0.59	Female	26	32.29	34.96	27.48	33.33	37.97	33.39	36.40	34.27	32.77
60	33	13.95	1.52	0.00	Female	26	30.11	31.41	24.25	30.64	38.00	30.64	30.30	31.07	29.41
60	41	13.48	1.87	0.00	Female	26	31.36	32.06	25.25	32.94	30.89	32.22	39.45	33.81	31.36
60	42	15.43	1.45	0.00	Female	26	29.48	32.46	23.75	29.49	37.09	30.33	31.14	29.66	29.02
60	43	11.63	0.78	0.00	Female	26	28.35	27.23	22.84	27.42	29.68	27.31	28.57	27.05	25.16
88	13	15.54	4.84	4.17	Female	50	43.44	49.38	44.90	46.24	47.63	45.58	43.15	47.72	46.14
88	23	15.54	9.10	4.23	Female	50	55.02	60.19	54.31	67.36	60.81	64.75	59.81	62.79	61.96
88	33	15.82	4.54	5.14	Female	50	43.43	50.49	47.00	44.36	55.00	44.23	46.01	45.96	44.79
92	32	13.08	3.67	4.14	Male	59	43.01	45.25	46.35	43.87	48.95	40.32	43.48	45.48	40.68
92	42	13.42	4.68	4.47	Male	59	46.17	48.44	49.50	49.12	54.73	44.86	45.02	50.27	45.42
93	11	12.46	6.27	2.09	Male	67	49.68	49.53	46.15	61.02	56.29	52.02	61.05	59.16	52.16
93	13	16.06	4.56	3.24	Male	67	41.09	42.50	40.54	44.12	46.44	44.32	41.67	45.73	44.88
93	31	14.77	3.54	3.63	Male	67	40.02	41.86	41.33	40.71	49.40	39.73	42.49	42.35	40.05
93	32	14.91	2.85	3.84	Male	67	38.19	40.33	40.30	36.98	43.42	36.63	39.71	38.39	36.58
93	33	14.77	6.29	3.63	Male	67	47.84	49.12	47.58	55.06	62.44	52.11	55.11	55.05	52.24
93	41	14.26	3.09	4.70	Male	67	40.56	43.32	44.88	38.94	41.98	37.71	42.74	40.51	37.80
93	42	14.54	2.77	3.54	Male	67	37.91	39.84	39.55	36.93	45.26	36.27	36.81	38.34	36.16
93	43	16.93	5.87	5.63	Male	67	46.08	48.88	49.40	48.96	60.91	50.22	52.49	50.14	50.55
100	11	13.16	8.31	2.31	Male	75	55.21	54.86	50.87	70.90	68.00	61.20	73.49	64.47	59.50
100	32	14.64	7.41	4.09	Male	75	51.82	53.21	52.01	61.24	64.99	57.15	60.69	59.31	56.44
100	33	15.57	9.14	3.92	Male	75	54.72	55.70	53.31	67.47	69.79	64.93	69.93	62.85	62.07
100	43	15.31	9.03	3.34	Male	75	54.23	54.80	51.67	67.69	67.15	64.44	77.88	62.95	61.75

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
101	13	10.61	2.85	4.85	Female	39	45.04	48.14	53.20	42.94	39.07	36.63	32.61	44.59	36.58
101	21	10.18	2.97	3.78	Female	39	44.47	45.91	49.55	44.73	41.72	37.17	38.57	46.31	37.19
101	22	10.74	2.41	2.01	Female	39	38.32	38.19	37.79	39.54	36.11	34.65	38.42	41.14	34.27
101	32	12.37	2.33	-	Female	39	-	-	-	36.76	39.54	34.29	37.32	38.16	33.85
101	41	10.11	1.74	3.29	Female	39	38.62	39.74	43.17	35.51	29.59	31.63	39.10	36.77	30.64
101	42	11.88	2.51	3.80	Female	39	40.16	43.04	44.20	38.53	43.76	35.10	35.69	40.07	34.80
149	11	11.27	0.00	0.56	Female	25	26.42	25.76	23.15	22.25	20.30	23.80	22.80	20.18	20.46
149	12	11.58	0.00	0.00	Female	25	25.53	24.56	20.59	22.25	18.80	23.80	28.90	20.18	20.46
149	21	12.18	0.00	1.31	Female	25	27.47	28.55	26.14	22.25	24.30	23.80	25.20	20.18	20.46
149	23	11.45	0.00	0.00	Female	25	25.53	24.42	20.59	22.25	25.27	23.80	22.50	20.18	20.46
149	31	10.51	2.75	2.34	Female	25	40.53	40.49	40.87	42.41	44.71	36.18	38.70	44.06	36.06
149	32	11.99	1.85	1.51	Female	25	34.28	34.93	32.27	34.14	35.70	32.13	35.11	35.21	31.25
149	33	13.58	0.00	1.00	Female	25	26.86	29.04	24.39	22.25	27.45	23.80	22.40	20.18	20.46
149	41	11.39	0.91	2.14	Female	25	32.27	33.29	32.97	28.41	20.69	27.90	36.86	28.30	25.92
149	42	11.77	0.00	1.38	Female	25	27.64	28.40	26.64	22.25	26.57	23.80	24.90	20.18	20.46
149	43	13.51	0.00	1.02	Female	25	26.89	29.02	24.49	22.25	23.30	23.80	24.90	20.18	20.46
151	31	12.93	1.53	2.14	Female	27	33.48	35.79	33.11	31.37	36.16	30.69	32.84	31.95	29.47
151	41	12.14	2.07	1.69	Female	27	35.20	36.14	33.50	35.39	32.86	33.12	39.99	36.63	32.45
151	43	15.17	1.68	1.01	Female	27	31.38	34.89	27.75	30.78	36.51	31.36	32.80	31.24	30.31
153	11	15.07	4.56	2.60	Male	57	41.34	42.23	39.66	45.56	46.47	44.32	50.62	47.09	44.88
153	12	14.27	4.69	2.81	Male	57	42.88	43.84	41.79	47.57	48.49	44.91	42.97	48.92	45.47
153	13	18.32	6.61	4.22	Male	57	44.83	46.67	44.60	50.05	54.95	53.55	52.53	51.07	53.48
153	21	14.23	4.70	3.03	Male	57	43.23	44.36	42.68	47.70	50.91	44.95	46.35	49.03	45.51
153	22	13.88	4.87	2.30	Male	57	43.25	43.74	40.93	49.28	48.97	45.72	47.52	50.41	46.27
153	23	19.54	7.73	3.56	Male	57	45.42	46.81	43.28	52.73	56.31	58.59	54.19	53.26	57.56
153	31	13.74	7.06	4.19	Male	57	52.60	54.11	53.59	61.84	62.09	55.57	59.39	59.67	55.17
153	32	14.74	4.92	4.08	Male	57	44.53	46.43	46.09	47.96	55.99	45.94	49.23	49.27	46.50
153	33	15.40	4.60	4.76	Male	57	43.64	46.09	46.58	45.26	55.28	44.50	46.32	46.81	45.06
153	41	14.84	7.22	5.07	Male	57	52.11	54.28	54.57	59.73	63.78	56.29	53.89	58.33	55.76

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
153	42	15.33	8.17	4.58	Male	57	53.29	54.92	53.91	63.31	64.81	60.57	60.03	60.56	59.04
153	43	16.21	7.58	2.38	Male	57	47.81	48.10	43.88	58.27	67.36	57.91	60.53	57.36	57.04
155	32	13.44	7.86	3.74	Female	54	55.10	58.04	54.60	67.30	65.91	59.17	62.76	62.76	58.01
155	42	13.61	7.56	4.75	Female	54	55.14	59.27	57.26	65.04	63.72	57.82	57.41	61.55	56.97
155	43	14.74	9.85	2.68	Female	54	56.87	59.73	52.43	73.73	69.47	68.13	71.20	65.65	64.08
158	11	13.62	7.51	3.29	Male	60	53.04	53.72	51.58	64.73	63.41	57.60	68.61	61.38	56.80
158	21	13.62	7.64	3.62	Male	60	53.87	54.80	53.15	65.46	64.87	58.18	59.58	61.79	57.25
158	31	11.82	3.76	5.20	Male	60	46.81	50.11	53.98	46.76	50.58	40.72	43.55	48.19	41.12
158	32	14.00	5.86	5.66	Male	60	50.39	53.32	55.52	54.50	60.17	50.17	53.56	54.63	50.51
158	33	17.87	7.26	2.31	Male	60	44.92	45.44	40.91	53.55	65.80	56.47	60.15	53.90	55.90
158	41	12.73	6.10	3.97	Male	60	51.27	52.81	52.78	59.17	60.26	51.25	50.87	57.96	51.48
158	42	15.20	8.51	4.22	Male	60	54.04	55.34	53.73	65.38	65.30	62.10	61.49	61.74	60.14
158	43	18.28	8.83	3.47	Male	60	49.23	50.26	46.62	59.46	70.78	63.54	66.40	58.16	61.14
160	11	11.10	0.75	0.75	Female	28	29.58	28.76	26.35	27.46	24.61	27.18	27.38	27.09	24.98
160	12	12.34	2.53	1.58	Female	28	36.45	37.36	34.09	38.05	35.71	35.19	36.49	39.55	34.91
160	13	16.83	7.91	1.37	Female	28	46.73	51.19	40.58	58.46	60.15	59.40	59.42	57.48	58.18
160	21	10.58	2.22	1.36	Female	28	36.66	35.63	34.27	38.42	37.52	33.79	35.19	39.95	33.26
160	22	12.30	0.00	1.48	Female	28	27.70	29.08	26.80	22.25	20.90	23.80	29.50	20.18	20.46
160	31	11.04	2.49	6.78	Female	28	46.06	51.80	59.86	39.63	43.02	35.01	37.45	41.23	34.70
160	32	10.52	2.21	3.49	Female	28	40.32	41.87	44.77	38.43	38.60	33.75	36.77	39.97	33.21
160	33	13.68	3.00	2.32	Female	28	37.79	40.68	36.71	39.14	46.99	37.30	38.00	40.72	37.35
160	41	10.55	2.77	5.06	Female	28	45.19	48.53	54.16	42.48	39.27	36.27	41.88	44.13	36.16
160	42	10.96	0.00	2.78	Female	28	30.10	31.74	33.68	22.25	26.57	23.80	24.90	20.18	20.46
160	43	13.24	0.00	3.40	Female	28	30.15	34.34	33.84	22.25	23.30	23.80	24.90	20.18	20.46
174	11	12.74	4.49	3.34	Female	45	45.05	47.71	45.96	49.40	46.07	44.01	50.19	50.52	44.56
174	13	17.33	7.44	2.78	Female	45	46.45	52.60	43.29	55.32	58.29	57.28	56.93	55.25	56.55
174	21	13.43	4.94	1.77	Female	45	43.35	45.02	39.75	50.59	52.12	46.03	47.43	51.52	46.58
174	32	14.23	7.29	2.70	Female	45	50.46	53.33	47.59	61.72	64.71	56.61	60.13	59.60	56.01
174	42	13.51	6.37	3.03	Female	45	49.37	52.02	48.01	58.57	60.78	52.47	52.29	57.56	52.55

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
194	11	17.21	3.98	5.75	Male	58	41.26	44.46	45.60	40.07	43.15	41.71	47.08	41.69	42.18
194	12	17.31	3.53	4.25	Male	58	38.51	40.84	40.11	37.96	41.82	39.69	39.49	39.46	40.00
194	13	22.76	6.04	10.52	Male	58	45.00	50.34	53.36	42.69	52.62	50.98	49.51	44.34	51.24
194	21	17.92	8.19	5.08	Male	58	49.83	51.90	50.57	57.46	67.26	60.66	62.06	56.79	59.11
194	22	17.99	4.38	4.19	Male	58	39.95	42.12	40.79	41.01	46.62	43.51	45.71	42.65	44.05
194	32	15.98	2.57	9.95	Male	58	43.49	49.90	58.12	34.64	41.37	35.37	38.42	35.78	35.12
194	33	21.21	3.94	7.71	Male	58	39.88	44.14	45.59	36.56	52.04	41.53	42.89	37.94	41.99
194	42	15.20	2.64	9.08	Male	58	43.58	49.55	57.25	35.63	44.52	35.68	36.25	36.90	35.49
194	43	19.46	4.69	6.91	Male	58	42.04	45.79	47.01	40.82	55.28	44.91	46.94	42.46	45.47
195	13	17.45	5.08	2.10	Female	54	39.92	46.10	36.58	44.68	48.64	46.66	44.42	46.26	47.20
195	41	12.17	6.64	-	Female	54	-	-	-	64.28	62.18	53.68	52.33	61.13	53.60
195	42	13.51	7.80	4.49	Female	54	55.76	59.50	57.14	66.73	64.19	58.90	58.44	62.46	57.80
195	43	14.19	3.26	2.60	Female	54	38.48	42.07	37.76	39.95	47.15	38.47	40.22	41.57	38.66
213	13	14.07	5.12	0.00	Female	22	40.81	39.47	32.82	50.28	48.80	46.84	44.64	51.27	47.37
213	42	14.11	3.88	-	Female	22	-	-	-	43.43	51.11	41.26	41.58	45.07	41.70
236	11	14.15	1.39	0.33	Male	24	30.08	29.80	25.10	29.82	28.28	30.06	31.28	30.06	28.68
236	12	15.55	2.55	0.00	Male	24	32.42	31.90	26.10	34.88	35.84	35.28	36.55	36.06	35.01
236	21	13.28	1.34	0.44	Male	24	30.36	30.06	25.69	30.02	32.42	29.83	31.23	30.31	28.39
236	22	14.72	2.46	0.00	Male	24	32.55	31.90	26.21	35.12	36.40	34.87	38.60	36.33	34.54
236	31	13.99	1.22	0.00	Male	24	29.19	28.67	23.52	28.97	33.73	29.29	31.36	29.01	27.71
236	32	15.17	1.29	0.00	Male	24	29.10	28.76	23.45	28.80	30.91	29.61	32.53	28.80	28.11
236	33	17.12	0.00	0.00	Male	24	25.53	25.74	20.59	22.25	27.45	23.80	22.40	20.18	20.46
236	41	13.68	1.37	0.00	Male	24	29.74	29.13	23.96	29.97	25.74	29.97	38.10	30.24	28.56
236	42	14.97	1.30	0.00	Male	24	29.18	28.80	23.51	28.94	36.08	29.65	30.49	28.97	28.17
236	43	16.37	0.00	0.00	Male	24	25.53	25.63	20.59	22.25	23.30	23.80	24.90	20.18	20.46
239	11	15.45	1.94	0.34	Male	23	31.20	31.02	25.95	31.92	31.44	32.53	34.63	32.62	31.74
239	12	14.48	1.21	0.00	Male	23	29.04	28.60	23.40	28.69	27.15	29.25	32.53	28.66	27.65
239	21	14.70	1.15	0.00	Male	23	28.82	28.43	23.22	28.28	31.30	28.98	30.38	28.14	27.31
239	22	13.91	3.62	0.44	Male	23	37.03	36.32	30.97	42.30	42.77	40.09	42.89	43.95	40.44

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
239	23	15.47	3.37	0.60	Male	23	35.38	35.11	29.91	39.03	39.88	38.97	36.32	40.61	39.21
239	31	15.04	2.67	0.65	Male	23	33.76	33.60	28.79	35.93	44.20	35.82	38.32	37.23	35.64
239	32	16.58	3.59	4.33	Male	23	39.32	41.68	41.34	38.93	48.44	39.96	43.11	40.50	40.29
239	33	17.29	1.96	2.23	Male	23	32.61	33.92	31.06	30.98	40.80	32.62	32.59	31.49	31.85
239	41	15.78	1.66	1.40	Male	23	31.55	32.21	28.70	30.35	28.77	31.27	38.88	30.72	30.19
239	42	17.90	2.68	4.52	Male	23	36.36	39.02	38.65	33.78	44.75	35.86	36.42	34.80	35.69
239	43	17.38	3.99	1.46	Male	23	36.68	37.17	32.64	39.94	51.48	41.76	43.65	41.55	42.22
243	11	11.91	5.63	1.44	Female	62	47.56	47.10	42.71	58.67	52.62	49.14	57.14	57.62	49.55
243	13	16.84	6.06	2.32	Female	62	43.12	48.65	39.79	49.97	52.70	51.07	49.62	51.00	51.32
243	21	13.14	5.81	3.57	Female	62	48.99	51.94	49.47	56.31	56.42	49.95	51.35	55.98	50.30
243	23	16.37	4.67	5.73	Female	62	43.81	51.80	48.24	44.23	45.07	44.82	41.65	45.83	45.38
243	31	15.38	6.78	-	Female	62	-	-	-	56.21	61.57	54.31	58.04	55.90	54.13
243	33	11.91	6.31	2.33	Female	62	51.30	51.65	48.49	63.07	62.51	52.20	55.21	60.42	52.32
243	42	16.87	8.81	3.20	Female	62	50.88	56.62	47.93	62.48	65.65	63.45	62.78	60.07	61.08
243	43	12.55	6.84	3.69	Female	62	53.71	56.00	54.08	64.24	64.82	54.58	57.05	61.10	54.36
246	11	12.41	2.53	-	Male	19	-	-	-	37.96	34.82	35.19	38.23	39.46	34.91
246	12	13.02	1.43	-	Male	19	-	-	-	30.71	28.62	30.24	33.19	31.16	28.90
246	13	15.72	0.00	-	Male	19	-	-	-	22.25	26.20	23.80	17.50	20.18	20.46
246	21	10.46	0.00	-	Male	19	-	-	-	22.25	24.30	23.80	25.20	20.18	20.46
246	22	12.67	0.00	-	Male	19	-	-	-	22.25	20.90	23.80	29.50	20.18	20.46
246	23	15.91	0.00	0.40	Male	19	25.98	26.29	21.89	22.25	25.27	23.80	22.50	20.18	20.46
246	32	12.68	2.34	1.52	Male	19	35.44	35.75	32.98	36.47	39.62	34.33	37.36	37.83	33.90
246	33	14.61	0.00	-	Male	19	-	-	-	22.25	27.45	23.80	22.40	20.18	20.46
246	41	11.79	1.93	1.17	Male	19	34.19	34.20	31.21	34.86	31.49	32.49	39.61	36.04	31.69
246	42	12.72	1.78	1.12	Male	19	32.99	33.09	29.84	33.03	39.26	31.81	32.55	33.92	30.86
246	43	14.40	0.00	0.89	Male	19	26.64	27.12	23.78	22.25	23.30	23.80	24.90	20.18	20.46
285	11	13.63	5.13	1.64	Male	71	43.50	43.38	39.45	51.25	49.75	46.89	54.09	52.06	47.42
285	21	15.27	6.05	1.14	Male	71	43.51	43.08	37.76	52.77	57.58	51.03	52.43	53.29	51.28
302	11	13.99	8.09	2.21	Female	73	52.66	54.66	48.17	66.80	66.74	60.21	72.15	62.50	58.78

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
302	13	15.19	15.19	0.00	Female	73	67.53	67.53	54.19	99.29	89.04	92.16	98.01	69.27	73.53
302	21	13.20	5.64	2.02	Female	73	46.23	47.75	42.84	55.17	55.60	49.18	50.58	55.13	49.59
302	23	14.41	14.41	0.00	Female	73	67.53	66.67	54.19	99.29	80.19	88.65	81.58	69.27	72.78
302	31	12.33	12.33	0.00	Female	73	67.53	64.38	54.19	99.29	81.16	79.29	84.68	69.27	69.71
302	33	13.94	10.10	0.00	Female	73	55.96	55.41	44.94	78.07	73.15	69.25	74.92	67.15	64.75
302	41	12.73	12.73	2.36	Female	73	70.87	70.57	63.76	99.29	74.99	81.09	68.77	69.27	70.42
303	11	14.13	4.95	1.35	Female	44	41.96	43.99	37.29	49.24	48.71	46.08	53.00	50.38	46.63
303	21	13.14	3.75	1.15	Female	44	39.09	40.12	34.70	44.24	45.95	40.68	42.08	45.84	41.07
303	22	13.05	3.27	-	Female	44	-	-	-	41.55	40.91	38.52	41.60	43.21	38.71
303	31	12.59	3.28	1.26	Female	44	38.27	38.93	34.51	42.32	47.93	38.56	41.24	43.97	38.76
303	32	13.70	3.20	1.10	Female	44	36.79	38.49	32.58	40.24	45.87	38.20	41.32	41.87	38.36
303	33	15.71	3.64	0.00	Female	44	35.26	38.14	28.38	40.10	50.48	40.18	41.33	41.72	40.54
303	41	12.07	2.33	1.35	Female	44	35.65	36.09	32.85	37.12	35.32	34.29	40.69	38.55	33.85
303	42	14.37	3.29	0.90	Female	44	36.27	38.50	31.52	39.89	48.12	38.61	39.05	41.50	38.81
303	43	16.40	3.44	0.00	Female	44	34.34	38.04	27.64	38.41	48.25	39.28	41.07	39.95	39.56
306	11	13.21	2.72	0.00	Male	31	34.18	33.18	27.51	38.11	35.91	36.04	39.39	39.63	35.90
306	12	12.96	2.51	0.00	Male	31	33.66	32.67	27.10	37.17	35.59	35.10	36.43	38.61	34.80
306	13	17.24	4.41	0.00	Male	31	36.27	35.73	29.19	41.96	45.81	43.65	40.87	43.61	44.19
306	21	12.48	2.80	0.00	Male	31	34.95	33.79	28.13	39.53	40.78	36.40	37.80	41.13	36.32
306	22	12.99	2.23	0.00	Male	31	32.74	31.81	26.36	35.48	35.07	33.84	37.75	36.73	33.31
306	23	17.55	4.37	0.00	Male	31	35.99	35.51	28.96	41.43	43.89	43.47	40.42	43.09	44.01
306	31	12.00	2.49	1.24	Male	31	36.11	36.06	32.90	38.24	43.02	35.01	37.45	39.76	34.70
306	32	13.82	3.15	1.02	Male	31	36.43	36.27	32.06	39.81	45.53	37.98	41.09	41.42	38.11
306	33	15.08	3.30	0.00	Male	31	34.72	33.97	27.94	39.11	48.66	38.65	39.56	40.69	38.86
306	41	12.08	2.05	1.86	Male	31	35.43	36.07	34.24	35.32	32.66	33.03	39.94	36.56	32.34
306	42	13.73	2.85	1.34	Male	31	36.00	36.16	32.60	38.24	45.72	36.63	37.16	39.77	36.58
306	43	15.66	1.71	0.00	Male	31	30.12	29.78	24.26	30.66	36.73	31.50	32.94	31.10	30.47
307	11	10.82	2.57	0.73	Female	21	36.72	35.08	32.05	40.55	35.05	35.37	38.48	42.18	35.12
307	12	9.44	3.02	0.00	Female	21	38.97	34.68	31.34	46.90	38.75	37.39	37.96	48.31	37.45

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
307	13	13.19	4.93	0.00	Female	21	41.23	40.91	33.15	51.05	48.01	45.99	43.63	51.90	46.54
307	21	11.54	2.39	0.00	Female	21	34.23	32.59	27.55	38.21	38.49	34.56	35.96	39.73	34.17
307	23	13.15	3.90	0.61	Female	21	38.82	39.29	32.95	45.10	42.02	41.35	38.49	46.66	41.80
307	31	11.34	2.21	0.91	Female	21	35.16	34.38	31.28	37.26	41.12	33.75	36.11	38.71	33.21
307	41	11.38	2.42	0.91	Female	21	35.90	35.11	31.86	38.63	36.15	34.69	40.93	40.18	34.33
307	42	13.41	2.71	-	Female	21	-	-	-	37.82	44.92	36.00	36.55	39.31	35.85
307	43	12.95	3.29	0.00	Female	21	36.20	35.97	29.13	41.82	47.33	38.61	40.36	43.48	38.81
309	43	15.53	4.89	3.71	Female	58	43.05	48.59	43.50	46.51	56.30	45.81	47.88	47.96	46.36
310	13	17.92	4.88	3.04	Male	35	40.02	41.40	38.49	43.23	47.80	45.76	43.36	44.87	46.32
310	23	17.27	5.19	1.89	Male	35	40.12	40.65	36.34	45.40	47.07	47.16	43.78	46.94	47.68
310	31	11.80	2.59	1.33	Male	35	36.78	36.77	33.78	39.16	43.68	35.46	37.93	40.74	35.22
310	32	12.23	2.67	1.18	Male	35	36.44	36.32	32.90	39.07	42.11	35.82	38.88	40.64	35.64
310	33	15.62	3.02	0.76	Male	35	34.53	34.46	29.60	37.15	47.10	37.39	38.10	38.58	37.45
310	41	11.85	2.75	3.33	Male	35	40.34	42.15	42.89	40.13	39.10	36.18	41.83	41.75	36.06
310	42	12.03	2.76	1.58	Male	35	37.53	37.73	35.08	39.93	45.21	36.22	36.77	41.54	36.11
310	43	15.30	3.08	2.53	Male	35	36.96	38.11	35.89	37.76	46.02	37.66	39.38	39.25	37.75
313	11	13.32	6.77	1.02	Male	46	48.26	47.21	41.62	61.41	59.16	54.27	64.10	59.41	54.09
313	21	12.53	7.41	1.38	Male	46	52.35	51.31	46.14	67.81	63.86	57.15	58.55	63.02	56.44
313	22	14.23	8.32	1.72	Male	46	52.26	51.61	46.47	67.29	62.46	61.24	60.28	62.75	59.53
313	32	14.39	7.37	1.84	Male	46	49.34	49.01	44.40	61.71	64.90	56.97	60.50	59.59	56.30
313	33	16.52	5.85	2.16	Male	46	42.76	43.25	39.24	49.53	60.73	50.13	52.82	50.63	50.46
313	41	12.09	6.72	3.32	Male	46	53.82	54.62	53.44	65.07	62.43	54.04	52.54	61.57	53.90
313	42	14.23	7.38	2.16	Male	46	50.04	49.93	45.85	62.20	63.35	57.01	56.63	59.90	56.33
313	43	14.35	4.25	1.64	Male	46	40.03	40.19	36.44	45.07	52.93	42.93	44.88	46.63	43.45
324	11	15.20	10.77	1.48	Male	54	57.04	55.91	49.42	76.84	82.16	72.27	88.50	66.76	66.42
324	21	14.76	7.64	1.33	Male	54	48.89	48.18	42.63	62.13	64.87	58.18	59.58	59.85	57.25
324	23	18.55	8.25	1.03	Male	54	45.21	44.91	38.40	56.51	58.09	60.93	56.33	56.12	59.31
324	31	16.75	7.68	-	Male	54	-	-	-	57.57	62.95	58.36	62.36	56.87	57.39
324	32	16.45	7.01	1.06	Male	54	44.59	44.13	38.23	55.08	64.00	55.35	58.85	55.07	54.99

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
324	41	15.88	7.59	2.28	Male	54	48.19	48.36	44.06	59.07	64.55	57.96	54.89	57.90	57.08
324	43	17.42	5.25	3.88	Male	54	42.20	44.00	42.21	45.47	58.07	47.43	49.58	47.00	47.94
325	23	19.64	3.49	0.40	Male	36	33.36	33.64	27.61	35.94	40.37	39.51	36.81	37.25	39.80
325	32	16.22	1.67	0.97	Male	36	30.93	31.35	27.14	30.18	34.20	31.32	34.28	30.51	30.25
325	33	17.72	4.60	0.00	Male	36	36.43	35.95	29.31	42.25	55.28	44.50	46.32	43.90	45.06
325	41	13.90	2.48	0.00	Male	36	33.02	32.21	26.59	36.00	36.70	34.96	41.10	37.31	34.64
327	11	10.22	2.05	0.98	Female	31/37	35.68	33.86	32.28	37.70	32.07	33.03	35.31	39.19	32.34
327	12	11.09	2.06	0.83	Female	31/37	34.68	33.58	30.69	36.56	32.73	33.07	35.08	37.94	32.39
327	13	15.32	2.98	0.00	Female	31/37	33.70	36.26	27.13	37.24	39.64	37.21	33.29	38.68	37.24
327	21	10.01	2.02	1.07	Female	31/37	35.93	34.01	32.89	37.80	36.38	32.89	34.29	39.29	32.18
327	22	10.57	2.37	0.00	Female	31/37	34.95	32.19	28.12	39.52	35.88	34.47	38.27	41.12	34.06
327	23	15.60	4.98	0.00	Female	31/37	38.94	41.43	31.32	46.84	46.27	46.21	42.92	48.26	46.76
327	31	11.21	3.38	1.14	Female	31/37	40.02	39.06	35.97	45.48	48.50	39.01	41.72	47.01	39.26
327	32	11.74	3.20	0.37	Female	31/37	37.55	36.34	31.38	43.25	45.87	38.20	41.32	44.89	38.36
327	33	15.22	2.72	0.00	Female	31/37	33.04	35.53	26.60	36.02	45.39	36.04	36.54	37.34	35.90
327	41	10.52	3.17	0.88	Female	31/37	39.69	37.74	35.03	45.46	42.63	38.07	42.96	47.00	38.21
327	42	11.59	2.93	0.78	Female	31/37	37.36	36.51	32.56	41.73	46.17	36.99	37.50	43.38	36.99
337	13	20.12	11.16	4.42	Male	68	52.78	54.19	50.56	64.98	72.88	74.02	76.65	61.52	67.32
337	31	13.65	8.23	-	Male	68	-	-	-	68.70	63.36	60.84	65.00	63.45	59.24
337	32	14.00	8.85	2.47	Male	68	55.26	55.04	50.93	70.95	67.15	63.63	67.31	64.50	61.20
337	33	17.32	5.01	2.57	Male	68	40.35	41.35	37.97	44.53	57.17	46.35	48.45	46.12	46.89
337	41	14.01	9.03	1.96	Male	68	55.12	54.47	49.47	71.91	64.11	64.44	58.78	64.91	61.75
337	42	13.78	9.14	2.70	Male	68	56.91	56.79	52.99	73.35	65.91	64.93	64.20	65.50	62.07
338	11	13.10	0.92	0.00	Female	33	28.48	28.97	22.95	27.66	25.58	27.94	28.41	27.36	25.98
338	12	12.06	1.56	0.00	Female	33	30.96	30.13	24.94	32.22	29.48	30.82	33.58	32.96	29.64
338	22	12.15	1.72	0.40	Female	33	32.07	31.73	27.05	33.16	32.02	31.54	35.86	34.07	30.53
338	23	14.59	1.92	0.00	Female	33	31.06	33.00	25.01	32.39	33.79	32.44	30.37	33.17	31.63
338	31	13.58	1.58	1.55	Female	33	32.47	34.83	30.39	31.21	36.54	30.91	33.08	31.76	29.75
338	32	14.50	1.50	0.85	Female	33	30.93	33.62	27.09	30.22	32.74	30.55	33.50	30.56	29.30

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
338	33	13.80	0.78	0.00	Female	33	27.90	29.20	22.49	26.60	33.03	27.31	26.46	26.00	25.16
338	41	12.66	1.77	1.64	Female	33	33.73	35.21	31.97	33.02	29.89	31.77	39.18	33.91	30.80
338	42	14.44	1.68	1.16	Female	33	31.86	34.73	28.65	31.21	38.61	31.36	32.12	31.76	30.31
338	43	13.20	1.26	0.00	Female	33	29.54	30.06	23.80	29.60	33.39	29.47	30.82	29.80	27.94
339	11	10.30	6.54	2.15	Female	64	55.96	54.38	52.70	71.17	57.84	53.23	62.69	64.59	53.21
339	12	10.82	6.67	1.22	Female	64	53.45	51.26	47.12	69.74	58.86	53.82	48.91	63.95	53.71
339	13	13.08	7.29	1.54	Female	64	51.06	51.59	45.39	65.19	57.69	56.61	56.14	61.63	56.01
339	23	13.40	6.18	1.59	Female	64	47.04	48.22	42.21	57.78	50.79	51.61	47.84	57.01	51.80
339	33	13.27	5.09	1.78	Female	64	44.05	45.53	40.40	51.80	57.53	46.71	48.87	52.52	47.24
339	43	13.55	4.68	2.25	Female	64	43.03	45.34	40.76	48.86	55.22	44.86	46.90	50.05	45.42
342	11	14.68	4.43	0.96	Male	75	39.38	39.04	34.10	45.50	45.73	43.74	49.82	47.03	44.28
342	12	15.85	3.30	0.49	Male	75	34.83	34.56	29.18	38.29	40.44	38.65	38.80	39.82	38.86
342	13	21.37	8.85	0.92	Male	75	43.70	43.78	36.73	54.15	63.82	63.63	64.41	54.37	61.20
342	21	15.12	4.47	2.14	Male	75	40.49	41.07	37.83	45.03	49.73	43.92	45.32	46.59	44.47
342	22	16.16	3.81	1.55	Male	75	37.16	37.57	33.46	40.41	43.76	40.95	43.60	42.05	41.36
342	23	22.42	11.98	2.44	Male	75	49.93	50.53	44.16	63.42	71.32	77.71	71.62	60.62	69.05
342	31	15.48	10.45	1.01	Male	75	55.06	53.71	46.64	74.26	73.20	70.83	75.66	65.85	65.64
342	32	17.77	4.39	0.85	Male	75	36.77	36.86	31.36	41.28	53.21	43.56	46.79	42.93	44.10
342	33	21.80	7.13	2.26	Male	75	41.13	42.20	36.93	47.45	65.38	55.89	59.48	48.81	55.43
342	41	16.16	5.57	1.85	Male	75	42.07	42.36	38.08	48.80	57.98	48.87	49.44	50.00	49.30
342	42	17.01	3.61	1.31	Male	75	35.83	36.23	31.70	38.60	49.77	40.05	40.42	40.15	40.39
342	43	20.92	7.28	-	Male	75	-	-	-	49.06	66.37	56.56	59.12	50.22	55.98
346	13	17.14	6.73	5.40	Female	59	47.69	55.75	50.04	52.50	55.43	54.09	53.17	53.08	53.94
346	22	14.26	3.47	4.85	Female	59	41.87	47.54	46.32	41.00	41.98	39.42	42.34	42.64	39.70
347	11	11.91	2.71	3.39	Male	56	40.21	42.08	42.92	39.78	35.86	36.00	39.33	41.39	35.85
347	12	16.44	3.02	4.12	Male	56	37.76	40.07	39.69	36.40	38.75	37.39	37.96	37.76	37.45
347	13	21.47	6.02	2.50	Male	56	39.40	40.70	36.02	43.85	52.54	50.89	49.41	45.47	51.16
347	21	12.89	3.53	2.55	Male	56	40.59	41.52	40.00	43.35	44.77	39.69	41.09	44.98	40.00
347	22	16.17	3.81	2.30	Male	56	37.99	38.91	35.85	40.40	43.76	40.95	43.60	42.03	41.36

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
347	31	13.80	5.12	-	Male	56	-	-	-	50.83	56.75	46.84	50.08	51.72	47.37
347	32	16.36	3.35	4.18	Male	56	38.73	41.02	40.66	38.03	46.88	38.88	42.01	39.53	39.11
347	33	19.31	4.61	5.74	Male	56	40.91	44.00	43.95	40.64	55.33	44.55	46.37	42.28	45.11
347	41	15.12	4.14	6.60	Male	56	44.89	48.78	52.31	43.34	49.82	42.43	45.58	44.98	42.93
347	42	16.02	4.52	4.99	Male	56	42.99	45.61	46.14	43.99	54.05	44.14	44.34	45.60	44.70
347	43	19.03	5.90	2.94	Male	56	41.33	42.60	38.98	46.14	61.04	50.35	52.63	47.62	50.67
350	11	14.24	0.00	0.72	Female	23	26.44	29.05	23.20	22.25	20.30	23.80	22.80	20.18	20.46
350	21	15.03	0.00	0.68	Female	23	26.34	29.76	22.93	22.25	24.30	23.80	25.20	20.18	20.46
350	31	14.59	0.00	0.88	Female	23	26.62	29.74	23.70	22.25	23.16	23.80	25.50	20.18	20.46
359	23	18.04	11.33	2.35	Female	46	54.25	60.20	48.42	70.63	68.94	74.79	68.95	64.36	67.70
359	31	13.12	10.30	7.97	Female	46	69.44	75.70	78.31	82.73	72.57	70.15	74.94	68.36	65.26
359	41	13.17	6.50	3.98	Female	46	51.70	54.92	52.77	60.27	61.73	53.05	51.95	58.69	53.06
359	42	14.18	7.26	5.15	Female	46	53.57	58.64	56.53	61.69	63.08	56.47	56.12	59.59	55.90
363	11	14.37	6.28	0.00	Male	61	43.88	42.37	35.27	55.92	56.35	52.06	61.11	55.69	52.20
363	12	12.02	2.74	0.00	Male	61	35.10	33.86	28.25	39.81	37.02	36.13	37.12	41.42	36.01
363	22	12.65	2.68	0.81	Male	61	35.58	35.19	31.01	38.57	37.66	35.86	39.42	40.12	35.69
363	23	17.19	8.19	1.07	Male	61	46.66	46.13	39.81	58.95	57.88	60.66	56.08	57.82	59.11
363	31	13.41	3.64	3.98	Male	61	42.27	44.37	45.03	43.16	49.94	40.18	42.97	44.80	40.54
363	32	13.76	4.46	-	Male	61	-	-	-	47.22	53.59	43.87	47.12	48.61	44.42
363	33	16.70	5.90	1.99	Male	61	42.51	42.91	38.61	49.47	60.93	50.35	53.08	50.57	50.67
363	41	12.53	2.69	2.95	Male	61	38.78	40.25	39.95	38.79	38.58	35.91	41.66	40.35	35.75
363	43	16.83	5.30	2.49	Male	61	41.42	42.27	38.81	46.51	58.31	47.65	49.81	47.96	48.15
369	31	11.39	0.00	1.75	Female	30	28.30	29.11	28.52	22.25	23.16	23.80	25.50	20.18	20.46
369	11	8.70	0.77	0.34	Female	30	29.95	26.05	25.58	29.07	24.72	27.27	27.50	29.13	25.10
369	12	12.56	0.00	0.00	Female	30	25.53	25.64	20.59	22.25	18.80	23.80	28.90	20.18	20.46
369	13	16.27	2.92	0.32	Female	30	33.42	37.33	27.64	36.08	39.37	36.94	32.98	37.40	36.94
369	21	10.22	1.26	1.96	Female	30	34.16	33.82	34.63	31.75	31.95	29.47	30.87	32.41	27.94
369	22	11.60	1.03	0.00	Female	30	29.26	28.04	23.57	29.09	27.72	28.44	33.31	29.16	26.61
369	23	16.07	3.39	0.00	Female	30	34.39	37.72	27.68	38.50	39.96	39.06	36.40	40.04	39.31

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
369	32	14.45	1.23	1.25	Female	30	30.66	33.72	27.91	28.81	30.37	29.34	32.26	28.81	27.77
369	33	14.85	2.54	0.76	Female	30	33.64	36.41	28.98	35.43	44.33	35.23	35.61	36.68	34.96
369	41	12.39	1.27	1.28	Female	30	31.69	32.65	29.37	30.15	24.67	29.52	37.83	30.47	27.99
369	42	13.46	1.90	1.26	Female	30	33.14	35.03	30.16	33.12	40.03	32.35	33.07	34.03	31.52
369	43	14.76	0.97	0.37	Female	30	28.74	31.40	24.09	27.31	31.17	28.17	29.46	26.91	26.27
374	33	17.77	12.18	-	Male	80	-	-	-	75.06	80.43	78.61	97.10	66.15	69.43
381	11	12.21	5.62	-	Male	68	-	-	-	57.71	52.56	49.09	57.08	56.97	49.51
383	11	12.12	6.27	0.81	Female	55	48.46	47.40	41.42	62.10	56.29	52.02	61.05	59.84	52.16
383	13	12.23	3.39	0.00	Female	55	37.17	36.08	29.90	43.60	41.42	39.06	35.47	45.23	39.31
383	32	11.81	6.80	1.06	Female	55	51.33	50.05	44.57	66.61	63.40	54.40	57.88	62.40	54.21
383	42	11.57	5.39	0.00	Female	55	45.10	42.72	36.24	58.14	57.54	48.06	48.08	57.26	48.54
385	11	11.61	1.52	1.32	Female	25	33.08	33.22	30.86	32.34	29.02	30.64	32.07	33.11	29.41
385	12	12.70	1.24	1.76	Female	25	32.13	33.89	31.02	29.77	27.35	29.38	32.62	30.01	27.82
385	13	15.09	1.88	0.95	Female	25	31.90	35.23	28.03	31.85	34.77	32.26	27.46	32.53	31.41
385	21	11.08	1.46	2.11	Female	25	34.49	35.05	34.84	32.40	33.13	30.37	31.77	33.18	29.07
385	22	12.92	2.50	1.90	Female	25	36.30	38.14	34.68	37.16	36.63	35.05	38.75	38.59	34.75
385	23	15.07	0.00	0.74	Female	25	26.41	29.92	23.12	22.25	25.27	23.80	22.50	20.18	20.46
385	31	11.81	1.54	1.03	Female	25	32.58	32.60	29.47	32.30	36.23	30.73	32.89	33.06	29.52
385	32	13.41	1.42	0.00	Female	25	29.98	30.70	24.15	30.41	32.05	30.19	33.13	30.79	28.85
385	33	14.54	1.87	0.00	Female	25	30.93	32.83	24.91	32.16	40.24	32.22	32.12	32.89	31.36
385	41	11.75	1.16	0.00	Female	25	29.68	28.60	23.91	29.86	23.47	29.02	37.53	30.11	27.36
385	42	13.08	1.63	0.00	Female	25	30.76	31.07	24.78	31.85	38.28	31.14	31.91	32.53	30.03
385	43	14.96	1.44	1.28	Female	25	31.11	34.68	28.24	29.67	34.75	30.28	31.67	29.87	28.96
386	12	12.91	6.30	0.73	Female	61	47.04	46.81	39.91	59.85	57.02	52.15	47.80	58.41	52.28
386	13	17.13	9.05	0.46	Female	61	48.20	52.10	39.73	62.95	64.42	64.53	65.47	60.35	61.81
386	21	11.60	6.07	1.50	Female	61	49.84	49.00	44.85	62.56	57.67	51.12	52.52	60.12	51.36
386	22	12.44	6.95	0.93	Female	61	50.34	49.61	43.22	65.29	57.74	55.08	55.22	61.69	54.77
386	31	12.17	5.63	2.18	Female	61	48.18	48.80	45.38	57.89	58.55	49.14	52.52	57.09	49.55
386	32	12.68	5.96	1.54	Female	61	47.46	47.86	42.65	58.46	60.56	50.62	54.02	57.48	50.91

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
386	33	13.75	7.24	-	Female	61	-	-	-	62.82	65.73	56.38	60.05	60.27	55.83
386	41	11.19	11.19	1.71	Female	61	70.28	67.87	62.08	99.29	70.46	74.16	64.61	69.27	67.39
386	42	12.68	7.23	1.55	Female	61	51.68	51.79	46.06	66.18	63.02	56.34	55.99	62.17	55.80
386	43	14.93	11.51	0.00	Female	61	57.91	58.31	46.49	81.64	74.19	75.60	79.00	68.11	68.09
390	12	13.24	8.51	2.02	Female	71	55.27	56.18	50.06	71.77	67.34	62.10	54.43	64.85	60.14
390	23	14.78	6.48	1.61	Female	71	45.90	48.55	40.94	56.03	51.88	52.96	49.07	55.77	52.98
390	32	14.02	4.36	0.00	Female	71	38.59	39.37	31.04	46.21	53.04	43.42	46.66	47.69	43.96
390	33	15.01	8.42	-	Female	71	-	-	-	65.47	69.10	61.69	66.18	61.79	59.86
390	42	15.37	8.17	0.00	Female	71	47.86	49.46	38.45	63.20	64.81	60.57	60.03	60.50	59.04
390	43	17.17	6.30	2.22	Female	71	43.27	49.02	39.59	50.52	62.72	52.15	54.51	51.46	52.28
394	23	14.30	6.44	1.47	Female	58	46.30	48.30	41.03	56.94	51.74	52.78	48.90	56.43	52.83
413	11	13.23	3.69	1.28	Female	39	38.99	40.25	34.95	43.74	41.48	40.41	45.31	45.36	40.78
413	12	13.35	3.58	0.58	Female	39	37.57	38.31	31.84	42.91	42.12	39.91	39.64	44.55	40.25
413	13	14.84	3.46	0.50	Female	39	35.93	38.28	30.16	40.21	41.73	39.37	35.84	41.84	39.65
413	21	13.71	3.01	0.83	Female	39	35.84	37.34	31.09	39.16	41.94	37.35	38.75	40.74	37.40
413	22	13.41	1.92	0.66	Female	39	32.43	33.68	27.94	33.28	33.23	32.44	36.60	34.22	31.63
413	31	12.82	4.01	1.08	Female	39	40.18	40.73	35.45	46.35	51.87	41.85	44.75	47.81	42.32
413	32	14.32	3.03	0.84	Female	39	35.47	37.64	30.73	38.55	44.70	37.44	40.54	40.10	37.50
413	41	12.22	3.17	1.43	Female	39	38.53	39.01	35.35	42.24	42.63	38.07	42.96	43.89	38.21
413	42	14.40	3.32	0.99	Female	39	36.45	38.78	31.89	40.01	48.28	38.74	39.18	41.63	38.96
413	43	14.68	3.14	0.86	Female	39	35.57	38.13	30.80	38.73	46.40	37.93	39.66	40.28	38.06
422	11	13.37	4.68	0.85	Female	29	41.38	42.15	35.63	49.22	47.16	44.86	51.35	50.36	45.42
422	13	13.72	3.19	0.69	Female	29	36.20	37.54	31.00	40.16	40.55	38.16	34.41	41.79	38.31
422	21	12.78	2.28	0.49	Female	29	33.71	34.02	28.56	35.99	37.86	34.06	35.46	37.31	33.58
422	22	12.66	3.84	0.00	Female	29	38.27	37.58	30.78	45.62	43.92	41.08	43.71	47.14	41.51
422	31	10.03	2.65	2.55	Female	29	41.20	41.04	42.59	42.60	44.07	35.73	38.22	44.25	35.54
422	32	12.35	4.08	1.98	Female	29	42.29	43.26	39.96	47.70	51.44	42.16	45.37	49.03	42.65
422	33	12.37	1.74	0.69	Female	29	32.44	32.64	28.20	33.09	39.42	31.63	31.45	33.99	30.64
422	41	10.79	3.58	1.51	Female	29	41.98	40.97	38.96	47.81	45.83	39.91	44.07	49.13	40.25

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
422	42	12.48	4.71	2.55	Female	29	45.06	46.60	43.82	51.33	54.86	45.00	45.15	52.13	45.56
422	43	11.99	3.47	0.79	Female	29	38.87	38.34	33.71	44.55	48.43	39.42	41.21	46.13	39.70
427	11	13.27	0.00	0.82	Male	27	26.64	26.95	23.78	22.25	20.30	23.80	22.80	20.18	20.46
427	41	11.94	2.77	1.43	Male	27	37.43	37.48	34.57	40.12	39.27	36.27	41.88	41.75	36.16
430	13	18.29	3.71	0.68	Female	30	34.72	41.00	29.32	37.88	42.81	40.50	37.16	39.37	40.88
430	21	10.79	0.99	0.59	Female	30	30.37	28.96	26.50	29.32	30.34	28.26	29.66	29.44	26.38
430	22	11.58	2.46	1.34	Female	30	36.54	36.43	33.70	38.62	36.40	34.87	38.60	40.16	34.54
430	23	17.51	2.30	0.70	Female	30	31.77	37.44	27.07	32.37	35.42	34.15	31.93	33.15	33.69
430	31	13.12	1.40	2.18	Female	30	33.00	35.56	32.75	30.47	35.15	30.10	32.22	30.86	28.73
430	32	15.06	1.41	0.74	Female	30	30.35	33.56	26.27	29.46	31.96	30.15	33.09	29.62	28.79
430	33	15.68	1.28	0.00	Female	30	28.96	32.25	23.33	28.54	36.42	29.56	29.06	28.47	28.05
430	41	13.07	1.22	3.12	Female	30	33.75	37.24	36.05	29.44	24.13	29.29	37.69	29.60	27.71
430	42	14.30	1.67	0.98	Female	30	31.67	34.23	28.05	31.25	38.54	31.32	32.08	31.80	30.25
436	13	15.17	5.59	2.28	Female	64	43.71	47.54	40.73	50.64	50.76	48.96	47.13	51.56	49.39
436	22	14.85	6.66	-	Female	64	-	-	-	56.80	56.63	53.77	54.14	56.33	53.67
436	43	13.30	5.09	1.35	Female	64	43.43	44.52	38.69	51.73	57.29	46.71	48.82	52.46	47.24
441	11	13.47	1.17	1.35	Female	23	30.98	33.13	28.68	28.94	27.02	29.07	29.94	28.97	27.42
441	12	14.16	1.52	0.00	Female	23	30.04	31.58	24.20	30.52	29.21	30.64	33.46	30.92	29.41
441	13	14.67	2.46	0.00	Female	23	32.57	34.50	26.23	35.17	37.35	34.87	30.54	36.38	34.54
441	21	13.64	1.38	0.00	Female	23	29.78	30.77	23.99	30.04	32.66	30.01	31.41	30.34	28.62
441	22	14.23	2.14	0.00	Female	23	31.85	33.34	25.64	33.84	34.54	33.43	37.42	34.86	32.83
441	23	15.63	2.61	0.00	Female	23	32.54	35.53	26.20	35.11	36.73	35.55	33.20	36.32	35.33
441	31	14.13	0.00	1.54	Female	23	27.49	30.74	26.21	22.25	23.16	23.80	25.50	20.18	20.46
441	32	14.94	1.88	0.52	Female	23	31.44	34.24	26.62	31.94	35.95	32.26	35.25	32.64	31.41
441	33	15.73	2.88	1.05	Female	23	34.42	38.33	30.19	36.36	46.31	36.76	37.38	37.71	36.73
441	41	13.90	2.91	1.22	Female	23	35.90	38.00	32.15	38.38	40.47	36.90	42.26	39.91	36.88
441	42	15.48	1.33	0.96	Female	23	30.25	34.12	26.68	28.87	36.28	29.79	30.62	28.88	28.34
441	43	16.46	2.05	0.00	Female	23	30.76	34.78	24.78	31.84	39.16	33.03	34.54	32.52	32.34
457	33	13.13	4.27	3.70	Female	57	44.26	47.68	46.06	47.30	53.69	43.02	44.60	48.68	43.54

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
461	11	12.09	1.56	-	Female	28	-	-	-	32.19	29.25	30.82	32.32	32.93	29.64
461	12	12.59	1.91	2.35	Female	28	35.26	37.37	35.32	33.94	31.76	32.40	34.63	34.98	31.58
461	21	11.73	1.89	1.97	Female	28	35.32	36.21	34.67	34.66	35.63	32.31	33.71	35.81	31.47
461	22	11.72	1.92	1.73	Female	28	35.07	35.68	33.71	34.87	33.23	32.44	36.60	36.05	31.63
461	23	11.88	0.00	1.06	Female	28	27.14	27.65	25.20	22.25	25.27	23.80	22.50	20.18	20.46
461	31	10.65	1.02	-	Female	28	-	-	-	29.63	32.11	28.39	30.40	29.83	26.56
461	32	12.64	0.00	-	Female	28	-	-	-	22.25	18.58	23.80	26.60	20.18	20.46
461	33	12.14	1.24	2.76	Female	28	33.91	36.21	35.75	30.12	36.16	29.38	28.85	30.43	27.82
461	42	12.44	0.65	-	Female	28	-	-	-	26.28	31.48	26.73	27.70	25.57	24.39
461	43	12.10	0.00	-	Female	28	-	-	-	22.25	23.30	23.80	24.90	20.18	20.46
466	31	12.28	2.31	2.92	Female	43	37.71	40.04	39.18	36.74	41.81	34.20	36.59	38.14	33.74
466	33	14.78	2.55	0.70	Female	43	33.63	36.27	28.83	35.54	44.39	35.28	35.66	36.80	35.01
466	41	12.08	2.52	3.13	Female	43	38.96	41.28	40.97	38.32	37.06	35.14	41.20	39.85	34.86
466	42	14.83	1.47	3.18	Female	43	33.55	38.65	34.99	29.89	37.22	30.42	31.22	30.15	29.13
473	11	15.21	3.44	2.09	Male	42	37.50	38.26	35.28	39.67	40.05	39.28	43.78	41.28	39.56
473	12	15.01	3.43	0.59	Male	42	35.84	35.47	30.30	39.85	41.22	39.24	39.19	41.47	39.51
473	21	15.56	2.83	2.84	Male	42	36.45	37.89	36.12	36.26	40.95	36.54	37.94	37.61	36.47
473	22	15.96	2.44	2.87	Male	42	35.19	36.74	35.01	34.03	36.29	34.78	38.53	35.08	34.43
473	31	16.46	3.17	1.03	Male	42	34.75	34.96	30.29	37.09	47.29	38.07	40.72	38.52	38.21
473	32	15.36	1.53	3.25	Male	42	33.52	35.49	34.86	29.92	33.00	30.69	33.64	30.19	29.47
473	33	15.12	2.67	1.49	Male	42	34.72	35.18	31.61	35.85	45.09	35.82	36.28	37.15	35.64
473	41	15.58	1.66	2.75	Male	42	33.18	34.78	33.28	30.46	28.77	31.27	38.88	30.85	30.19
473	42	15.61	2.52	1.44	Male	42	33.97	34.48	30.78	34.69	43.82	35.14	35.74	35.84	34.86
473	43	15.85	3.05	1.21	Male	42	34.99	35.27	31.00	37.07	45.84	37.53	39.24	38.50	37.60
476	11	13.06	2.35	0.80	Female	31	34.19	35.10	29.80	36.11	33.79	34.38	37.14	37.44	33.95
476	12	12.50	2.25	1.47	Female	31	35.21	36.24	32.71	36.12	33.94	33.93	35.65	37.45	33.42
476	13	15.63	4.12	1.23	Female	31	38.02	41.73	33.51	42.56	44.57	42.34	39.34	44.21	42.84
476	21	12.46	1.59	1.01	Female	31	32.35	33.02	29.06	32.08	33.89	30.96	32.36	32.80	29.80
476	22	11.12	1.39	0.00	Female	31	30.78	28.93	24.79	31.88	29.99	30.06	34.64	32.56	28.68

Feature no.	Tooth no.	Root height	Transparency	Periodontosis	Known sex	Known age	Lamendin	P. & U.	Schmitt	Singhal	B. & R.	W. & A.[1]	W. & A.[2]	Formula 1	Formula 2
476	23	15.91	3.82	0.71	Female	31	36.42	40.07	30.96	40.75	41.70	40.99	38.16	42.39	41.41
476	31	11.50	2.44	0.55	Female	31	35.30	34.23	30.19	38.60	42.69	34.78	37.21	40.14	34.43
476	32	12.51	1.85	0.00	Female	31	31.74	31.35	25.56	33.64	35.70	32.13	35.11	34.64	31.25
476	41	11.46	1.70	0.97	Female	31	33.28	32.84	29.94	33.68	29.18	31.45	38.99	34.68	30.42
476	42	13.09	2.14	0.79	Female	31	33.48	34.47	29.20	34.84	41.53	33.43	34.10	36.02	32.83
476	43	14.30	2.36	0.71	Female	31	33.36	35.53	28.70	34.96	41.30	34.42	35.99	36.15	34.01
482	12	12.46	1.60	0.68	Male	36	31.91	31.63	27.72	32.14	29.74	31.00	33.70	32.88	29.86
482	21	12.55	1.99	0.72	Male	36	33.22	32.90	28.88	34.47	36.21	32.76	34.16	35.58	32.01
482	22	12.36	1.97	0.71	Male	36	33.26	32.91	28.91	34.53	33.53	32.67	36.79	35.66	31.90
482	23	13.38	2.59	1.01	Male	36	35.02	34.92	30.99	37.16	36.64	35.46	33.12	38.60	35.22
482	31	11.97	2.05	1.29	Male	36	34.66	34.77	31.91	35.44	40.00	33.03	35.34	36.69	32.34
482	32	12.73	1.56	0.85	Male	36	31.88	31.80	28.15	31.69	33.26	30.82	33.78	32.34	29.64
482	33	13.92	2.60	0.00	Male	36	33.37	32.54	26.87	36.64	44.68	35.50	35.92	38.03	35.28
482	41	11.65	2.05	0.51	Male	36	33.71	33.05	28.76	35.81	32.66	33.03	39.94	37.10	32.34
482	42	13.02	1.90	0.53	Male	36	32.39	31.99	27.59	33.49	40.03	32.35	33.07	34.46	31.52
482	43	14.01	3.27	0.00	Male	36	35.33	34.37	28.43	40.23	47.21	38.52	40.27	41.86	38.71
487	21	9.43	0.00	1.05	Female	29	27.53	25.64	26.34	22.25	24.30	23.80	25.20	20.18	20.46
487	42	12.28	3.25	-	Female	29	-	-	-	42.64	47.91	38.43	38.88	44.29	38.61
521	11	14.17	5.74	0.71	M	69	39.59	39.42	33.31	46.75	49.15	49.63	46.03	48.18	53.99
521	12	14.02	5.44	1.00	M	69	43.11	42.47	37.31	52.14	52.57	48.28	45.22	52.79	52.69
521	23	18.05	4.84	0.89	M	69	37.49	37.63	31.97	42.59	56.40	45.58	47.57	44.24	49.94
521	31	14.64	4.77	2.12	M	69	42.36	42.76	39.62	48.18	47.68	45.27	51.90	49.46	49.60
521	32	16.43	4.49	0.00	M	69	35.91	35.54	28.90	41.30	54.22	44.01	46.00	42.95	48.23
521	33	18.33	4.51	0.00	M	69	37.06	36.34	29.81	43.40	53.86	44.10	47.35	45.03	48.33
521	41	14.36	3.36	0.00	M	69	35.36	34.45	28.45	40.28	44.14	38.92	43.47	41.90	42.22
521	43	18.16	3.86	0.00	M	69	36.60	35.65	29.45	42.56	51.10	41.17	44.03	44.21	44.97

Appendix 2

Mean estimated age-at-death (in years) using root translucency of Middenbeemster individuals with estimated sex and age-at-death:

Feature no.	No. of teeth	Est. sex	Age category	Formula 1	Formula 2	Singhal *et al.*
108 (V192)	6	M	LYA-MA	43,30	45,72	41,70
180 (V432)	6	M	EYA	26,69	25,00	27,19
183 (V311)	10	F	LYA	38,61	37,06	37,24
186 (V411)	4	M	MA	42,60	42,93	38,45
198 (V601)	9	PF	LYA	29,73	28,90	29,96
216 (V233)	3	F	MA	50,27	52,04	49,25
220 (V232)	5	PF	MA	44,47	45,48	42,89
242 (V338)	5	M	OA	51,15	55,09	50,43
251 (V624)	7	M	MA	39,73	40,99	38,49
257 (V1006)	11	M	LYA	33,47	35,10	32,78
270 (V1067)	8	M	EYA	21,24	20,92	23,06
278 (V584)	4	F	MA	38,73	40,28	37,75
281 (V542)	4	PM	MA	48,43	45,06	47,54
311 (V956)	7	F	EYA	49,49	48,32	49,20
349 (V752)	1	M	OA	55,46	61,62	55,61
368 (V794)	11	M	LYA	34,57	35,31	33,72
397 (V842)	1	PF	OA	65,51	66,41	73,39
401 (V876)	9	F	LYA	37,95	37,46	36,76
405 (V882)	7	F	MA	44,30	44,51	42,72
437 (V1501)	11	PF	LYA	33,41	31,37	32,79
455 (V976)	5	PM	OA	50,22	52,34	49,24

Mean estimated age-at-death (in years) using root translucency of Arnhem (*Eusebiuskerk*) individuals with estimated sex and age-at-death:

Feature no.	No. of teeth	Est. sex	Age category	Formula 1	Formula 2	Singhal *et al.*
258 (V246)	4	M	MA	38,31	39,36	37,03
438 (V687)	7	PF	LYA	29,97	28,47	29,84
597 (V1040)	5	M	OA	52,56	54,43	52,26
643 (V1253)	6	M	MA	45,24	45,83	45,30
659 (V1298)	8	M	OA	46,31	47,97	45,14
697 (V1375)	9	M	MA	34,47	35,34	33,66
711 (V1585)	12	PF	LYA	32,29	31,73	31,71
722 (V1434)	7	F	EYA	25,05	24,18	26,03
730 (V1454)	10	PF	EYA	20,52	20,14	22,50
752 (V1500)	6	PM	LYA	31,40	30,62	31,08
781 (V1588)	5	F	MA	50,40	46,17	49,57
801 (V1638)	11	F	LYA	27,17	25,82	27,67
807 (V1659)	12	M	MA	47,79	49,16	47,41

862 (V1752)	8	F	MA	41,34	43,27	40,73
864 (V1754)	4	PF	MA	47,78	47,30	46,95
902 (V1837)	3	M	OA	63,47	64,35	69,23
905 (V1840)	5	PF	MA	57,43	57,71	60,38
1021 (V2062)	9	M	EYA	25,94	26,07	26,68
1245 (V2433)	8	F	MA	35,86	34,55	34,84
1255 (V2451)	9	M	OA	52,92	55,60	52,79

Est. sex (estimated sex): F = Female, PF = Probable Female, PM = Probable Male, M = Male.

Age category: EYA = Early Young Adult (18-25 years), LYA = Late Young Adult (26-35 years), MA = Middle Adult (36-49 years), OA = Old Adult (50+ years).